Smart and Scalable Satellite High-Speed Processing chain

D1.3 – On-board Payload Processing Requirements

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List of acronyms

Acronym/abbreviation	Description
CA	Consortium Agreement
CCD	Charge Coupled Device
CFS	Certificate on the Financial Statement
CO	Confidential to the Consortium (including EC services) dissemination
DP	Deliverable Process
DoA	Description of Action
EC	European Commission
EU	European Union
FLOP	Floating Point Operation
FLOPS	Floating Point Operation per Second
GA	Grant Agreement
GSD	Ground Sampling Distance
GPS	Global Positioning System
HW	Hardware
HRS	High Resolution Geometric
IMR	Internal Management Report
IPR	Intellectual Property Rights
MS	Milestone (Project)
NASA	National Aeronautics and Space Administration
NIR	Near InfraRed
ORDP	Open Research Data Pilot
PBSOTA	Progress beyond the state of the art
PM	Person Months
PU	Public (dissemination)
RE	Restricted (dissemination)
REA	Research Executive Agency
S3NET	Satellite Swarm Sensor Network
S4Pro	Smart and Scalable Satellite High-Speed Processing Chain
SAB	S4Pro Advisory Board
SAR	Synthetic Aperture Radar
SDR	Software defined radio
SEB	S4Pro Executive Board
SGA	S4Pro General Assembly
SPO	S4Pro Project Office
SSO	Sun Synchronous Orbit
SW	Software
SWIR	Short Wave InfraRed
TRL	Technology Readiness Level
TT&C	Telemetry Tracking and Command
UHF	Ultra High Frequncy
VHF	Very High Frequency
WBS	Work Breakdown Structure
WP	Work Package
WPL	Work Package Leader

1 EXECUTIVE SUMMARY

This document represents deliverable D1.3 prepared in the frame of Task 1.3 of Work Package 1 of S4Pro project H2020 Grant agreement number 822014.

This deliverable contains the description of identified S4Pro applications relevant to deriving:

- different payloads' on-board resources requirements;
- analyses of requirements to identify, for each payload, the requirements in terms of data throughput and computational load;
- identification of the most suitable radar (DLR) and optical (OHB-I) applications for the S4PRO computing system;
- selection for implementation of a significant subset of payload data processing algorithms suitable for the applications considered in T1.1;
- preliminary benchmark plan.

Finally, a summary of formalized requirements on the S4Pro hardware concludes the document.

2 INTRODUCTION

This document provides the collection and derivation of the S4PRO payload processing requirements, based on the representative set of applications selected in Task 1.1 and described in D1.1. It includes the initial definition of benchmarking activities to be executed on the S4Pro compute system.

Future optical EO and SAR missions tend to acquire data at an enhanced orbit duty cycle, at higher resolution and eventually larger swath widths. Combined with the increasing need for low latency products there is a clear demand for more efficient and flexible onboard data handling, which includes payload data processing for data volume reduction and/or towards user specific products. At the same time, for some missions the amount of data to be handled will become one order of magnitude larger, compared to present day missions (e.g. Tandem-L).

This document provides the requirements collection for onboard EO payload data processing of the missions and applications identified in task 1.1 of S4Pro. In chapter 3 the requirements are presented for two optical use cases related to ship detection and vegetation index monitoring, respectively. The numerical evaluations for the onboard data volume are presented for SPOT-5, Quickbird, Eaglet-2 and IKONOS sensors. For each application case, three different algorithms, selected as possible candidates for implementation with the S4Pro system in D1.1, are analyzed in terms of computational requirements, including estimation of computational cost for a Sentinel-2 reference scenario.

Similarly, the requirements for the SAR case are presented in chapter 4 for several mission proposals presently under investigation at ESA (ROSE-L, Sentinel-1 Next Generation) or German national level (Tandem-L, HRWS). All these missions target wide swath coverage at high resolution (HRWS) and onboard data processing beyond the most used BAQ algorithm is mandatory to bring the required downlink rate to a feasible level. Depending on the sensor antenna and operating mode, different algorithms can be adopted for this purpose. A strong candidate is the staggered SAR concept, which operates the radar with sequentially changing pulse repetition frequency PRF. The associated resampling and decimation step is selected for demonstration within S4Pro.

A preliminary benchmark plan is included for both EO cases, optical and radar, at the end of their respective chapters.

3 OPTICAL PAYLOADS’ ON-BOARD PROCESSING REQUIREMENTS

The on-board processing requirements are quantified for the different candidate optical applications described in D1.1. In section 3.2 final candidates for optics to be implemented are selected and in section 0 the high level preliminary benchmark plan is presented.

3.1 On-board data handling requirements

3.1.1 Ship detection

In order to derive requirements on ship detection it is useful to analyze those missions used as candidate reference missions to perform ship detection. In literature, the following missions are commonly used as source for ship detection (as stated in D1.1.) SPOT-5 and QuickBird. Besides these missions, it is useful to consider also candidate future missions to derive consistent requirements on ship detection; EAGLET-2 is selected for this purpose. All the cited missions are analyzed hereafter in order to extrapolate useful on-board data handling requirements in the hypothesis that only panchromatic channels are required for ship detection applications. This hypothesis is supported by the fact that in literature ship detection is performed mainly by using panchromatic data source (see D1.1).

3.1.1.1 SPOT-5

Since February 22, 1986, SPOT satellites have monitored the Earth. For over 25 years, this series of optical observation satellites has provided images of our planet for an extensive range of applications [1, 4, 5, 6]. These data are also useful to test ship detection algorithms, due to the high spatial resolution (5 m or lower) that is required to run such algorithms [2]. Main mission parameter are reported in Table 1.

Parameter	Panchromatic Band
Orbit	Type: SSO 10:30 a.m. Descending Node Period: 101.4 min
Sensor Resolution and Spectral Bandwidth	PA-1 (Panchromatic) : 5 m, 0.49-0.69 µm PA-1 (Panchromatic) : 5 m, 0.49-0.69 µm B1 (Green) : 10 m, 0.49-0.61 µm B2 (Red) : 10 m, 0.61-0.68 µm B3 (NIR) : 10m, 0.78-0.89 µm SWIR : 20m, 1.58-1.75 µm
Swath Width	Nominal Swath Width: 60 km per sensor
Attitude Determination and Control	0.05º and an attitude restitution of 6 x 10^{-5} radians
On-board Storage	90 Gbit solid state memory
Communications	Data Rate (X-band) : 2 x 50 Mbit/s TT&C (S-band) rate : 4 kbit/s
Revisit Frequency	145 Revolutions every 26 days
Metric Accuracy	50 m
Capacity	Not Found

Table 1 Summary of SPOT-5 features [1;2;3;8;9;16].

SPOT-5 embarked two High Resolution Geometric (HRG) instruments. Each of these instruments works with a parallel configuration of two linear Charge Couple Device (CCD) detectors for the panchromatic band. Each CCD is composed of 12000 detectors (i.e. 12000 pixels). The CCD integration time is within 0.75 ms for a dual-array observation in cross-track of 60 km. In Table 2, a summary of HRG characteristics are presented while in Table 3 on-board data handling requirements are derived from the HRG payload characteristics.

Parameter	Panchromatic Band
Spectral Range (µm)	0.49-0.71 µm
Detector elements/line	12000
Number of Lines	2
Detector Size (pitch)	6.5 µm
Integration time per line	0.752 ms
GSD	5m x 5m single image 3.5m x 3.5m dual image

Table 2 Summary of HRG characteristics.

An integration time of 0.75 ms is considered as fixed for the whole life cycle of the instrument. This property can be in fact tuned accordingly to the user needs within minimum and maximum integration time. A data rate of approximately 0.5 Gbit/s is estimated.

Parameter	Unit	Value
Number of channels	/	4
Elements per channel	/	12000
Dynamic range	bit	8
Average Integration time	ms	0.75
Sampling rate	kHz	1,33
Output Data Rate per channel	Mbit/s	122.07
Output Data Rate all channels	Mbit/s	488.28

Table 3 SPOT-5 ship detection on-board data handling requirements for ship detection (panchromatic channels only).

3.1.1.2 QuickBird

QuickBird was a high-resolution commercial Earth observation satellite collecting panchromatic (black and white) imagery at 61 centimeter resolution and multispectral imagery at 2.44 (at 450 km) to 1.63 meter (at 300 km) resolution, as orbit altitude is lowered during the end of mission life [17]. The main features of this satellite are shortly listed in Table 4.

Parameter	Altitude 482 km	Altitude 450 km
Orbit	Type: SSO 10:00 am Descending Node Period: 94.2 min	93.6 min
Sensor Resolution and Spectral Bandwidth	Panchromatic: 65 cm GSD at nadir Black & White: 0.405-1.053 µm Multispectral: 2.62 m GSD at nadir Blue: 0.430-0.545 µm Green: 0.466-0.620 µm Red: 0.590-0.710 µm Near-IR: 0.715-0.918 µm	Panchromatic: 61 cm GSD at nadir Multispectral: 2.44 m GSD at nadir
Swath Width	Nominal Swath Width: 18.0 km at nadir	Nominal Swath Width: 16.8 km at nadir
Attitude Determination and Control	Type:3-axis stabilized; Star Tracker/IRU/Reaction Wheels, GPS	
On-board Storage	128 Gb capacity	
Communications	Payload Data: 320 Mbps X-Band Housekeeping: X-Band from 4.16 and 256 kbps, 2 kbps S-Band uplink	
Revisit Frequency (at 40°N Latitude)	2.5 days at 1 m GSD or less 5.6 days at 20° off-nadir or less	2.4 days at 1 m GSD or less 5.9 days at 20° off-nadir or less
Metric Accuracy	23 m CE90, 17 m LE90 (without ground control)	
Capacity	200.000 km^2 per day	

Table 4 Summary of QuickBird features [17;18;19;20;21;22,32].

In panchromatic mode, the detector is composed of 27552 pixels while in multispectral mode of 6888 pixels. The dynamic range is 11 bits per pixels. Assuming that QuickBird panchromatic camera has similar integration time to the one of SPOT-5, the data rate can be estimated as it was done in Table 5.

Parameter	Unit	Value
Number of channels	/	1
Elements per channel	/	27552
Dynamic range	Bit	11
Average Integration time	ms	0.75
Sampling rate	kHz	1,33
Output Data Rate per channel	Mbit/s	404.10
Output Data Rate all channels	Mbit/s	404.10

Table 5 QuickBird ship detection on-board data handling requirements (panchromatic channel only).

The QuickBird on-board storage capacity is of 128 Gb. Considering that this satellite has 5 optical channels (panchromatic, blue, green, red, near-infrared) and considering that each of them has 6888 elements per channel with the exception of panchromatic one that has 27552, the data storage allocation for the panchromatic channel can be estimated. Panchromatic channel has exactly the same number of elements of the sum of the others. Therefore, it is reasonably conceivable that approximately half of the on-board storage capacity is devoted to the panchromatic channel, while the other half is allocated to the remaining channels (in the hypothesis that all channels have the same duty cycle). In this scenario, for ship detection application a requirement of tens of gigabit is derived for the on-board storage capacity.

3.1.1.3 EAGLET-2

EAGLET-2 is the name of the second micro/nano-sat class mission of the EAGLET initiative by OHB Italia. EAGLET-2 is a 20U micro-sat satellite (20x20x50 cm^3), which will operate in sun-synchronous orbit (SSO) at 475 km of altitude. Main mission parameter are reported in Table 6.

Parameter	Panchromatic Band
Orbit	SSO Altitude: 475
Sensor Resolution and Spectral Bandwidth	Panchromatic: 1.8m at nadir, 0.45-0.75 µm Red: 1.8m at nadir, 0.6-0.7 µm Green: 1.8m at nadir, 0.5-0.6 µm
Swath Width	18 km
Attitude Determination and Control	3-axis inertial pointing
On-board Storage	100 scenes (approximately 100 Gbit)
Communications	Payload Data: X-band 100Mbit/s
Revisit Frequency	3 days nadir pointing
Metric Accuracy	Not found
Capacity	Not Found

Table 6 Summary of EAGLET-2 features.

The satellite will have two payloads, one of which will be an optical payload capable of capturing panchromatic and RGB images of the Earth with a GSD of less than 2 meters. The second payload will relay AIS data received by the satellite in VHF and retransmitted in UHF. With a sampling rate of 0.4 Hz, data rate can be estimated as it was done in Table 7.

Parameter	Unit	Value
Number of channels	/	1
Elements per channel	/	10k x 10k
Dynamic range	Bit	10
Maximum Integration time	/	Not found
Sampling rate	Hz	0.4
Output Data Rate per channel	Mbit/s	381.47
Output Data Rate all channels	Mbit/s	381.47

Table 7 Eaglet-2 ship detection on-board data handling requirements (panchromatic channel only).

3.1.2 Vegetation index monitoring

In order to derive requirements on vegetation index monitoring it is useful to analyze those missions used as candidate reference missions to perform vegetation index monitoring. In literature, the following missions are commonly used as source for vegetation index monitoring (as stated in D1.1.): SPOT-5, QuickBird, and IKONOS. All the cited missions are analyzed hereafter in order to extrapolate useful on-board data handling requirements in the hypothesis that a minimum of 3 channels are required for vegetation index monitoring. This hypothesis is supported by the fact that, in literature, vegetation index monitoring is performed mainly by using multispectral to hyperspectral data source (see D1.1).

3.1.2.1 SPOT-5

The mission overview is already described at page 7. In order to perform vegetation index monitoring on SPOT-5 an additional sensor, called Vegetation or Vegetation Monitoring Instrument (VMI), was provided [6, 14]. This instrument has a ground swath of 2200 km, and a resolution close to 1 km, providing the capability of wide-area monitoring of the Earth's vegetation (VMI features advanced optics that allow perfect geometrical rectification of the pictures despite the wide swath width. The VMI optics virtually cancel the curvature of the Earth to provide directly usable geographical information). The instrument collects radiation reflected by the Earth's surface. Silicon linear detector arrays are used for spectral band B0 (blue), B2 (red) and B3 (near infrared), while indium gallium arsenide photodiodes are used for the Short Wave InfraRed (SWIR) band. Each array features 1728 individual CCD detectors. Main characteristics of these bands are reported in Table 8, Table 9, Table 10, and Table 11.

Parameter	B0 (blue)
Spectral Range (µm)	0.43-0.47 µm
Detector elements/line	1728
Number of Lines	1
Detector Size (pitch)	Not found
Integration time per line	Not found
GSD	1.15 km x 1.15 km
Optimized to detect	Chlorophyll

Table 8 Blue channel main features.

Parameter	B2 (red)
Spectral Range (µm)	0.61-0.68 µm
Detector elements/line	1728
Number of Lines	1
Detector Size (pitch)	Not found
Integration time per line	Not found
GSD	1.15 km x 1.15 km
Optimized to detect	vegetation

Table 9 Red channel main features.

Parameter	B3 (NIR)
Spectral Range (µm)	0.78-0.89 µm
Detector elements/line	1728
Number of Lines	1
Detector Size (pitch)	Not found
Integration time per line	Not found
GSD	1.15 km x 1.15 km
Optimized to detect	vegetation, atmospheric correction

Table 10 NIR channel main features.

Parameter	SWIR
Spectral Range (µm)	1.58-1.75 µm
Detector elements/line	1728
Number of Lines	1
Detector Size (pitch)	Not found
Integration time per line	Not found
GSD	1.15 km x 1.15 km
Optimized to detect	vegetation, atmospheric correction

Table 11 SWIR channel main features.

The VMI payload storage capacity is of 2.25 Gbits. The mass memory is structured around a 10-page memory stack composed of 8 columns × 32 Mbit (DRAM random access memory component). In the hypothesis that the average integration time is the same of the SPOT-5 panchromatic CCD (i.e. 0.75

ms), the sampling rate can be computed and so the output data rate from sensors. Results of such computations are listed in Table 12.

Parameter	Unit	Value
Number of channels	/	4
Elements per channel	/	1728
Dynamic range	Bit	10
Average Integration time	ms	0.75
Sampling rate	kHz	1.33
Output Data Rate per channel	Mbit/s	23.04
Output Data Rate all channels	Mbit/s	92.16

Table 12 SPOT-5 vegetation index monitoring on-board data handling requirements.

3.1.2.2 QuickBird

Main characteristics and a quick overview of the QuickBird mission are already reported at page 8. For vegetation index monitoring multispectral data are used. As already stated, multispectral arrays are composed of 6888 pixels each. The dynamic range is 11 bits per pixels. Assuming that the 4 multispectral cameras have similar integration times to the one of SPOT-5, the data rate can be estimated as it was done in Table 13.

Parameter	Unit	Value
Number of channels	/	4
Elements per channel	/	6888
Dynamic range	Bit	11
Average Integration time	ms	0.75
Sampling rate	kHz	1,33
Output Data Rate per channel	Mbit/s	101.03
Output Data Rate all channels	Mbit/s	404.10

Table 13 QuickBird vegetation index monitoring on-board data requirements.

3.1.2.3 IKONOS

Ikonos is a commercial high-resolution imaging satellite of DigitalGlobe (Longmont, CO, USA) providing high-resolution imagery on a commercial basis. With Ikonos, a new era of 1 m spatial resolution imagery began for space borne instruments in the field of civil Earth observation [26]. Main characteristics are reported in Table 14.

Parameter	Panchromatic Band
Orbit	Type: SSO Altitude: 681-709 km Inclination: 98.1° Period: 98 min 10:30 AM descending node
Sensor Resolution and Spectral Bandwidth	Panchromatic : 0.82 m, 0.45-0.90 µm MS1: 3.2m, 0.45-0.52 µm MS2: 3.2m, 0.52-0.60 µm MS3: 3.2m, 0.63-0.69 µm MS4: 3.2m, 0.69-0.90 µm
Swath Width	Nominal Swath Width: 12.2 km per sensor
On-board Storage	64 Gbit solid state memory
Communications	Data Rate (X-band) : 2 x 320 Mbit/s TT&C (S-band) rate : 2 x 2 kbit/s (up-link) 2 x 32kbit/s down-link)
Revisit frequency	1-3 days
Metric Accuracy	12 m
Capacity	Not Found

Table 14 Summary of IKONOS features [26;27;28;29;32;33].

Considering that line rate of each array is of 1625 lines per second it is possible to compute the expected data rate as it is done Table 15.

Parameter	Unit	Value
Number of channels	/	4
Elements per channel	/	3454
Dynamic range	Bit	11
Average Integration time	/	Not Found
Sampling rate	kHz	1.625
Output Data Rate per channel	Mbit/s	61.74
Output Data Rate all channels	Mbit/s	246.96

Table 15 IKONOS vegetation index monitoring on-board data requirements.

3.2 Optical Algorithm Selection for S4Pro Compute System Definition

3.2.1 Ship detection

The identified ship detection algorithms have been analyzed, focusing on their computational requirements. First, each algorithm has been cracked down into computational blocks, and for each block an estimation formula for the total number of Floating Point Operations (FLOPS) has been derived from the available description. Then, absolute computational costs have been determined taking the features of Sentinel-2 MSI as a reference, i.e. applying the estimation formulas to S-2 data features. This has been done in order to get a coarse, yet reliable, reference term for the expected complexity and maximum FLOPS capacity required onboard the satellite.

The reference algorithm has been derived from the following paper:

Yang, G., Li, B., Ji, S., Gao, F., & Xu, Q. (2014). Ship detection from optical satellite images based on sea surface analysis. IEEE Geoscience and Remote Sensing Letters, 11(3), 641-645.

The identified, relevant computational blocks are reported in Table 16 together with the respective formulas expressing the estimated computational cost.

Computational block	FLOPs
Reckon intensity and texture similarities	2 * (N*M) * kernel_size_1 (pixels)
Threshold to keep just candidate blocks	2 * (N*M)
Two texture-based features	2 * candidate-rate * (N*M) * kernel_size_2 (pixels)
Application of two thresholds	2 * candidate-rate * (N*M)
Two shape-based analyses	2 * candidate-rate * (N*M) * kernel_size_3 (pixels)
Application of two thresholds	2 * candidate-rate * (N*M)

Table 16 Ship detection FLOPs estimation, case 1.

The above parameters are:

- N, M: # of rows and columns of the image;
- kernel_size_*: size in pixels (area, not side) of square windows when applying kernel-based analysis;
- candidate-rate: value of the ratio between # of blocks with presence and # of blocks without presence of ships within the image.

In case of the Sentinel-2 satellite, the first processing levels (i.e. 0, 1A, and 1B) are sub-images of a given number of lines along track and separated by detector. They are 25 km across track and 23 km along track in size. Sentinel-2 completes a single orbit in 100 minutes and during each orbit it acquires approximately 3500 images. This means that each image is acquired in around 1.7 seconds. Moreover, the number of bands equals 13, and they are clustered in different spatial resolutions, namely: four bands at 10m, six bands at 20m, and three bands at 60m. The pixel size of the image at 10m resolution is approximately 2500 x 2300.

The three kernel size values have been set to 256x256, 5x5, and 5x5. The candidate-rate is set to 0.04. Consequently, an estimation of the required number of FLOPs is 753*10^9. These values refer to a single optical image, which is acquired, as already mentioned, every 1.7 seconds. Therefore, an average of 4.43*10^11 FLOPS.

If we instead consider the case of EAGLET-2, which has a 10k x 10k pixel sensor, the FLOPs become 1.31*10^13 on a single image, which is acquired every 3 seconds (in the considered scenario). This leads to an estimation of 4.3*10^12 FLOPS.

If we refer instead to the method outlined in the following papers (the second building on the first):

Yang, F., Xu, Q., Gao, F., & Hu, L. (2015, July). Ship detection from optical satellite images based on visual search mechanism. In Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International (pp. 3679-3682). IEEE.

Yang, F., Xu, Q., & Li, B. (2017). Ship detection from optical satellite images based on saliency segmentation and structure-LBP feature. IEEE Geoscience and Remote Sensing Letters, 14(5), 602-606.

relevant computational blocks can be identified and they are reported in Table 17, together with the respective formulas expressing the estimated computational cost.

Computational block	FLOPs
Reckon intensity similarity	(N*M) * kernel_size_1 (pixels)
Threshold to identify ship candidates	(N*M)
Three shape-based analysis	3 * candidate-rate * (N*M) * kernel_size_2 (pixels)
Three thresholds	3* candidate-rate * (N*M)
Reckon of local binary patterns	candidate-rate * (N*M) * kernel_LBP (pixels)
Support vector machine classifier	candidate-rate * (N*M) * (2 * n − 1) + 2 * candidate-rate * (N*M)

Table 17 Ship detection FLOPs estimation, case 2.

The above parameters are:

- N, M: # of rows and columns of the image;
- kernel_size_*: size in pixels (area, not side) of square windows when applying kernel-based analysis
- kernel_LBP: size of the local binary pattern feature set;
- candidate-rate: value of the ratio between # of blocks with presence and # of blocks without presence of ships within the image
- n: number of features used in input to the classifier. In this case, it is coherent with the kernel size of the local binary pattern analysis.

The two kernel size values have been set to 512x512 pixel and 40x40 pixel. The local binary pattern feature is set to 8, and thus ‘n’ is also set to 8. The candidate-rate is set to 0.04. Consequently, an estimate for the required number of FLOPs is 1.50*10^12. As per the previous case, considering one image every 1.7 seconds leads to a total amount of 8.87*10^11 FLOPS.

For EAGLET-2, instead, these values are 2.62*10^13 FLOPs and 8.6*10^12 FLOPS.

Considering the method described in the following papers:

Ji-yang, Y., Dan, H., Lu-yuan, W., Jian, G., & Yan-hua, W. (2016, November). A real-time on-board ship targets detection method for optical remote sensing satellite. In Signal Processing (ICSP), 2016 IEEE 13th International Conference on (pp. 204-208). IEEE.

Ji-yang, Y., Dan, H., Lu-yuan, W., Xin, L., & Wen-juan, L. (2016, November). On-board ship targets detection method based on multi-scale salience enhancement for remote sensing image. In Signal Processing (ICSP), 2016 IEEE 13th International Conference on (pp. 217-221). IEEE.

The identified, relevant computational blocks are reported in Table 18, together with the respective formulas expressing the estimated computational cost.

Computational block	FLOPs
Reckon two texture-based features	2 * (N*M) * kernel_size_1 (pixels)
Application of morphological closing	(N*M) * kernel_size_2 (pixels)
Intensity similarities	(N*M) * kernel_size_3 (pixels)
Threshold	(N*M)
Adaptive iterative threshold segmentation	candidate-rate * (N*M) * cycles
Connected domain labelling	candidate-rate * (N*M)
Two shape-based analysis	2 * candidate-rate * (N*M) * kernel_size_4 (pixels)
Two thresholds	2* candidate-rate * (N*M)

Table 18 Ship detection FLOPs estimation, case 3.

The above parameters are:

- N, M: # of rows and columns of the image;
- kernel_size_*: size in pixels (area, not side) of square windows when applying kernel-based analysis;
- cycles: number of region growing cycles within the segmentation step;
- value of the ratio between # of blocks with presence and #of blocks without presence of ships within the image;

The four kernel size values have been set to 7x7, 5x5, 5x5 and 3x3. The 'cycles' value is set to 3. The candidate-rate is set to 0.04. Consequently, an estimate for the required number of FLOPs is 862*10^6, with a number of FLOPS equals to 507*10^6.

Considering the EAGLET-2 scenario, these values become 14.7*10^9 FLOPs and 4,91*10^9 FLOPS.

3.2.2 Vegetation index monitoring

The same analysis has been carried out for the three algorithms related to vegetation monitoring. As for the previous analysis, Sentinel-2 is used as the reference instrument to determine data features.

The first method is referred to:

Dawelbait M., Morari F. (2012). Monitoring desertification in a Savannah region in Sudan using Landsat images and spectral mixture analysis Journal of Arid Environments 80:45–55 doi:10.1016/j.jaridenv.2011.12.011.

Relevant computational blocks are listed in Table 19 as well as an estimation of FLOPS required.

Computational block	**FLOPs**
Endmembers calculations	#_GroundTruth_pixels * cycles * bands
Classifications of pre- and post- images	2 * (N*M) * bands
Difference vector composed of two parameters	2 * (N*M)
Threshold pixels	(N*M)

Table 19 Vegetation index monitoring FLOPs estimation, case 1.

The parameters used in the table are:

- N, M: # of rows and columns in the image;
- bands: number of multi-spectral bands;
- #_GroundTruth_pixels: number of pixel used as ground truth reference ;
- cycles: number of cycles in defining the endmembers values.

The total number of bands is set to 10. The 'cycles' value is set to 10. The total number of pixels, which will be used as reference is 100. Consequently, an estimation for the number of FLOPs is 132*10^6 and 77.8*10^6 FLOPS, whereas for EAGLET-2 these values are 2.3*10^9 FLOPs and 754*10^6 FLOPS.

The second considered approach to vegetation monitoring derives from the following paper:

Bastarrika A. , Chuvieco, E., Martin, M.P. (2011). Mapping burned areas from Landsat TM/ETM + data with a two-phase algorithm: Balancing omission and commission errors. Remote Sensing of Environment, 115 (2011), pp. 1003–1012.

Relevant computational blocks are listed in Table 20 as well as an estimation of FLOPS required.

Computational block	FLOPs
Vegetation indices	#_GroundTruth_pixels * cycles * bands
Threshold values identifications	2 * (N*M) * bands
Threshold pixels (candidates identification)	2 * (N*M)
Region growing	candidate-rate * (N*M) * cycles
Logistic regression	candidate-rate * (N*M)
Classification	candidate-rate * (N*M)

Table 20 Vegetation index monitoring FLOPs estimation, case 2.

The parameters used in the table are:

- N, M: # of rows and columns in the image;
- #_indexes: number of vegetation indices;
- candidate-rate: number of pixels identified as seeds divided by the total number of pixels in the dataset;
- cycles: number of region growing cycles within the segmentation step.

The total number of indexes is set to 7. The 'cycles' value is set to 10. The total number of pixels which will be used as reference is set to 1000. The candidate-rate is set to 0.1. Consequently, an estimation for the number of FLOPs is 87*10^6. The number of FLOPS are, instead, 58.2*10^6.

Using EAGLET-2 these figures become 1.72*10^9 FLOPs and 564*10^6 FLOPS.

The third considered approach to vegetation monitoring derives from the following paper:

DeFries R., Townshend, J.R. (1994). NDVI-derived land-cover classifications at a global-scale Int. J. Remote Sens., 15 (17) (1994), pp. 3567–3586.

Relevant computational blocks are listed in Table 20 as well as an estimation of FLOPS required.

Computational block	FLOPs
NDVI calculation	(N*M)
Difference with past classification	(N*M)
Threshold pixels	(N*M)

Table 21 Vegetation index monitoring FLOPs estimation, case 3.

The parameters used in the table are:

- N, M: # rows and columns of the image;

An estimate for the number of FLOPs is 17*10^6, with 10*10^6 FLOPS, for Sentinel-2 and 300*10^6 FLOPs, with 98.3*10^6 FLOPS, for EAGLET-2.

3.3 Optical Algorithm Preliminary Benchmark Plan

Throughput tests:

1. The S4Pro compute system shall be able to handle the input data rate provided by the instruments (the final definition of the instruments shall be consolidated during WP2) and the mass memory shall be able to store the according output data rate.

Algorithm functionality tests:

2. Accuracy assessment at various levels of spatial resolution (from VHR to HR);
3. Accuracy assessment at various levels of spectral resolution (from panchromatic to multispectral bands);
4. Accuracy assessment stability across different geographic regions

Computational performance tests:

5. Assessment of computational load for different image sizes.

3.4 References Optical Case

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4 RADAR PAYLOADS’ ON-BOARD PROCESSING REQUIREMENTS (DLR-HR)

The on-board processing requirements are quantified for the different candidate SAR missions described in D1.1. In section 4.2 the radar algorithm to be implemented for the S4Pro compute system is selected and in section 4.3 the high level preliminary benchmark plan is presented.

4.1 On-board data handling requirements

This section summarizes the data volume and throughput requirements for SAR missions presently under evaluation. The requirements of the special algorithms for onboard data reduction are discussed.

4.1.1 Tandem-L

Tandem-L is a German bi-static radar mission proposal in L-band, spearheaded by DLR in close cooperation with industry partners. The mission applies several innovative techniques to deliver high-resolution wide-swath imaging, allowing a timely observation of several dynamic processes on the Earth’s surface. Scientific applications span several domains such as the cryosphere, geosphere, hydrosphere and biosphere, as detailed in D1.1. Next, a first set of requirements for on-board processing is provided, taking as reference mode B1 (high resolution in single-polarization).

The parameters for on-board data handling are summarized in Table 22. A echo window duration of 1.42 ms is assumed, based on the swath extension of 350 km ground range. The ADC sampling assumes an oversampling of 31% over the 84 MHz chirp bandwidth (after intermediate frequency filtering and decimation, the original sampling rate of the ADC is higher). It should be stressed that the system possesses multiple channels in elevation (a total of $N_{el} = 32$), which are used 5 at a time to form $N_{beam} = 5$ beams simultaneously (by means of a complex-coefficient linear combination). Each beam represents an independent data stream written to memory at positions corresponding to different ranges. Thus, a buffer of 5 range lines needs to be filled before the azimuth processing takes place (see Figure 1). The processing is executed independently for each of the N_{pol} polarizations.

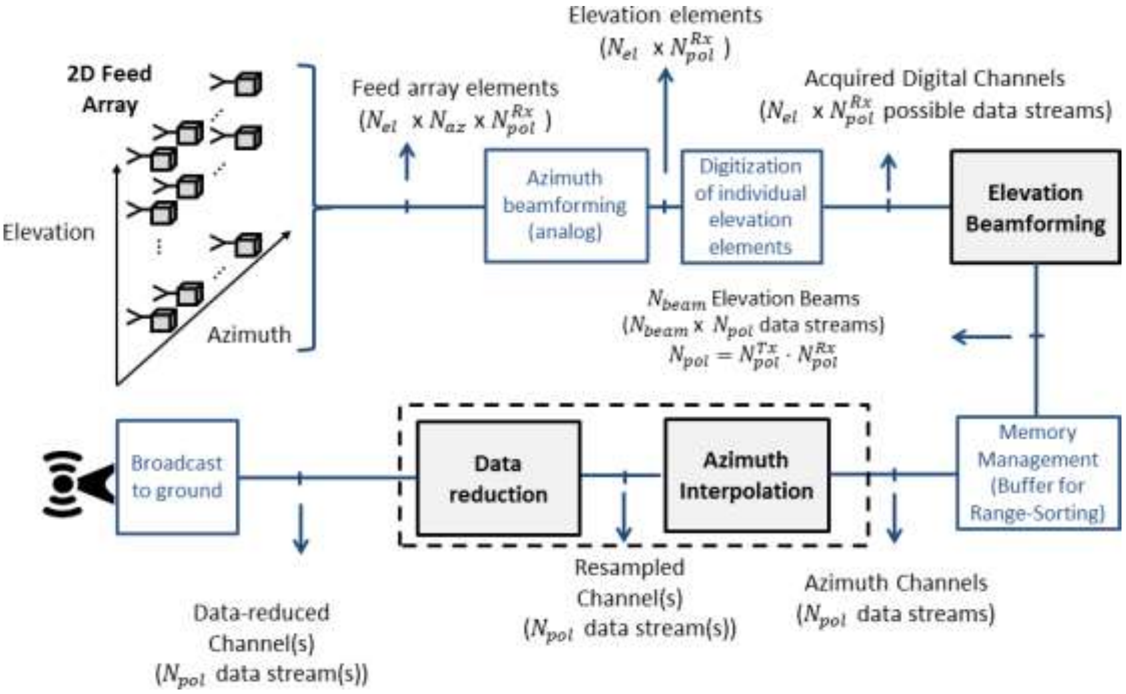

Figure 1: Overview of data flow for a multi-beam HRWS SAR instrument (e.g. Tandem-L).

Elevation channel overlap, i.e. a channel contributing to multiple beams, is possible. The burst length and the input data rate listed refers only to the channel which results from the combination of the 5 beams, and needs to be processed in the azimuth direction, after transposition.

The staggered SAR mode is assumed to be operated and data reduction by a factor of approx. 2 is supposed to be performed by the azimuth filter. The transpose matrix size lists two values, which refer to different resampling/data reduction filter lengths: 15 is the absolute minimum and 25 is the desirable length, which are required to obtain the minimum of a single output azimuth sample at the desired reduced sampling rate. Higher efficiency is expected for larger matrix sizes in the transpose operation. For one data take, approximately 6500 different filter coefficient sets of length 15 or 25 are foreseen to be kept in memory to execute the staggered SAR azimuth filter. The computational load is dominated by the dot product of the radar data and the filter coefficients. The Floating Point Operations per Second (FLOPS) values in the table refer to the 15 tap filter.

Two cases are considered for the indicated output data rate after BAQ: first, no azimuth filtering is assumed (data are sampled with the average PRF of the instrument) and second, a dedicated onboard azimuth processing is used in addition, leading to data sampled slightly above the required Doppler bandwidth, which allows to reduce the amount of data by an additional factor of 2.

For Tandem-L operation scenario, a Ka-band downlink is confirmed to be suitable to manage the transmission to ground of the azimuth processed and BAQ compressed data.

Parameter	Unit	Value
Echo window length	ms	1.42
Burst length (range line)	Samples (2x 16bit)	160*1e3
No of channels		1 (after elevation DBF)
Number of simultaneous elevation beams		5
ADC sampling rate	MHz	110
PRF (mean value, as PRI changes continuously)	Hz	2600
Processed Doppler bandwidth	Hz	1100
Maximum input data rate (all 5 beams)	Gbit/sec	17.6 (after DBF in elevation)
Output data rate (16bit, w/o BAQ)	Gbit/sec	6.6 (after azimuth filter)
Minimum transpose matrix size	Samples by Samples / MByte	160*1e3 x 15 / 10 (minimum) 160*1e3 x 25 / 16 (desirable)
Output data rate (4bit BAQ)	Gbit/sec	3.2 (@ PRF, w/o az processing) 1.6 (@ 1.2 x Doppler bandwidth)
Data per orbit for downlink (50% orbit duty cycle / 50 min data acquisition)	GByte	1220 (@ PRF) 620 (@ 1.2 x Doppler bandwidth)
Computational load for real-time operation	FLOPS	12.4e+9 (minimum) + 1.9e+9 (for BAQ)

Table 22: Tandem-L on-board data handling requirements

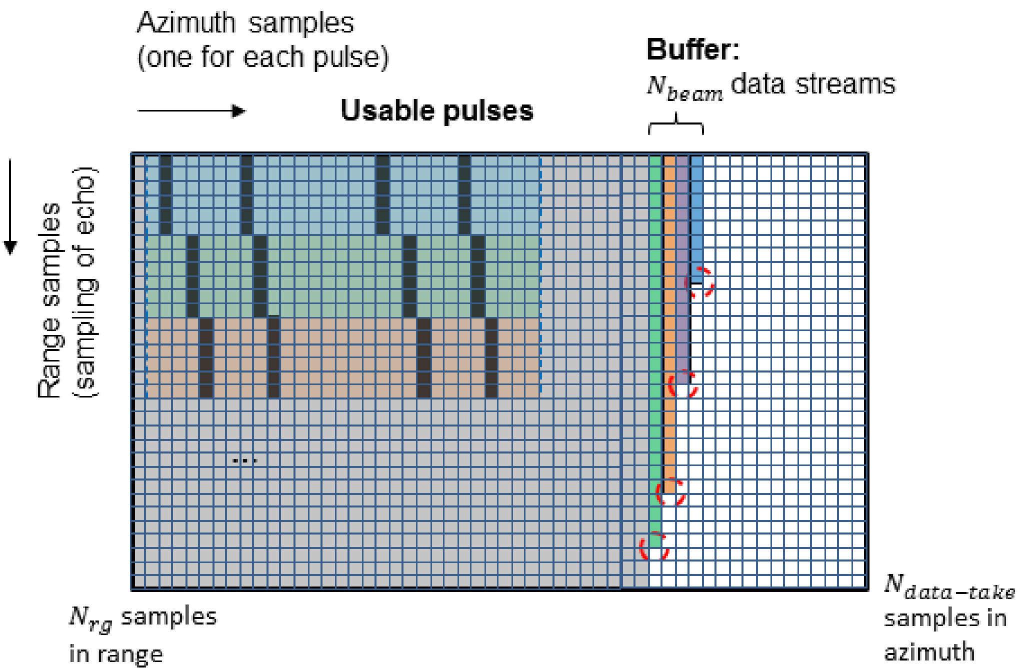

Figure 2: Allocation of memory buffer for a multi-beam HRWS SAR instrument (e.g. Tandem-L). Blocks of range bins use the same set of coefficients for azimuth filtering. The gaps migrate in range due to changes in the PRF and repeat cyclically in azimuth. In this example 4 beams are collected within a buffer and write data simultaneously to the memory (red circles).

4.1.2 ROSE-L

ROSE-L (Radar Observatory System for Europe in L-band) is a candidate mission for the expansion of ESA's Copernicus program. Its focus lies on monitoring of land (notably forestry and agriculture), ice and oceans (especially Arctic ice monitoring), as well as emergency management. The imaging requirements rule out conventional SAR systems, requiring the application of high-resolution wide-swath system architectures. The mission is described in in D1.1 in more detail. Next, an overview of on-board data handling requirements is provided, taking as example a high-resolution wide-swath single-polarization staggered SAR mode, intended for a reflector system with multiple elevation beams (one of multiple concepts presently under evaluation in the scope of the project).

The staggered SAR mode considered as an example follows essentially the same processing steps and logic highlighted in section 4.1.1, with different parameters. The echo window duration of 1.0 ms is assumed, based on the swath extension of 260 km ground range. The system possesses again multiple channels in elevation ($N_{el} = 27$) combined 9 at a time to form $N_{beam} = 4$ simultaneous beams, and the input data rate described applies to the output of the elevation DBF step. The parameters are summarized in Table 23.

The data flow within the ROSE-L instrument and the allocation of memory buffers needs to follow the same principles as discussed for Tandem-L. As indicated in Figure 1, the required azimuth processing consists in an alignment (range sorting) within the buffer and the azimuth processing itself (interpolation & resampling).

Compared to Tandem-L, the data rate and computational load are less by approximately a factor 2.5.

Parameter	Unit	Value (tbc)
Echo window length	ms	0.99
Burst length (range line)	Samples (2x 16bit)	54*1e3
No of channels		1 (after elevation DBF)
Number of simultaneous elevation beams		4
ADC sampling rate	MHz	55
PRF (mean value, as PRI changes continuouly)	Hz	3150
Processed Doppler bandwidth	Hz	1350
Maximum input data rate (all beams)	Gbit/sec	7.0 (after DBF in elevation)
Output data rate (16bit, w/o BAQ)	Gbit/sec	2.8 (after azimuth filter)
Transpose Matrix Size	Samples by Samples / MByte	54*1e3 x 15 / 3 (minimum) 54*1e3 x 25 / 5 (desirable)
Output data rate (4bit BAQ)	Gbit/sec	1.4 (@ PRF) 0.7 (@ 1.2 x Doppler bandwidth)
Data per orbit for downlink (50% orbit duty cycle / 50 min data acquisition)	GByte	515 (@ PRF) 265 (@ 1.2 x Doppler bandwidth)
Computational load for real-time operation	FLOPS	5.3e+9 (minimum) + 0.8e+9 (for BAQ)

Table 23: ROSE-L on-board data handling requirements. The values are not yet finally consolidated.

4.1.3 Sentinel-1 Next Generation

The second generation of Sentinel-1 will be able to serve more applications and services through increased capabilities. One example of particular importance is the development of so-called High-Resolution Wide-Swath techniques that will allow to image wider swaths at fine spatial resolutions. For the main mission parameters, see D1.1. Here we concentrate on the requirements for on-board data processing.

First Sentinel-1 follow-on activities proposed a planar antenna concept operating 8 azimuth channels to allow HRWS imaging [1-4]. Presently, these concepts are revised considering also reflector based antenna concepts. Depending on the adopted concept, different data rate requirements must be considered to achieve the required 400 km swath widths at 5m resolution [1-4].

Table 24 summarizes the anticipated input data rates of the instrument, assuming two different instrument types/operation modes: a staggered SAR mode for the reflector based antenna (in principle similar to Tandem-L and ROSE-L) and a ScanSAR mode with 8 parallel receive channels for a planar system. In the latter case, the ADC sampling together with the PRF and the number of receive channels determine the average input data rate to be stored in the satellites mass memory.

The requirements for the reflector case with staggered SAR mode are derived in a similar way as for Tandem-L. Due to the larger swath coverage and the necessity of twice the number of simultaneous beams, the input data rate is approximately larger by a factor of 2.

With respect to the planar case, the input data rate is even larger, because of the multiple azimuth channels which need to be combined after AD conversion. In S4Pro-D1.1 we propose a multi-channel BAQ data reduction approach based on DFT [5]. For this purpose the 8 channels need to be combined onboard, which defines the size of the matrix transpose for this use case.

The indicated matrix size for the transpose operation considers a single range line (burst) for all channels, which is the minimum requirement. However, one may implement multiples of this size if massive parallelisation is considered.

Parameter	Unit	Staggered SAR (Reflector) (tbc)	ScanSAR 4 burst (Planar) (tbc)
Echo window length	ms	1.7	0.3 to 0.5
Burst length (range line)	Samples (2x 16bit)	170e3	30*1e3 to 50*1e3
No of azimuth channels		1 (after elevation DBF)	8
Number of simultaneous elevation beams		10	1
ADC sampling rate	MHz	100	100
PRF (mean value, as PRI changes continuously)	Hz	5500	1000 (constant)
Processed Doppler bandwidth	Hz	1290	1200
Maximum input data rate (all beams)	Gbit/sec	32 (after DBF in elevation)	12
Output data rate (16bit, w/o BAQ)	Gbit/sec	6.6 (after azimuth filter)	10.2
Transpose Matrix Size	Samples by Samples / MByte	170*1e3 x 15 / 3 (minimum) 170*1e3 x 25 / 5 (desirable)	50*1e3 x 8 / 0.8
Output data rate (4bit BAQ)	Gbit/sec	5.8 (@ PRF) 1.6 (@ 1.2 x Doppler bandwidth)	2.6
Data per orbit for downlink (50% orbit duty cycle / 50 min data acquisition)	GByte	2175 (@ PRF) 600 (@ 1.2 x Doppler bandwidth)	1125 (@PRF)
Computational load for real-time operation	FLOPS	15.8e+9 (minimum) + 2.4e+9 (for BAQ)	3.1e+9 (for BAQ)

Table 24: Sentinel-1 Next Generation on-board data handling requirements. The planar case does not consider onboard processing options for data volume reduction, except for the BAQ.

4.1.4 HRWS – TerraSAR-X follow-on

The successor of TerraSAR-X will be a X-band SAR system designed by Airbus DS capable of providing spatial resolution as good as 25 cm in spotlight mode. One promising imaging mode is the so-called FScan mode, which allows Wide-Swath mapping with high resolution in stripmap mode (as an alternative to the HRWS concepts adopted for Tandem-L, ROSE-L and S1-NG). For the main mission parameters and a brief description of FScan, see D1.1 and [6]. Here we concentrate on the requirements for on-board data processing.

The advantages of the F-Scan mode come with the requirement of dedicated on-board processing. The concept makes use of a very high system bandwidth (1200 MHz) but the instantaneous target bandwidth of the recorded data is much less (approx. 300 MHz), sufficient to satisfy the range resolution requirement of ~1m.

Table 25 summarizes the anticipated input data rate of the instrument, assuming a 80km wide swath at a spatial resolution of 1m, for which 4 azimuth receive channels are required [6]. The ADC sampling together with the PRF and the number of receive channels determine the average input data rate to be stored in the satellites mass memory, unless bandpass filtering and decimation proposed in D1.1 is performed in real-time.

Parameter	Unit	Value
Burst length (range line)	Samples (2x 8bit)	547700
No of azimuth channels		4
ADC sampling rate	MHz	1380
PRF (burst rate)	Hz	2000
Input Data Rate (all channels)	Gbit/sec	70.1
Transpose Matrix Size	Samples by Samples / MB	Not needed
Output Data Rate (4bit BAQ)	Gbit/sec	8.8
Computational load for real-time operation (all channels)	FLOPS	80e+9 + 10e+9 (for BAQ)

Table 25: HRWS on-board data handling requirements

In a first assessment, the number of receive channels is irrelevant for the intended on-board application, as the data reduction works on individual range lines. Thus there is no need for a matrix transpose and the 4 channels can be processed either independently in parallel or sequentially. IN the table the computational load for all 4 channels is indicated, assuming a FIR filter length of 25 taps.

The data reduction is twofold: a factor of 4 is achieved by the filtering and decimation step and an additional factor of two is achieved by the final BAQ operation.

4.1.5 NewSpace SAR

Although limited in performance, the deployment as a constellation of dozens of “cheap” SAR sensors based on NewSpace technology offers favorable revisit time and thus good commercial opportunities (e.g. for maritime security). The generation of ready to use SAR images on-board the satellite can offer savings in downlink and faster data availability to the users.

For a first assessment of on-board computational requirements we consider an X-band SAR sensor operating in stripmap mode with TerraSAR-X like parameters (orbit height of 514 km and resolution of 3m) and swath widths of 20km. SAR image formation works on 2D data blocks. At some point of the processing a transpose operation on floating point data is needed to prepare data for FFT computation in the azimuth dimension, which explains the relatively large size for the transpose operation.

The reduced output data rate is a consequence of range compression (factor 4), multi-looking (factor 4) (assuming as output 16bit magnitude only SAR image data).

Parameter	Unit	Value
Burst length (range line)	Samples (2x 8bit)	34000 (8500 after range compression)
No of channels		1
ADC sampling rate	MHz	125
PRF (burst rate)	Hz	3000
Input Data Rate (all channels)	Gbit/sec	0.75
Transpose Matrix Size	Samples by Samples / MB	8500 x 4000 / 1000
Output Data Rate	Gbit/sec	0.05
Computational load for real-time operation (all channels)	FLOPS	300 (rough order of magnitude)

Table 26: NewSpace SAR on-board data handling requirements

The high computational load for this application prohibits real-time processing during data acquisition, thus that raw data need to be buffered in mass memory.

4.2 Radar Algorithm Selection for S4Pro Compute System Definition

Considering that the staggered SAR operation concept is one of the candidate modes, if not the favorite mode, for at least 3 HRWS radar missions to be implemented at European and German national level in the (very) near future, the consortium decided to implement the azimuth filtering and resampling processing algorithm of this mode to operate on the S4Pro compute system.

Since all HRWS radar mission pose very high requirements in terms of data throughput, a suitable architecture has to be defined. Two concepts have been identified and traded against each other:

- Memory based architecture:
  - The input data stream is stored into a large mass memory bank
  - The compute system gets output of memory (complete azimuth lines/samples) and performs resampling and stores the resampled data back to memory
  - Benefit: less stringent data rate requirements, ease of implementation (no streaming)
  - Drawback: ~3x memory requirement (worst-case) and fast mass memory access

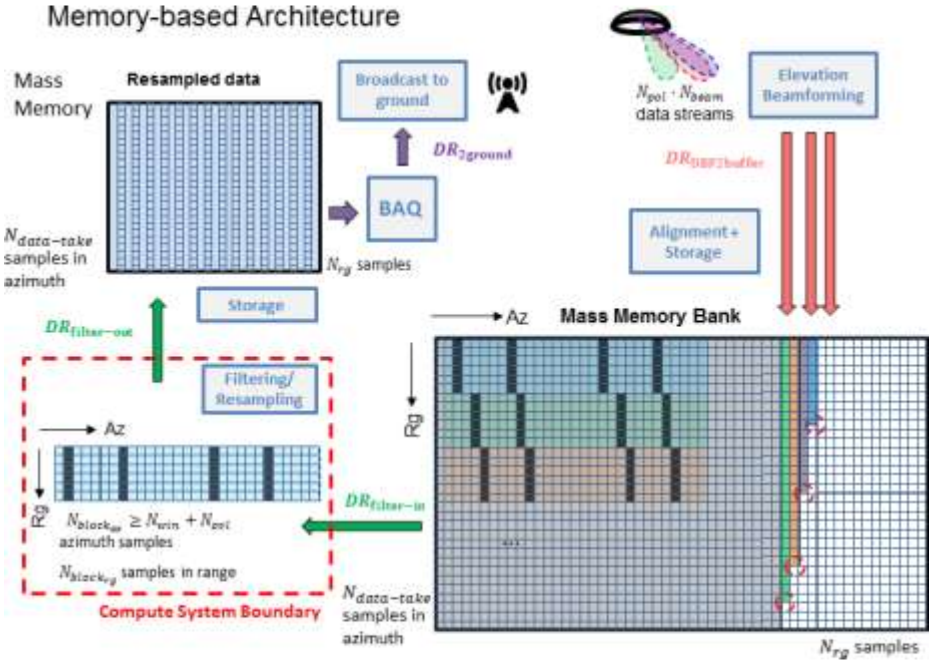

Figure 3: Memory based architecture alternative for implementing the HRWS azimuth filter.

- "Real-time" architecture:
  - The system gets directly the output of the beamformer units, handles "alignment" (corner turning), transposition and outputs filtered samples.
  - Internally, usable pulses (all range bins filled) are processed blockwise (full region N_{set} with same coefficients)
  - Benefit: Long-term storage is required only for the resampled data.
  - Drawback: Extremely high input data rate and complexity of implementation because of streaming requirement.

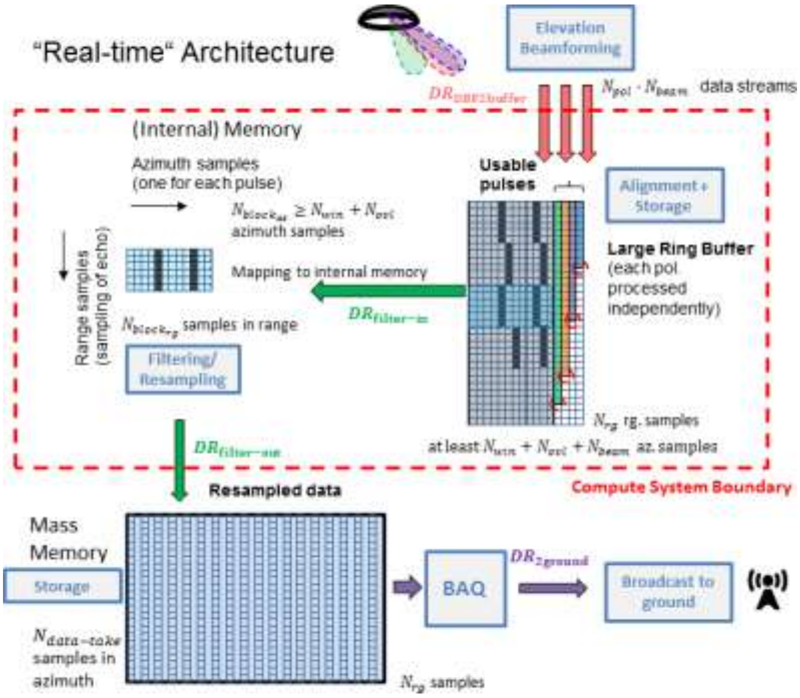

Figure 4: Preferred "real-time" architecture for implementing the HRWS azimuth filter.

Although very challenging because of the high input data rate, especially for the Tandem-L and Sentinel-1 NG cases, the "real-time" architecture is aimed for implementation and shall become the basis for follow-on implementation and benchmarking activities within S4Pro. It is common sense, that the memory based architecture will not be able to support the high input data rate and will also not be able to implement efficiently the range alignment.

Due to limited funds for hardware procurement, it is proposed that ROSE-L parameterization shall be the baseline for implementation within the S4Pro compute system.

4.3 Radar Algorithm Preliminary Benchmark Plan

Throughput tests:

1. The S4Pro compute system shall handle the input data rate of 7 Gbit/sec.
2. The mass memory shall be able to store the output data rate of 2.8 Gbit/sec.

Algorithm functionality tests:

3. Test of resampling and decimation on a 1D array.
4. Test of resampling and decimation on a 2D array according to a block of size N_{set}.
5. Test of resampling and decimation for a representative data take.

Computational performance tests:

6. Test of resampling and decimation for a representative data take.

4.4 References Radar Case

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5 CONCLUSIONS

Regarding optical on board processing requirements, we derived maximum data rate; in all scenarios considered this value was less than half Gbit/sec. Regarding kernels instead, they have in general odd sizes instead of multiples of four, as it would be preferable for mass memory optimization usage. Those dimensions come from the need of symmetry (with respect to the diagonal); odd sizes are always used in this kind of applications. Nevertheless, we see no big issues in modifying the kernels sizes to target kernels of size in the powers of 2 if required within the project. The matrixes will just be shifted and the indexes rearranged in order to cope with the exceeding dimensions. Coming to the number of FLOPS that needs to be addressed by the system, some of the considered algorithms may seem overly demanding in terms of processing power: this is actually due to the fact that a (quasi)real-time elaboration was considered, meaning that every single image is directly processed after it is acquired, before processing the next one which is being acquired. If this assumption is relaxed, considering an acquisition that stores in memory a sub-set of images per orbit and then elaborates them before downlink, these values could be lowered down to an arbitrary level, depending on the handling strategy, which is influenced by multiple factors (such as the number of Ground Stations, their availability, their positions over the globe, the downlink opportunities, etc.). For the purposes of defining the requirements (see table below), these values are therefore not considered, deriving the sizing figure from the ROSE-L case: this allows the use of one of the Ship Detection algorithm in a (quasi)real-time condition and the others to be evaluated in light of a different, more complex acquisition strategy. These evaluations will be taken into account during the final decision about the algorithms that will be taken later in the project and will be described in deliverable D2.1.

Regarding SAR onboard processing requirements, we found input data rates in the order of several Gbit/sec, depending on the SAR mission, which are at the limit of present day technology. Nevertheless, it is concluded that ROSE-L parameters are in line with the capabilities of the envisaged architecture of the S4Pro system and the resampling and decimation processing for a staggered SAR system can be benchmarked within the project. The biggest challenge is expected to be the real-time throughput requirement to be handled by a single system, considering the large amount of data and high orbit duty cycle.

For the S4Pro compute system and mass memory modules to be developed in S4Pro we thus derive the high level requirements summarized in Table 27, where throughput requirements are determined by the radar application, whilst power consumption and size limits by the optical payload.

Req-ID	Name	Description
RQ-HL1	Compute System Data Rate	The S4Pro compute system shall be capable of handling input data rates of at least 7 Gbit/sec (determined by ROSE-L parameters).
RQ-HL2	Compute System FLOPS	The S4Pro compute system shall be capable of handling a computational load of at least 6.5 GigaFLOPS (determined by ROSE-L parameters).
RQ-HL3	Compute System Scalability	The S4Pro compute system shall be scalable in performance to at least a factor of 4 (in order to support also the other radar missions).
RQ-HL4	Mass Memory Data Rate	The S4Pro mass memory module shall be capable of handling input data streams with data rates of at least 1.5 Gbit/sec (determined by the output of the ROSE-L staggered SAR filter).
RQ-HL5	Mass Memory Size	The S4Pro mass memory module shall be capable of storing a data amount of at least 32 GByte (determined by the size of one ROSE-L azimuth filtered data take of 6 minutes duration).
RQ-HL6	Power	The S4Pro compute system and mass memory modules should have a power consumption of less than 20W (to comply with resources on a smallsat operating an optical payload).
RQ-HL7	Size	The S4Pro compute system and mass memory modules should have a form factor compatible with smallsats.

Table 27: Summary of high level requirements for the S4Pro system HW.