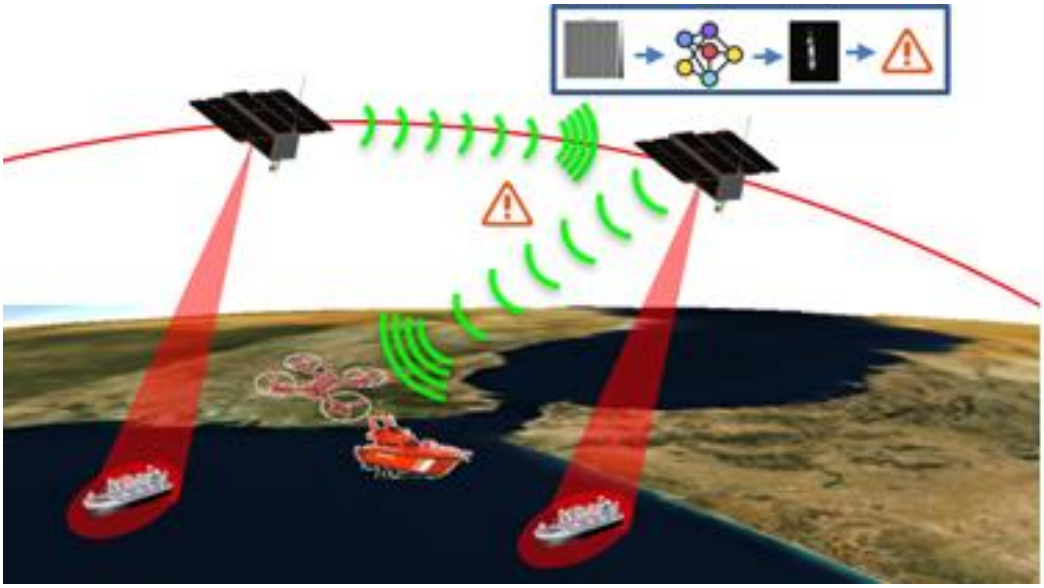

PERTEO

Final executive summary

EISI Study

Deimos Engineering & Systems, German Aerospace Center (DLR), KP Labs

Activity summary:

Persistent Responsive Real-Time Earth Observation small satellite constellation mission (PERTEO) is a study dedicated to provide a global democratic service to support disaster management. Earth observation and satellite-based communications play a key role to support disaster management targeting responsiveness and the persistence of the service. In the terminology of on-demand Copernicus services, responsiveness is determined by the lead-time and latency. The persistence is determined by the availability and by the revisit time of the service. Current satellite-based disaster management services are neither persistent nor are they highly responsive. In the proposed mission, a responsive real-time service would be provided, through the combination of edge-computing for on-demand applications (ML/AI) and global persistent communications. Persistency would be provided through a heterogeneous constellation of small satellites, including optical and SAR payloads. A persistent comms link, e.g. GEO-relay or ISL, enables software defined real-time changes in the satellite tasking, in the satellite application configuration (i.e. AI app change), and enables real-time global product delivery. To provide a democratic global service, this will also include direct-to-ground delivery. This idea and mission would dramatically improve satellite-based disaster management services, allowing nations to prepare and respond to future crises more effectively.

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Document Preparation

The document was prepared with contributions from:

Deimos
M. Quintana
S. Campo
R. C. Hinz
P. Hermosin
F. Membibre
P. Minacapilli
B. D´Andrea
A. Perera
A. Morón
DLR / Remote Sensing Technology Institute
H. Breit
S. Wiehle
DLR / Microwave and Radar Institute
M. Villano
N. Ustalli
DLR / The German Remote Sensing Data Center
G. Strunz
KP Labs
R. Zogala
P. Kuligowski

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1. INTRODUCTION

1.1. Purpose

The main objective of this activity is to define and analyse the feasibility and performance of a Persistent Responsive Real-Time Earth Observation small satellite constellation mission (PERTEO) to support disaster management. This mission would provide a global democratic service to support disaster management, in both the pre disaster (mitigation, preparedness) and post disaster (response) phases, and would dramatically improve satellite-based Disaster Management services Space applications and thus allow nations to manage more effectively emergency and crisis situations.
The purpose of this document is to serve as the final executive report, by following both the DEIMOS Corporate Management System and targeting the ESA Open Space Innovation Platform (OSIP) for the ESA Initial Support for Innovation (EISI).
This document covers the whole activity of the project from June to December 2022.

1.2. Scope

This report covers the period from June 1st to November 30th and provides a final executive summary report of the PERTEO project.

1.3. Acronyms and Abbreviations

- **AI:** Artificial Intelligence
- **AIS:** Automatic Identification System
- **AQI:** Air Quality Index
- **COTS**: Commercial Off-The-Shelf
- **DEM:** Digital Elevation Model
- **DL:** Deep Learning
- **DLR:** German Aerospace Centre
- **DPU**: Data Processing Unit
- **EPS:** Electric Power System
- **ESA**: European Space Agency
- **EW:** Extreme Weather
- **HR:** High Resolution
- **HRWS**: High Resolution Wide Swath
- **HSI:** Hyperspectral Imaging
- **I/O:** Input and Output

- **iDRS:** Inter Satellite Data Relay System
- **IG**: Image Generation
- **IoT:** Internet of Things
- **IR:** Infrared
- **LRIT**: Long Range Identification and Tracking
- **n/a**: Not available
- **NIR:** Near Infrared
- **NWP**: Numerical Weather Prediction
- **OPERA**: Operational Programme for the Exchange of weather RAdar information
- **PERTEO**: Persistent Responsive Real-Time Earth Observation small satellite constellation mission
- **PRF**: Pulse Repetition Frequency
- **RADAR**: Radio Detection and Ranging
- **SAR:** Synthetic Aperture Radar
- **SEVIRI:** Spinning Enhanced Visible Infra-Red Imager
- **TIR:** Thermal Infrared
- **TMTC**: Telemetry and Telecommand
- **TT&C:** Telemetry, Tracking and Command
- **UV:** Ultra-violet
- **VIS:** Visible Range
- **VMS:** Vessel Monitoring System

2. RELATED DOCUMENTS

2.1. Applicable Documents

The following table specifies the applicable documents supporting the generation of the current document.

Table 1 Applicable documents.

Reference	Code	Title	Issue
[AD 1]	4000138108	ESA Purchase order N.: 4000138108	

2.2. Reference Documents

The following table specifies the reference documents that shall be taken into account during project development.

Table 2 Reference documents.

Reference	Code	Title	Issue
[RD]	Idea_I-2022-00376_PERTEO	Description of the idea	1.0
[ASTRO]		Santilli, Giancarlo, et al. "CubeSat constellations for disaster management in remote areas." Acta Astronautica (11-17).	2018
[EO-AL]		Hinz, R. et al. Eo-alert: Machine learning-based on-board satellite processing for very-low latency convective storm nowcasting. In EMCWF-ESA Workshop	2020
[FAW]		Fawwaz Ulaby; M. Craig Dobson; José Luis Álvarez-Pérez, Handbook of Radar Scattering Statistics for Terrain, Artech.	2019
[IX2]		https://earth.esa.int/eogateway/missions/iceye	
[KPL]		Leopard DPU Technical sheet: https://kplabs.space/wp-content/uploads/Leopard-technical-sheet.pdf	
[GEO]		Viatte, Camille, et al. "Air pollution and sea pollution seen from space." Surveys in Geophysics 41.6 (1583-1609).	2020

Reference	Code	Title	Issue
[ICEYE]		Laaninena, Neerota, Homssia, Szczygielskab, and Jakub Niemczykb, “ICEYE Radar Constellation Development and Evolution”. EUSAR 2022	2022
[LoRaWan]		Steven J. Johnston et al. “City Scale Particulate Matter Monitoring Using LoRaWAN Based Air Quality IoT Devices”. MDPI Sensors	2019
[OPE]		E. Saltikoff et al. “OPERA the Radar Project”. *Atmosphere (Basel).*, 10, 320, https://doi.org/10.3390/atmos10060320.	2019
[SEN]		https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p	
[SEV]		Aminou, Donny et al. “Meteosat Second Generation: On-Ground Calibration, Characterisation and Sensitivity Analysis of SEVIRI Imaging Radiometer.” *Proceedings of SPIE - The International Society for Optical Engineering*. 3750. 10.1117/12.363538.	1999
[UNE]		Chen, W et al. S3D-UNet: Separable 3D U-Net for Brain Tumor Segmentation. *Lecture Notes in Computer Science()*, vol 11384. *Springer, Cham*. https://doi.org/10.1007/978-3-030-11726-9_32	2019
[UST]		Ustalli, N.; Villano, M. High-Resolution Wide-Swath Ambiguous Synthetic Aperture Radar Modes for Ship Monitoring. Remote Sens.	2022

3. WP1000 User requirements and scenarios definition

This chapter is initially intended to describe the relevant use cases concerning natural disasters and the selection performed in PERTEO.

3.1. Use cases

The metric defined for the evaluation of the use cases can be explored below and the results obtained are exposed in Table 3.

$$\text{Score} = 0.275 * v_{App.\ Maturity} + 0.225 * v_{Env.\ Impact} + 0.175 * v_{Revisit} + 0.125 * v_{Resolution} + 0.125 * v_{Latency} + 0.075 * v_{Ec.Impact}$$

Table 3: Evaluation of the disaster management applications.

	App. Maturity	Env. Impact	Revisit	Resolution	Latency	Ec. Impact	Score
Storm	1	2	3	2	2	1	**1.825**
Floods	1	1	3	2	1	1	**1.475**
Ship detection	1	1	3	3	2	1	**1.725**
Fire	2	1	2	2	2	2	**1.775**
Air pollution	1	2	2	2	1	3	**1.675**
Oil spill	2	1	2	2	3	3	**1.975**
Earthquake	3	1	2	1	3	1	**1.975**

3.2. Requirements

This section consolidates (without formalization) some system and user requirements that will drive the design of the mission and system in later stages of the project. They are exposed in Table 4.

Table 4: Payload, Mission and System Requirements generation from User Requirements.

Use case	Supporting Data	Spectral Ranges	User Req.	Payload Req.	Mission Req.
Floods	IoT, crowd-sourced data	SAR, HSI, VIS, IR	USER-001 Monitoring and forecasting	Spatial Resolution: 30 – 100 m [ASTRO]	Revisit Time: 12 h [ASTRO]
			USER-002 Situation analysis and early help development	Spatial Resolution: 10 – 100 m [ASTRO]	Revisit Time: 3 - 12 h [ASTRO]
Air pollution	Ground based measurements, atmospheric models, IoT, Hyperspectral data [SEN]	HSI, NIR, IR,	USER-003 Monitor fine particulate matter levels	Spectrometer with high spectral resolution ranging from IR to UV [GEO]	Revisit Time: 1 h [LoRaWan]
			USER-004 Chemical spill after disaster		Revisit Time: 1 h [LoRaWan]
Ship detection	IoT, Automatic Identification System (AIS), Long Range Identification and Tracking (LRIT) and Vessel Monitoring System (VMS) data	SAR, VIS	USER-005 Monitoring of coasts and early detection of ships	Spatial Resolution: 1 - 10 m [ASTRO]	Revisit Time: 3 h [ASTRO]
			USER-006 Ship identification and tracking	Spatial Resolution: 1 - 3 m [ASTRO]	Revisit Time: 0.5 h [ASTRO]
Fire	Numerical Weather Prediction (NWP), IoT,	SAR, VIS, IR	USER-007 Fire-risk assessment, monitoring and detection	Spatial Resolution: 100 m [ASTRO]	Revisit Time: 1 – 3 h [ASTRO]

	crowd-sourced data		USER-008 Near real time monitoring of fires	Spatial Resolution: 30 m [ASTRO]	Revisit Time: 0.25 h [ASTRO]
Storm	Earth radars, lighting information, Numerical Weather Prediction (NWP), IoT	SAR, VIS, NIR and IR	USER-009 Prediction, detection and tracking of storms	Spatial Resolution: 30 m (assumed)	Revisit Time: 1 h (assumed)
			USER-010 Extent, water depth and propagation	Spatial Resolution: 30 m (assumed)	Revisit Time: 1 h (assumed)

4. WP2000 System and mission engineering

This chapter introduces the design of the new constellation explored in PERTEO.

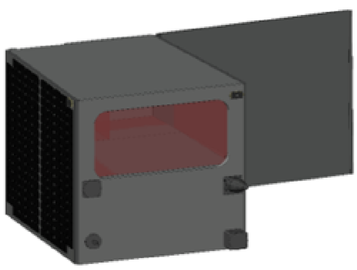
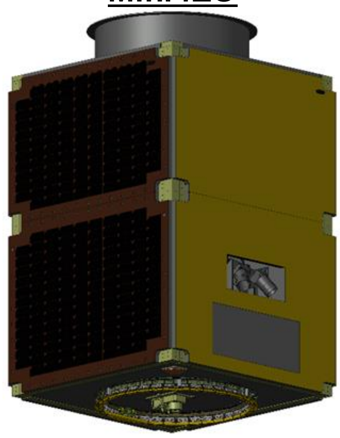
4.1. System overview

The main challenges identified at platform level are here listed:

- Duty cycling management for payloads due to the variety of scenarios.
- Availability of the service under request (influence visibility, EPS design, pointing capabilities, data handling, communication).
- Thermal architecture (to be compatible with SAR power requirements).
- Data management to guarantee the desired responsiveness.

Two spacecraft platforms under development in the Deimos dependencies are proposed for PERTEO, exploiting their modularity and tailoring capabilities for the mission needs. Their main performances are reported and compared in Table 5. Their compliance with the PERTEO payloads will be studied in the next subsections. eventually introducing system modifications.

Table 5 Deimos platforms overview.

	Mini4EO Lite	**Mini4EO**
		

Envelope Dimensions	692 x 770 x 821 mm	900 x 900 x 1550 mm
Wet Mass	~ 100 kg (w/o payload)	~ 200 kg (w/o payload)
Max. power generation @ Sun pointing	~ 357 W with deployable	~ 400 W (only body mounted)
Lifetime	>5 years operational lifetime in LEO	>5 years operational lifetime in LEO
Original Payload Mass	15 kg	40 kg
Power System	- Power Control and Distribution Unit - Secondary Battery pack (778 Wh) - Body-mounted solar arrays	- Power Control and Distribution Unit - Secondary Battery pack (1555 Wh) - Body-mounted solar arrays
Communications	Low data rate (TMTC): - S-Band Transceiver (TT&C) - 2 x S-Band Antenna High data rate (image data downlink): - X-Band Transmitter - X-Band Antenna ISL Link: - iDRS	Low data rate (TMTC): - 2 x S-Band Transceiver (TT&C) - 2 x S-Band Antenna High data rate (image data downlink): - X-Band Transmitter - X-Band Antenna steerable ISL Link: - iDRS
Thermal Control	- Primarily passive (MLI, paint…) - Limited use of heaters and thermistors	- Primarily passive (MLI, paint…) - Limited use of heaters and thermistors

4.1.1. Instrument Coverage Analysis

For the PERTEO mission, the orbital duty cycle plays a key role in the S/C data flow and data volume issues and the compliance with the data latency requirement. The coverage coverage analysis has been directed towards two configurations:

- Entire constellation: 48 instruments (6 per plane)
- Part of the constellation: 16 instruments (2 per plane)

4.1.1.1. Coverage and Revisit Time Performance Analysis

Figure 4-1 shows the average revisit time maps respectively for the two configuration (16 and 48 instruments placed in 8 planes). 48 satellites placed in 8 orbital planes can provide a revisit time over the Equator below 1.2 hours and 1 hour over Europe.

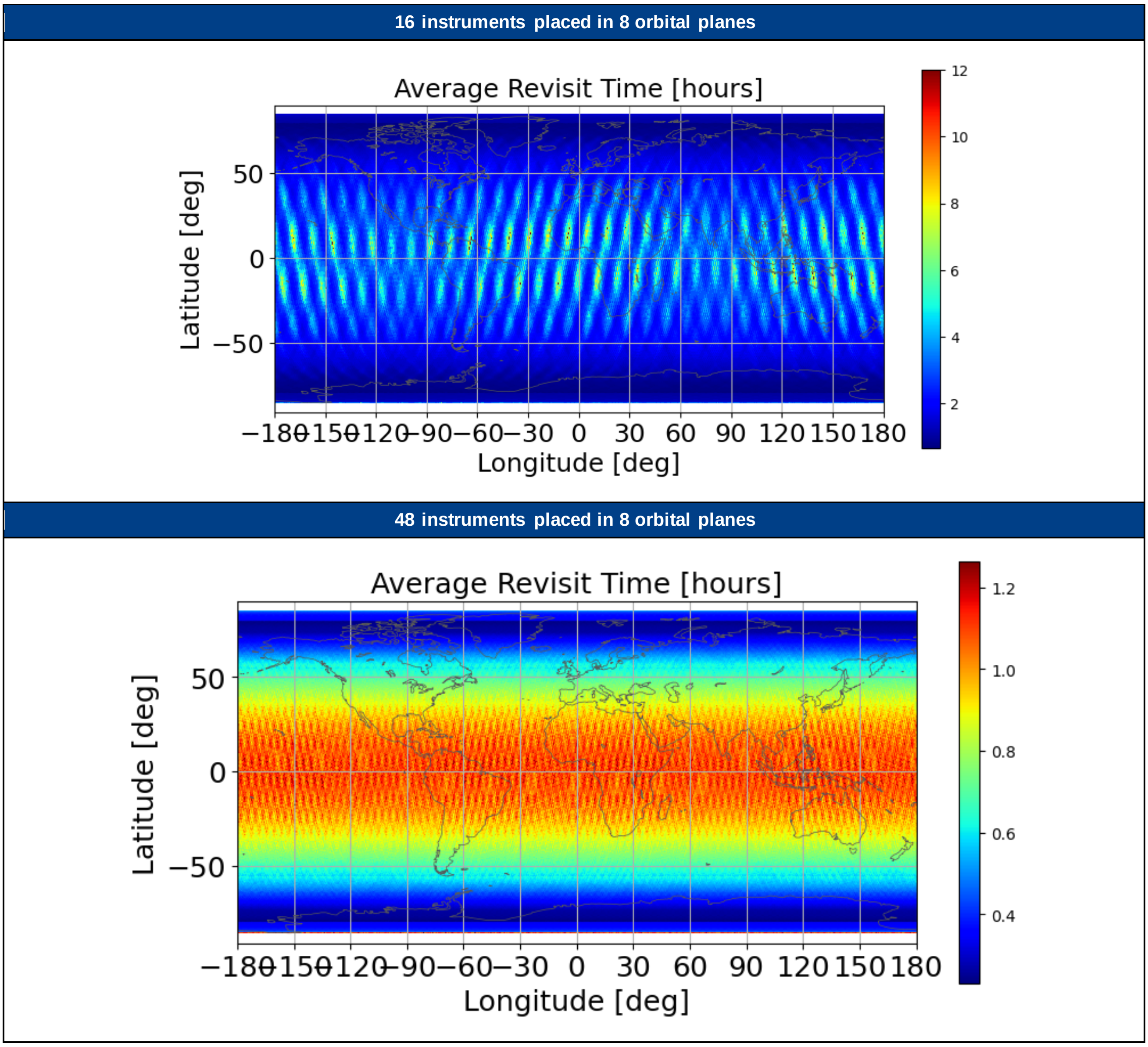


Figure 4-1: Average Revisit Time over the entire globe after 1 day for the two configurations

5. WP3000 Satellite, Payloads and GS Engineering

This chapter introduces the refined design for the platforms considered for the constellation,

5.1. Platform design

The different parameters that have been considered to propose a complete design of the platforms included in the constellation are iterated in this section.

5.1.1. EPS

Table 6 SAR Duty Cycles

Component	Duty cycle
SAR orbit	> 5%
SAR instrument	20

5.1.2. Batteries

Table 7 Power consumption assumptions.

ECLIPSE	Power (W)	Time of operation (min)	Energy (Wh)
Mini4EO Lite (average) + DPU (worst case)	200 + 40	37.85	151.38
SAR instrument peak	3200	1	74.67
SAR instrument nominal	320	4	
Total energy consumed Mini4EO Lite eclipse worst case (Wh)	**226.05**		

Therefore, the batteries of Mini4EO Lite are enough for operating SAR and DPU in eclipse.

5.1.3. Solar Panels

To ensure **continuous service in one orbit**, solar panels must be able (in the worst-case scenario) to:

1) Recharge the battery (the **recharging power is 271.26 W**).
2) Provide power to the platform and DPU for the time in sunlight (200 W + 40 W).
3) Ensure SAR operation at any time (3200 W + 320 W).

The configuration here proposed, which resembles the one of ICEYE satellites (SAR antenna and solar panels orthogonally mounted) is depicted in Figure 5-1.

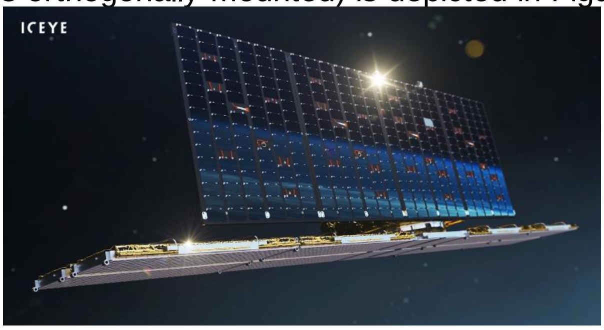


Figure 5-1 ICEYE solar panels configuration.

5.1.4. TCS

Table 8 summarises the individual contributions due to the incoming solar radiation.

Table 8 Thermal environment in the worst hot case.

Q Sun (W)	344.61
Q Albedo Earth (W)	49.62
Q Earth IR (W)	200.53
Q generated (W)	3060

5.1.5. TMTC

The performances guaranteed by Mini4EO Lite communication subsystem are expressed in Table 9.

Table 9 Communication in X-band and iDRS Mini4EO Lite.

	X-band Transceiver	iDRS Transceiver
Frequency	8025-8400 Mhz	L band Tx operation: 1.6265–1.675 GHz L band Rx operation: 1.518–1.559 GHz
Useful Data Rate	Up to 600 Mbps	Data rate TX: 2 kbps to 2 Mbps Data rate RX: 4 kbps to 64 kbps
Modulation	BPSK, QPSK, OQPSK, 8PSK, 16APSK (DVB-S2)	Tx: BPSK, QPSK, OQPSK Rx: BPSK with BCH coding
RF Output Power	Up to 10 W	2 Tx channels each up to +30 dBm

5.2. SAR specification

The requirement for the payload spatial resolution to be considered for the payload selection is **10 meters**. No COTS are available in the market.

5.2.1. PERTEO SAR Swath, Coverage, and Data Rates

The range of incidence angles being specified for the Iceye-X2 Stripmap mode stretches from 10° to 30° degrees. The relationship between incidence angles and off-nadir look angles for an orbit height of 500 km and targets at sea level are given in Figure 5-2.

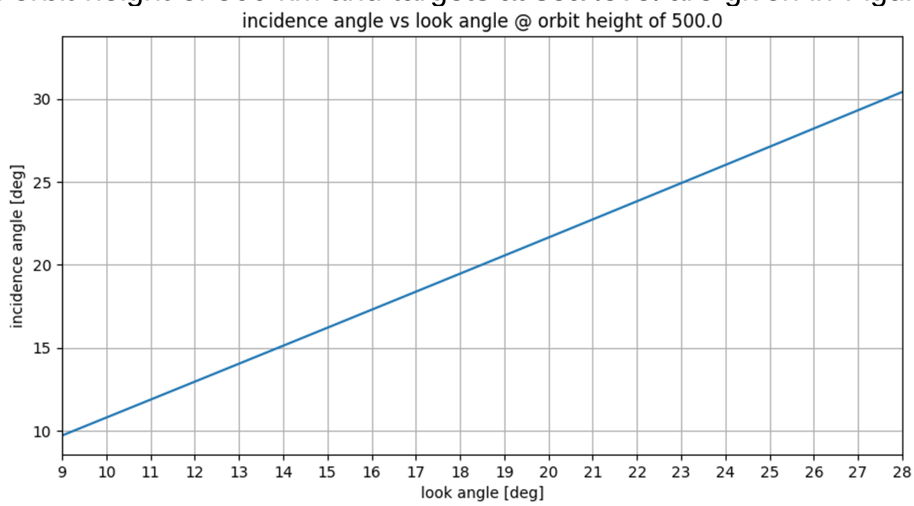


Figure 5-2 Incidence angles as a function of look angles for an orbit height of 500.0 km.

The parameters concerning the data rates for the 6 beams are exposed in Table 10.

Table 10 PERTEO SAR data rates.

Beam	Look start (Deg)	Incidence start (Deg)	Ground swath (Km)	Range extent (Km)	Samples per echo	MiB / s MiB / 210 km^2

1	9.2	9.9	27	5.5	15766	62
2	12.2	13.2	28	7.1	13264	52
3	15.2	16.4	30	9.3	12354	48
4	18.2	19.7	31	11.3	10917	41
5	21.2	23.0	33	13.6	10614	42
6	24.2	26.2	34	16.1	10546	41

5.2.2. Instrument Design

The main SAR parameters for the stripmap mode are summarized in Table 11.

Table 11 SAR parameters for the stripmap mode.

Parameter	Value
Wavelength	0.03 m (X-band)
Orbit height	500 km
Antenna size (length × height)	3.2 m × 0.4 m
Elevation beamwidth	3°
Instrument duty cycle	20%
Number of sub swaths	6
Look angle range	9.2° - 27.2°
Incidence angle range	9.9° - 29.5°
Doppler bandwidth	4215.42 Hz
Processed Doppler bandwidth	2107 Hz
Azimuth processing window	Generalized Hamming with α =0.75
Range processing window	Generalized Hamming with α =0.75
Impulse response broadening factor due to the processing window	1.13
Backscatter model	Soil and rock in HH polarization from [FAW]

- **High-Resolution Wide-Swath Ambiguous Mode for Ship Detection**

A low PRF ambiguous mode to achieve high-resolution wide-swath (HRWS) imaging without using digital beamforming as in [UST] is proposed. This mode image a wide swath using a wide elevation beam. Within the 180 km ground swath, the ground range resolution ranges from 3.4 m at near range to 1.1 m at far range, considering a Hamming window with α =0.75 in the processing, as shown in Figure 5-3.

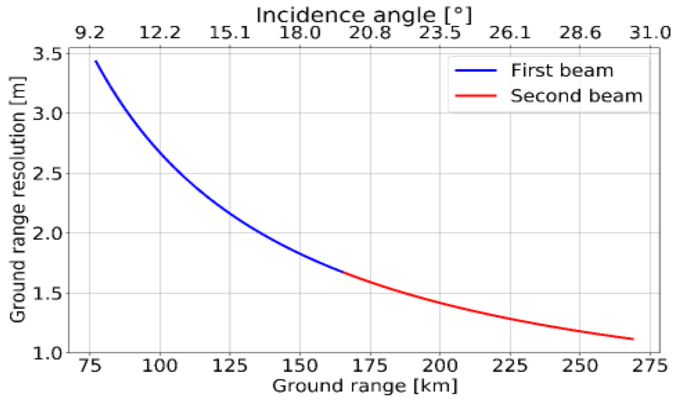


Figure 5-3 Ground range resolution as function of the ground range for the two beams.

Figure 5-4 shows how phase tapering techniques with 16 elevation array elements are used to achieve a wide beam in elevation.

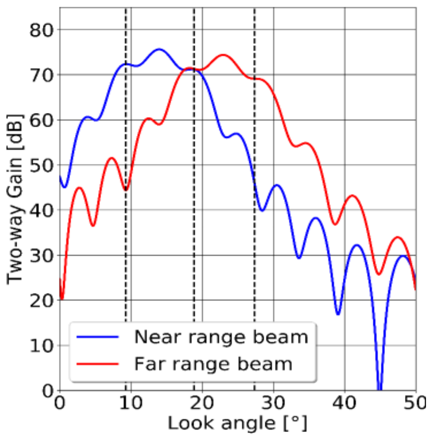


Figure 5-4 Achieved sector beams as function of look angle. The look angle span between the near range and the far range is highlighted for each beam.

5.3. Payload data flow analysis

This section details the data acquisition with the sensing devices designed in the system.

5.3.1. SAR

The PERTEO SAR payload is specified to provide 2 different image acquisition modes:

1. **Stripmap mode**
   - FoV range of 10° to 30°.
   - beam covers approximately a **swath of 30 km**.
   - designed to support the **ship detection**, **storm**, and the **flood** use case.
2. **High-Resolution Wide-Swath Ambiguous (HRWS-Ambi) mode**
   - FoV range of 10° to 30°.
   - beam covers approximately a **swath of 90 km** or **60 km**.
   - Designed to support the **ship detection** uses case for large geographical coverages.

Four variants of the HRWS-Ambi mode are investigated trading off. instrument data rates versus ship detection performance. The parameters being subject to variation are *pulse bandwidth*, *instrument duty cycle*, and *swath width*. The corresponding values for each of them can be noticed in Table 12.

Table 12 Specification of the SAR acquisition modes.

SAR mode	Swath width (km)	Number of beams	Pulse bandwidth (MHz)	Instrument duty cycle	Pulse duration (ms)	Pulse repetition frequency (Hz)
Stripmap	30	6	174/132/106/ 89/77/68	20%	46/44/44/36/35/34	3910/3910/3910/ 3780/3950/3862
HRWS Ambi V1	90	2	300	20%	80/97	2450/2058
HRWS Ambi V2	90	2	**150**	20%	80/97	2450/2058
HRWS Ambi V3	90	2	300	**10**%	40/48	2450/2058
HRWS Ambi V4	**60**	3	300	20%	54/62/97	3666/3241/2052

5.3.1.1. SAR geographical coverage and acquisition date rates

The geographical coverage and acquisition rates related to the SAR instrument are specified in Table 13.

Table 13 SAR geographical coverage and acquisition rates.

SAR mode	Swath width	Coverage rate	max. coverage within one orbit	min/max. instrument data rate (w/o BAQ)	min/max L0 data rate (4bit/4bit BAQ)	min/max L1 data rate (8 bit amplitude data, full resolution)
	[km]	[km²/ s]	[km²/120 s]	[MBit/s]	[MBit/s]	[Mbit/s]
Stripmap	30	210	25200	652 / 990	359 / 544	215 / 247
HRWS Ambi V1	90	630	75000	3079 / 3734	1693 / 2054	1022 / 1340
HRWS Ambi V2	90	630	75000	1539 / 1867	846 / 1027	510 / 670
HRWS Ambi V3	90	630	75000	2561 / 3202	1409 / 1761	1022 / 1340
HRWS Ambi V4	60	420	504000	2852 / 3444	1569 / 1894	903 / 1192

Instrument data rates are calculated as follows:

$$instrument\ data\ rate\left[\frac{bit}{s}\right] = \left(\Delta r_{swath} \cdot \frac{2}{c} + \Delta t_{pulse}\right) \cdot f_s \cdot PRF \cdot n_{bit}$$

where Δr_{swath} represents the swath width, c the speed of light, Δt_{pulse} the pulse duration, f_s the sampling frequency which is selected to be 10% higher than the pulse bandwidth, PRF the pulse repetition frequency, and $n_{bit}$the number of bits per radar sample. The analogue digital converts typically provide 8 bit for the in-phase component and 8 bit for quadrature component.Some parameters related to the processing latencies are expressed in Table 14.

Table 14 Coverage show cases and level 0 to level 1 processing latencies.

SAR mode	Data take duration (s)	Coverage (km x km)	Radar echoes (max)	Azimuth blocks	Range blocks	Latency level 0 to level 1 (s)	Real Time Factor
Stripmap	4.5	30 x 30 = 900	17775	3	1	12	0.38
HRWS Ambi V1	13,5	90 x 90 = 8100	33075	10	3	120	0.11
HRWS Ambi V2	13,5	90 x 90 = 8100	33075	10	1	40	0.34
HRWS Ambi V3	13,5	90 x 90 = 8100	33075	10	2	80	0.17
HRWS Ambi V4	9.0	60 x 60 = 3600	33000	10	2	80	0.11

The favoured variant #2 achieves the best latency of the HRWS ambi variants. As a first guess the latencies for level 1 to level 2 processing are estimated to be half of level 0 to level 1 latencies.

5.3.2. Optical

The features of two types of optical cameras: high-resolution and hyperspectral in terms of data acquisition are explored in the next subsections

5.3.2.1. Hyperspectral

The data acquisition features of a generic hyperspectral camera are exposed in Table 15.

Table 15 Data acquisition features of hyperspectral camera.

Active pixels (px)	Channels		Swath (km)@ 500 km	GSD (m) @ 500km	GPU	Bit depth	Acquisition rate (MB/s)
	Vis & NIR	MIR					
4096	45	3	280	67	Yes	12	45.5

5.3.2.2. High resolution

The data acquisition features of an optical HR camera are exposed in Table 16.

Table 16 Data acquisition features of HR camera.

Active pixels (px)	Channels		Swath (km)@ 500 km		GSD (m) @ 500km		GPU	Bit depth	Acquisition rate (MB/s)
	Vis & PAN	NIR & SWIR	Vis & PAN	NIR & SWIR	Vis & PAN	NIR & SWIR			
4096	4	4	7.5	8.5	0.8	2. 2	Yes	8,10,12	8,2

6. WP4000 Service analysis and recommendations

This chapter exposes the service analysis of the use cases selected in chapter 1, and exposes the implementation details of the prototype implemented for EW based on Deep Learning algorithmics.

6.1. Service analysis

The analysis of the services contemplated for PERTEO are included in Table 17.

6.1.1. High level

Table 17 PERTEO high-level service analysis

Use case	Scenarios			Sensing	Pipeline	Approach	Accuracy
	Pre	In	Post				
Floods	Input from storm use case to assess the ROIs with a higher risk	Monitoring sensitive areas by joining SAR and HSI data	Change detection	SAR & HSI	TBD	Satellite HSI + SAR segmentation	TBD
Fire	Monitoring of fire events and their propagation.	Hot spot detection.	Fire risk assessment + burned area mapping	Optical	TBD	Wildfire detection: Deep learning hosted based on thermal imaging Mapping: Optical change detection detail	TBD
Air pollution	Early detection of abnormal levels of Nitrogen Oxide and Fine Particulate Matter (PM).	Spread of the anomaly by levels of Nitrogen Oxide and Fine Particulate Matter (PM).	Assessment of the impact of the disaster.	HSI	TBD	Deep learning feed by HSI data relying on the reflecting properties of the elements on-ground + fine detail by WSN sensors on-ground	TBD
Ship detection	Routine Surveillance of ROIs or On-demand surveillance triggered by	Detection of ships and generation of ship detection alerts for downlink and autonomous triggering of subsequent optical	Large-area scan in search for captured ship	SAR & HR	SAR focusing & generation of geo-referenced SAR image Ship detection: CFAR mask generation	SAR: E2E on-board processing: SAR processing parameter processing on ARM cores	The dedicated PERTEO Ship Detection High resolution Wide Swath Ambiguity mode is designed to detect ships

	external information	and SAR acquisitions			Local thresholding Azimuth Filtering Land object removal Ship parameter extraction	FPGA SAR image generation FPGA CFAR mask generation Further ship detection processing on ARM cores and Vitis AI	down to 21 m x 6 m size
Storm	Extreme Weather identification and tracking	Damage assessment of buildings, roads, bridges (critical infrastructures).	Monitoring of rebuilding	SAR & HSI	EW: Convective cell candidates + Segmentation + Tracking (On-board) SAR: Change detection (Hybrid)	EW pipeline on-board hosted by Vitis AI SAR: TBD	TBD

6.1.2. Processing

6.1.2.1. Scope

Table 18 Platform processing scope and ground validation.

	SAR	Hyper	HR	Validation (ground)
Ship	Ship detection		Ship Classification	AIS
Storm	Change detection	Convective cell segmentation		Pluviometry + RADAR
Flood	Flood-mask	Flood-mask		IoT (Water level)
Air quality	Wind-Velocity	AQI		IoT (AQI)
Fire		Wildfire detection	Hot-spot detection	IoT (Temperature)

6.1.2.2. Data input

Table 19 PERTEO service analysis input.

<table>
<tr><th rowspan="2"></th><th colspan="2">SAR</th><th colspan="2">Hyper</th><th colspan="2">HR</th><th rowspan="2">Mask</th><th rowspan="2">Extra</th><th rowspan="2">Geoloc.</th></tr>
<tr><th>Mode</th><th>Swath (km) x time (s)</th><th>Spectrum/ Index</th><th>Swath (km) x time (s)</th><th>Spectrum</th><th>Swath (km) x time (s)</th></tr>
<tr><td>Ship</td><td>Stripmap, HRWS</td><td>20 -90 x 3-13</td><td></td><td></td><td>Vis</td><td>8.5 x TBD</td><td>Land-water, Water-owner</td><td></td><td>SAR:
As good as the on-board orbit determination: approx. < 5 m</td></tr>
<tr><td>Storm</td><td>Stripmap</td><td rowspan="2">20-30 x 3-4.5</td><td>NIR + MIR</td><td rowspan="3">280 x TBD</td><td></td><td></td><td>Land-water, country, Domestic-facilities</td><td>DEM</td><td>Depending on the height variation of the area:
<10 m
<100 m</td></tr>
<tr><td>Flood</td><td>Stripmap</td><td>HDWI</td><td></td><td></td><td>Land-water, country, Domestic-facilities</td><td>EW Product, DEM, Wind-Velocity</td><td>Depending on the height variation of the area:
<10 m
<40 m</td></tr>
<tr><td>Air quality</td><td></td><td></td><td>Vegetation indices</td><td></td><td></td><td>Land-water, country, Land-Tº, Airport-Harbour, Road-density</td><td>DEM/DSM/ DTM (TBC)</td><td>Depending on the height variation of the area:
<10 m
<100 m</td></tr>
</table>

Fire			TIR		NIR + SWIR	7.5 x TBD	Land-water, Land-Tº, Rural-Urban, country, Land-country	DEM	

6.2. Extreme weather prototype

The extreme weather prototype has been implemented based on the inherited architecture from EO-ALERT [EO-AL].

6.2.1. Extreme weather service

Several tests concerning the image processing chain have been performed in the KP Labs Leopard breadboard [KPL], but the main objective of this subtask is the implementation of the candidate discrimination by Deep Learning means. The following assets are considered for that aim:

- Input:
    - SEVIRI instrument image [SEV]
    - OPERA mask corresponding to the acquired image [OPE]
    - Cell candidates from the Image Processing chain

- Output:
    - Classified convective cells

6.2.1.1. Convective cell segmentation training

The original dataset has been divided into a 90-10 split for training/validation – testing where RADAR coverage is available and where a minimum event of convection is detected. This split results in 7185 images for training, 1268 images for validation and 1160 images for testing. A U-net [UNE] like CNN has been selected to be trained in the VITIS AI framework and modified due to some restrictions of this framework.

The U-net model previously specified has been fed by different combinations of data extracted from the SEVIRI dataset to compose the optimal combination of channels that maximizes the accuracy of the inference performed. A sample image and its corresponding ground truth can be seen in Figure 6-1.

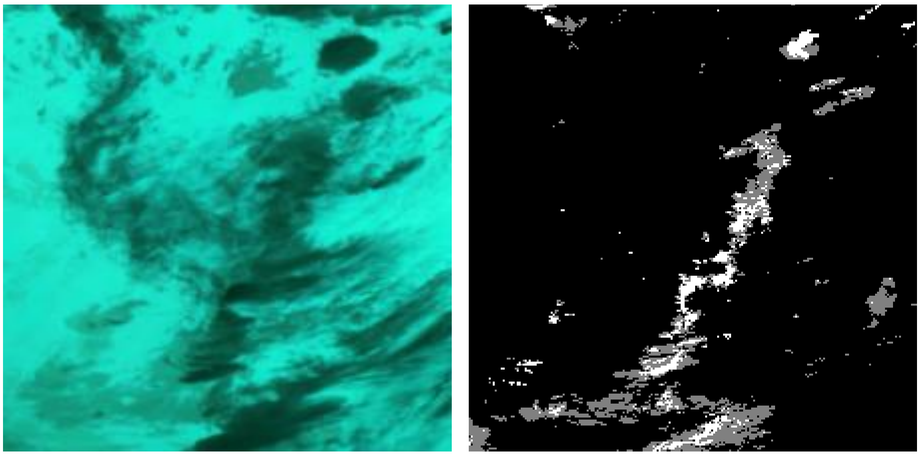


Figure 6-1 Sample input image from SIVIRI and its corresponding GT from OPERA.

6.2.1.2. Visual results

One sample of visual results is exposed in Figure 6-2 whose corresponding image enumeration is detailed in Table 20.

Table 20 Image composition of the convective cell segmentation visual results

Number	Image definition
1	Opera radar ground truth data
2	Opera radar coverage mask
3	DL implementation with opera coverage mask
4	DL implementation result
5	On-board implementation with coverage mask
6	On-board DL result

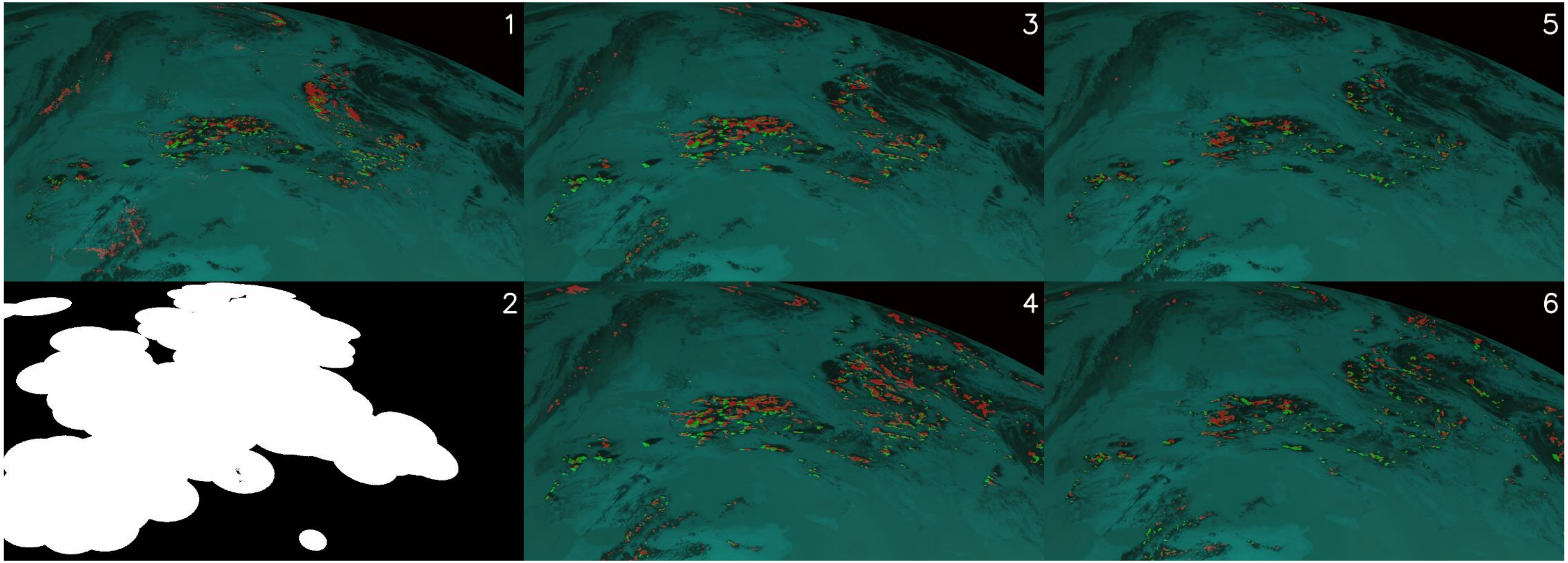


Figure 6-2 Sample 1 of convective cell segmentation visual result.

6.2.1.3. Metrics

The metrics obtained in terms of accuracy and latency are exposed in this subsection.

6.2.1.3.1. Accuracy

The accuracy results obtained for the segmentation of the convective cells by the train, validation and test datasets are exposed in Table 21.

Table 21 Deep learning results for the convective cell segmentation with the dataset built (patch scale).

		TP	FP	FN	IoU	DICE
TRAIN	No Cloud	335619722	26779	13354007	0.962	**0.980**
	Non-Severe	12619988	11534374	505441	0.512	**0.645**
	Severe	5470883	2668862	370567	0.643	**0.748**
VALIDATION	No Cloud	59340679	143098	2409283	0.959	**0.978**
	Non-Severe	1980251	2146741	249730	0.452	**0.575**
	Severe	806186	560965	191791	0.517	**0.611**
TEST	No Cloud	44992351	302113	1927704	0.953	**0.975**
	Non-Severe	1311423	1794903	406868	0.373	**0.492**
	Severe	481172	541398	303842	0.363	**0.445**

6.2.1.3.2. Latency

The latency results obtained for the segmentation of the convective in the Leopard breadboard are exposed in Table 22 and Table 23.

Table 22 Latencies for the different stages of the Extreme Weather processing chain.

Stages	Time per crop (sec)	Time per image (sec)
Pre-processing	0.007	0.126
DPU implementation	0.4	-

DPU inference	0.07	1.26
Postprocessing	0.019	0.34

Table 23 Latencies for the different processes of the Extreme Weather processing chain.

Process	Time per crop (sec)	Time per image (sec)
Candidate extraction	-	15
Candidate discrimination	0.1	1.9

7. FUTURE WORK

This chapter exposes the next steps to be performed to mature the different technologies selected for PERTEO

7.1. WP2000 System and mission engineering

The configuration of the constellation and the mission analysis will also be iterated focused on the user-experience relying on the following parameters:

- Number of satellites
- Revisit time
- Coverage
- Inter-satellite and inter-orbital plane comms

7.2. WP3000 Satellite, payloads and GS engineering

The specific features of each satellite may be refined according to the new trends in terms of optical/SAR/processing payload to select cutting-edge technologies that may imply refinements in terms of:

- Platform design
- Data acquisition modes
- Data flow
- Latencies

7.2.1. Extreme weather prototype

The high-level details missing on the tests performed in Leopard DPU are the following:

- IG integration
- Data compression

- Tracking optimization and re-alimentation by the convective cell segmentation
- Radiance/temperature conversion integrated in the patching method in the DL I/O

Regarding the convective cell implementation the following areas should be iterated to optimize the results obtained in terms of accuracy:

- Massive multi-payload training
- Payload-specific fine-tuning
- Spectral analysis
- Last layer on-board implementation