Abstract— Modern operational and/or high resolution SAR satellite missions impose stringent requirements on on-board data compression such as a higher data reduction ratio, more flexibility, and faster data throughput. A novel approach is Flexible Dynamic Block Adaptive Quantization (FDBAQ). This method outperforms currently used Block Adaptive Quantization with respect to Signal-to-Noise-Ratio related to the compression ratio. The FDBAQ method allows bit rate programmability with non-integer rates. This allows the SAR information throughput to be optimized for different types of targets and down-link scenarios using a tradeoff between thermal and quantization noise.

I. INTRODUCTION

Raw SAR data compression has been applied for the first time in the NASA Magellan mission to Venus from 1989 to 1994 [1]. Also the ASAR data from the ENVISAT satellite is transmitted in a raw compressed format [2]. The type of compression applied in these cases has been called Block Adaptive Quantization (BAQ). Raw SAR data compression is not lossless. The digitization and coding process introduce additional noise and effects on the SAR images to be processed. Until today most space SAR sensors have been built to fulfill scientific or technology demonstration objectives. But the coming years will show a trend towards more and more operational use of remote sensing data. This will have its impact on the user and the system requirements imposed on on-board data compression. In Section II we will introduce the GMES Sentinel-1 operational mission including the requirements on resolution, and radar duty cycle over an orbit related to the down link data rate limitations. In Section III a novel algorithm for SAR compression is presented, that is able to meet in particular the interferometric requirements for the Sentinel-1 mission by taking the limitations of the traditional compression schemes related to a poor response of weak targets in the presence of strong permanent scatterers in consideration: Flexible Dynamic Block Adaptive Quantization (FDBAQ). Section IV reports on simulation results with FDBAQ based on ENVISAT ASAR GM Mosaic data, followed by a number of conclusions in Section V.

II. GMES SENTINEL-1

The global Monitoring for Environment and Security (GMES) space component relies on existing and planned space assets by European States, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the European Space Agency (ESA), as well as new complementary developments by ESA. The new developments are implemented in terms of five families of satellites called Sentinels. The Sentinel-1 mission 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. Fig. 1 shows an artist impression of Sentinel-1A in orbit.

Three priorities (fast track services) for the mission have been identified by user consultation working groups of the European Union: Marine Core Services, Land Monitoring and Emergency Services. These cover applications such as: monitoring sea ice ice zones and the arctic environment, surveillance of marine environment, monitoring land surface motion risks, mapping of land surfaces: forest, water and soil, agriculture, mapping in support of humanitarian aid in crisis situations.

Figure 1. Artist impression of Sentinel-1A

Sentinel-1 has been designed to address medium resolution applications. It includes a main mode of operation that features a wide swath (250 km) and a medium resolution (20 m x 5 m, azimuth x range). The observation geometry is...
given in Fig. 2. The two-satellite constellation offers six days exact repeat and the conflict-free operations based on the main operational mode allow exploiting every single data take.

Figure 2. GMES Sentinel-1 observation geometry

Sentinel-1 is being realized by an industrial consortium lead by Thales Alenia Space Italy as Prime Contractor, with Astrium Germany being responsible for the C-SAR payload, incorporating the central radar electronics sub-system developed by Astrium UK. The spacecraft is based on the PRIMA (Piattaforma Italiana Multi Applicativa) bus, with a mission specific payload module as per the PRIMA concept. Experience gained from the RadarSat-2 and from the Cosmo-Skymed programs, in which PRIMA also was selected as the spacecraft baseline, is a benefit for the Sentinel-1 implementation. The Sentinel-1 main characteristics are shown in Table 1.

![Table 1: Sentinel-1 Spacecraft Characteristics](image)

The Sentinel-1 mission requirements ask for a wide variety of data products with different image characteristics, which require the implementation of four different measurement modes:

- Stripmap Mode
- Interferometric Wideswath Mode
- Extra-Wideswath Mode
- Wave Mode

Except for the Wave Mode, which is a single polarisation mode (HH or VV), the SAR instrument has to support operation in dual polarisation (HH-HV, VV-VH), which requires the implementation of one transmit chain (switchable to H or V) and two parallel receive chains for H and V polarisation.

The specific needs of the four different measurement modes with respect to antenna agility require the implementation of an active phased array antenna. In Stripmap mode the instrument has to provide an uninterrupted coverage with a high geometric resolution (5 m x 5 m) at a medium swath width of 80 km. Six overlapping swaths cover the required access range of 375 km. For each swath the antenna has to be configured to generate a beam with fixed azimuth and elevation pointing. Appropriate elevation beam forming has to be applied for range ambiguity suppression.

To meet the ambitious image requirements, the Interferometric Wideswath mode has to be implemented as a ScanSAR mode with progressive azimuth scanning. This requires a fast antenna beam steering in elevation for ScanSAR operation, i.e. transmitting a burst of pulses towards a sub swath. In addition, fast electronic azimuth scanning has to be performed per sub swath (TOPS operation) in order to average the performance in along track direction (reduction of scalloping). Hence, the Interferometric Wideswath mode will allow combining a large swath width (250 km) with a moderate geometric resolution (5 m x 20 m). Interferometry has to be ensured by sufficient overlap of the
Doppler spectrum (in the azimuth domain) and the wave number spectrum (in the elevation domain).

Extra-Wideswath mode and Wave mode complement the SAR data products. In Extra-Wideswath mode a huge swath width of 400 km has to be covered with low resolution (20 m x 40 m), which can be met by the implementation of a ScanSAR mode with a fast beam scanning capability in elevation. As the Interferometric Wideswath mode also the Extra-Wideswath mode is implemented with a progressive azimuth scanning (TOPS operation).

Finally, the Wave mode data product is composed of single stripmap operations with an alternating elevation beam (between 23 and 36.5 mid incidence angle) and a fixed on/off duty cycle, which results in the generation of vignettes of 20 km x 20 km size in regular intervals of 100 km.

A summary of the SAR instrument measurement modes and their characteristics is given in Table 2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Access Angle Deg.</th>
<th>Single Look Resolution</th>
<th>Swath Width</th>
<th>Polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip Map</td>
<td>20-45</td>
<td>5 x 5 m</td>
<td>&gt; 80 km</td>
<td>HH+HV or VV+VH</td>
</tr>
<tr>
<td>Interferometric Wide Swath</td>
<td>&gt; 25</td>
<td>5 x 20 m</td>
<td>&gt; 250 km</td>
<td>HH+HV or VV+VH</td>
</tr>
<tr>
<td>Extra Wide Swath</td>
<td>&gt; 20</td>
<td>20 x 40 m</td>
<td>&gt; 400 km</td>
<td>HH+HV or VV+VH</td>
</tr>
<tr>
<td>Wave mode</td>
<td>23 and 36.5</td>
<td>20 x 5 m</td>
<td>&gt; 20 x 20 km Vignettes at 100 km intervals</td>
<td>HH or VV</td>
</tr>
</tbody>
</table>

For All Modes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometric accuracy (3 σ)</td>
<td>1 dB</td>
</tr>
<tr>
<td>Noise Equivalent Sigma Zero</td>
<td>-22 dB</td>
</tr>
<tr>
<td>Point Target Ambiguity Ratio</td>
<td>-25 dB</td>
</tr>
<tr>
<td>Distributed Target Ambiguity Ratio</td>
<td>-22 dB</td>
</tr>
</tbody>
</table>

Table 3 provides a brief overview on the instrument key parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Frequency</td>
<td>5.405 GHz</td>
</tr>
<tr>
<td>Instrument Mass</td>
<td>945 kg</td>
</tr>
<tr>
<td>DC-Power Consumption</td>
<td>4075 Watt (programmable)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0 … 100 MHz (programmable)</td>
</tr>
<tr>
<td>Polarisation</td>
<td>HH-HV, VV-VH</td>
</tr>
<tr>
<td>Antenna Size</td>
<td>12.3 m x 0.821 m</td>
</tr>
<tr>
<td>RF Peak Power</td>
<td>4368 W</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>5-100 us (programmable)</td>
</tr>
<tr>
<td>Transmit Duty cycle</td>
<td>• max 12%</td>
</tr>
<tr>
<td></td>
<td>• Stripmap 8.5 %</td>
</tr>
<tr>
<td></td>
<td>• Interferometric Wide Swath 9 %</td>
</tr>
<tr>
<td></td>
<td>• Extra Wide swath 5 %</td>
</tr>
<tr>
<td></td>
<td>• Wave 0.8%</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>3 dB</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>1000- 3000 Hz (programmable)</td>
</tr>
<tr>
<td>ADC Sampling Frequency</td>
<td>260 MHz (real sampling) (Digital down-sampling after A/D conversion)</td>
</tr>
<tr>
<td>Sampling</td>
<td>10 bits</td>
</tr>
<tr>
<td>Data Compression</td>
<td>According to FDBAQ</td>
</tr>
</tbody>
</table>

The key design aspects of the C-SAR Payload can be summarized as follows:

- Active phased array antenna providing fast scanning in elevation (to cover the large range of incidence angle and to support ScanSAR operation) and in azimuth (to allow use of TOPS technique to meet the required image performance)
- Dual channel Transmit & Receive Modules and H/V-polarised pairs of slotted waveguides (to meet the polarisation requirements)
- Internal Calibration scheme, where transmit signals are routed into the receiver to allow monitoring of amplitude/phase to facilitate high radiometric stability.
- Metallised Carbon Fibre Reinforced Plastic radiating waveguides to ensure good radiometric stability even though these elements are not covered by the internal calibration scheme.
- Digital Chirp Generator and selectable receive filter bandwidths to allow efficient use of on-board storage considering the ground range resolution dependence on incidence angle.
- Flexible Dynamic Block Adaptive Quantisation to allow efficient use of on-board storage and minimise downlink times with negligible impact on image noise.

III. FDBAQ PRINCIPLE

FDBAQ is designed to provide a variable bit rate coding that increases the number of bits to be allocated to the bright scatterers. In other words, the actual Clutter level of the raw data determines the number of allocated bits. The basic principle of FDBAQ is introduced below.

The quantization of raw data introduces a quantization noise power that depends upon the input signal, clutter and thermal noise, and the quantizer performance:

\[ Q_{TC} = C + T \]

where \( C \) is the clutter power at the receiver, \( T \) the thermal noise power, \( Q \) the quantization noise power and \( g(R) \) the quantizer gain, a function of the bit rate. This gain actually depends on the quantizer implementation. The following expression has been derived in [3] for the performance of this type of quantizers:

\[ g(R) = 10^{-0.156} \cdot 10^{0.595R/10} \]

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\[ g(R) = g^{-1}(R) + T/C(r) + g^{-1}(R, T) \]

(4)

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\[ CTR(r) = \frac{C(r, n(r))}{T, n(r)} = \frac{\sigma_0(r)}{NESZ(r)} \]

where \( \sigma_0 \) is the scene backscatter and NESZ is the Noise Equivalent Sigma Zero. The range varying CNR leads to the use of a VBR quantizer, where a larger number of bits is used for the strongest scatterers. The implementation of the quantizer is given in the block diagram shown in Fig. 3.

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A. Bit Rate Estimation

In the general SAR case, the received clutter power is depending on target backscatter (that itself depends on e.g. wavelength, incidence angle, and polarization), acquisition geometry and system parameters (transmitted power etc), the behavior being modeled by the RADAR equation. In particular, there is a systematic variation of CTR with range that is mainly due to the antenna pattern, with minor contribution from spreading loss and incidence angle variation that can be taken into account in the design of the FDBAQ quantizer.

The quantizer performance can be described as a function of range:

\[ CNR(r) = \left[ g^{-1}(R) + T/C(r) + g^{-1}(R, T) \right]^{-1} \]

(4)

The CNR at each range is uniquely related to the ratio between the received clutter power, which depends on the target and the range, and the thermal noise power. For the purpose of optimization and performance evaluation, it is more simple to calibrate the raw data, e.g. to compensate for the systematic variations with range, due to spreading loss, antenna pattern and incidence angle variation, so that the clutter would represent the backscatter coefficient of the scene. If we define \( n(r) \) the calibration function, we can express the clutter to thermal noise ratio as follows:

\[ CTR(r) = \frac{C(r, n(r))}{T, n(r)} = \frac{\sigma_0(r)}{NESZ(r)} \]

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Notice that the FDBAQ quantizer measures the local clutter power by exploiting raw data in blocks of a few hundred samples, like any other FBAQ. However, the quantizer needs also the knowledge of the NESZ that is not measured on board, but assumed known (e.g. estimated using on ground instrument characterization). The principal difference between the FDBAQ and the FBAQ is that the number of bits per sample, \( R \), is selected according to the local CTR and some criterion. The idea is the minimization of the total error related to the total bit-rate.

A threshold is defined as:

\[ f_{th} = Q/n(r) + NESZ(r) \]
which leads to the following expression for the range dependent bit rate:

\[
R(r) = \left[10\log_{10}\left\{\sigma_0^2(r)+\text{NESZ}(r)\right\} - 10\log_{10}\left\{f_{th}-\text{NESZ}(r)\right\} + 1.56\right] / 5.95 (7)
\]

In the case of Sentinel-1 R is restricted to the range:

\[
3 \leq R \leq 5 (8)
\]

The upper bound avoids the indefinite increase in R as NESZ(r) becomes close to \(f_{th}\) (e.g. trying to remove any quantization noise in targets more affected by thermal noise). The lower bound of R is used, together with a tuning of \(f_{th}\), to satisfy the overall bit rate constraint of the mission, in the sense that an increase in the minimum value of R would increase the bit rate, and an increase in \(f_{th}\) would have the opposite effect.

It should be noted that the NESZ used in (6), is a slant-range/orbit dependent function and is evaluated on the raw data, unfocused both in range and in azimuth.

IV. SIMULATION RESULTS

The simulation described in this section calculates performances in terms of CNR and bit rate by using synthetic Sentinel-1 acquisitions along the orbit. The simulation assumes the nominal Sentinel-1 orbit and swaths, and estimates the ground backscatter by using a Global Monitoring ENVISAT/ASAR Mosaic covering almost the entire world (Fig. 4). Such mosaic has been normalized after processing, therefore a renormalization and calibration is needed in order to use this data for simulation purposes. The calibration and validation of the mosaic are beyond the scope of this paper. In the frame of the GS1 mission the block size is not critical, as all the samples within the duration of a chirp are correlated. Typical samples within the duration of a chirp are correlated. Typical chirp duration corresponds to several km on the ground, therefore several thousands of samples. Therefore the km quantization of the backscatter mosaic is sufficient. Likewise, the azimuth resolution of the unfocused SAR, due to the real antenna pattern, is in the order of a few km, here again we observe that the mosaic sampling of 1 km is more than sufficient. A Sentinel-1 Interferometric Wide (IW) swath mode simulation has been performed over a Greenland test site. Eight different strips have been considered, each one comprising 400 [s] of acquisition time. A net download capacity of 260 MBit/s for one channel has been assumed and a threshold level of -22 dB was chosen. Fig. 5 shows the ENVISAT/ASAR GM calibrated mosaic of all the considered strips.

![Figure 4. ENVISAT GM Mosaic](image)

The FDBAQ operates block wise in the range direction, as usual for BAQ SAR compression. The block size should be dimensioned in order to have enough samples to estimate the clutter power and, at the same time, to exploit an homogeneous set of samples, from a statistical point of view. In the frame of the GS1 mission the block size is not critical, as all the samples within the duration of a chirp are correlated. Typical samples within the duration of a chirp are correlated. Typical chirp duration corresponds to several km on the ground, therefore several thousands of samples. Therefore the km quantization of the backscatter mosaic is sufficient. Likewise, the azimuth resolution of the unfocused SAR, due to the real antenna pattern, is in the order of a few km, here again we observe that the mosaic sampling of 1 km is more than sufficient. A Sentinel-1 Interferometric Wide (IW) swath mode simulation has been performed over a Greenland test site. Eight different strips have been considered, each one comprising 400 [s] of acquisition time. A net download capacity of 260 MBit/s for one channel has been assumed and a threshold level of -22 dB was chosen. Fig. 5 shows the ENVISAT/ASAR GM calibrated mosaic of all the considered strips.

![Figure 4. ENVISAT GM Mosaic](image)

![Figure 5. ENVISAT ASAR GM calibrated mosaic of eight GMES Sentinel-1 acquisitions over Greenland.](image)

Fig. 6 presents the estimated quantization bits. Discrete quantization levels haven't been applied, so that estimated values can change continuously from a minimum of 3 to a maximum of 5 bit/sample.

![Figure 6. Estimated number of quantization bits over 8 simulated GMES Sentinel-1 IW strips](image)

![Figure 7. Estimated quantisation bits. Discrete quantisation levels haven't been applied, so that estimated values can change continuously from a minimum of 3 to a maximum of 5 bit/sample.](image)
It can be seen, that the IW1 (the right hand swath) is the swath with the highest value of Total Noise Power.

In the next simulation five different quantization levels have been used: 3.0; 3.4; 3.8; 4.2; and 5.0. Fig. 8 shows the mean bit rate for all IW beams and acquired strips. As it can be seen, the IW1 mean data rate is higher than the required 260 Mbit/s, but the overall average is well within the limits.

V. CONCLUSIONS

The Sentinel-1 synthetic aperture radar (SAR) constellation represents a completely new approach to SAR mission design by ESA in direct response to the operational needs for SAR data expressed under the EU-ESA Global Monitoring for Environment and Security (GMES) programme. The mission ensures continuity of C-Band SAR data to applications and builds on ESA’s heritage and experience with the ERS and ENVISAT SAR instruments, notably in maintaining key instrument characteristics such as stability and accurate well-calibrated data products. At the same time a number of mission design parameters have been vastly improved to meet major user requirements collected and analyzed through EU Fast Track and ESA GSE activities, especially in areas such as reliability, revisit time, geographical coverage and rapid data dissemination. As a result, the Sentinel-1 constellation is expected to provide near daily coverage over Europe and Canada, global coverage all independent of weather with delivery of radar data within 1 hour of acquisition – all vast improvements with respect to the existing SAR systems. In addition to responding directly to current needs of the GMES program, the design of the Sentinel-1 satellite mission with its focus on stability, reliability, global coverage, consistent operations and quick data delivery is expected to enable the development of new applications and meet the evolving needs of GMES, for instance in the area of climate change and associated monitoring needs.

The FDBAQ quantizer has been introduced and a method for the evaluation of FDBAQ performances has been presented. The FDBAQ theoretical performances have been evaluated and different TOPSAR IW simulations using Sentinel-1 orbits and parameters have been performed. The FDBAQ simulator exploits an ENVISAT ASAR GM worldwide mosaic, absolutely calibrated and compensated for the expected variation of backscatter with incidence angle, in order to retrieve an estimate of the on-ground reflectivity. This information, together with the a priori information on range-varying NESZ is used to compute the number of quantization bits for each 1 x 1 km pixel on the earth. The obtained results lead to the following conclusions. FDBAQ satisfies the requirement of an average bit rate of less than 260 Mbit/s. A figure of merit (Total Noise Power) has been evaluated, showing that the IW1 sub-swath tends to be noisier then IW2 and IW3.

REFERENCES