ΦSAT-2 MISSION OVERVIEW FOR THE #ORBITALAI CHALLENGE

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1. INTRODUCTION

As an initiative to promote the development and implementation of innovative technologies onboard Earth Observation (EO) missions, in 2018 the European Space Agency (ESA) kicked off the first Φsat related activities with the aim to enhance the already ongoing FSSCAT project with Artificial Intelligence (A.I).

Thanks to the success of the Φ-sat-1 experiment, it was decided to promote the Φ-sat line to full missions and this time under the name of Φsat-2. The call has been issued at the end of 2019 seeking new ideas and innovative approaches to on-board EO data processing and AI exploitation and after the evaluation phase, the project implementation started at the end of 2020. The mission is now due for launch in Q4 2023 / Q1 2024.

1.1. Scope

The purpose of this document is to present the Φsat-2 mission in the context of the organization of the #orbitalAI challenge. It is to provide a high view information package to understand the global objectives of this mission, its ambitions, the operations with its multispectral optical sensor empowered by an AI accelerator. This should allow the participants of the challenge to better understand which could be the most interesting thematic applications to propose in relation to the different constraints related to the spacecraft performances and its concept of operations.

1.2. Applicable and Reference Documents/Content

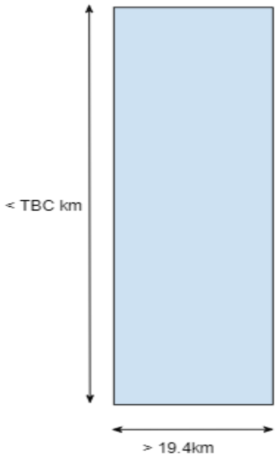
Reference documents and external content are listed in the table below

RD01	DTACS: onboard atmospheric correction with end-to-end deep learning emulators	https://github.com/spaceml-org/DTACSNet
RD02	CEOS calibration sites	https://calval.cr.usgs.gov/apps/test_sites_catalog
RD03	Supported Framework Layers for OpenVINO 2020.3	https://docs.openvino.ai/2020.3/_docs_MO_DG_prepare_model_Supported_Frameworks_Layers.html

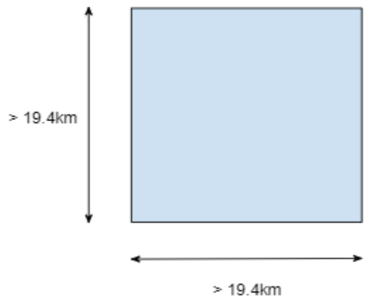
1.3. Terms and Definitions and Acronyms

The following terms are used in the document and their definition is as follow:

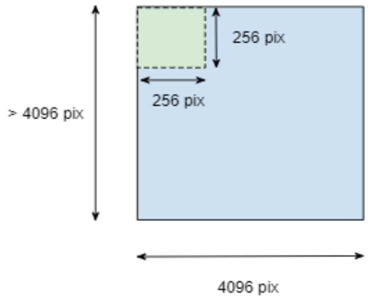
StripData, this dataset corresponds to several continuous lines acquired along the satellite track without interruption. It's on-ground projection is at least 19.4km wide and up to 2000 km long when captured at Nadir from 500km reference altitude. An image may contain either all bands or any selected subset of bands



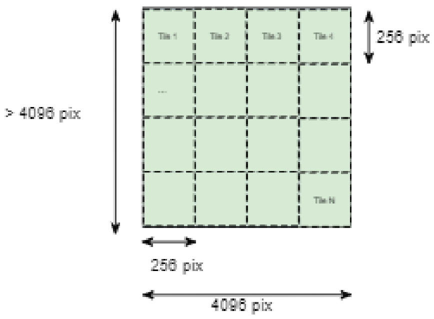
Image, a square part of a frame, is 4096 pixels width and 4096 pixels long which corresponds to it's on ground projection being at least 19.4km wide and 19.4km long when captured at Nadir from 500km reference altitude.



Tile, a tile is a square subset of an image. It can have one of the following sizes in pixels: 512x512 or 256x256



Tiling, the tiling process corresponds to dividing an image into subset of tiles of a predefined size. The tiles are adjacent to each other meaning that if tile N-1 ends on pixels X_N-1, then tile N will start at pixel X_N as shown on the image



1.4. Acronyms

ADCS	Attitude Determination and Control System
AI	Artificial Intelligence
AI4EO	Artificial Intelligence for Earth Observation
AOI	Area of Interest
AVA	Autonomous Vessel Awareness
BBM	Bread Board Mates
CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial off-the-shelf
CV	Computer Vision
CVAI	Computer Vision and Artificial Intelligence
DL	Deep Learning
ESA	European Space Agency
EO	Earth Observation
FWHM	Full Width at Half Maximum
GAN	Generative Adversarial Network
GNSS	Global Navigation Satellite System
GSD	Ground Sampling Distance
HSI	Hyperspectral Imager
ISP	Image Signal processing
LTDN	Longitude of the Ascending Node
MEMS	Micro Electro-Mechanical System
ML	Machine Learning

MTF	Modulation Transfer Function
NIR	Near Infra Red
NMF	NanoSat MO Framework
NN	Neural Network
OBC	OnBoard Computer
ONNX	Open Neural Network Exchange
OpenVINO	Open Visual Inference and Neural network Optimization
PAN	Panchromatic
RAAN	Right Ascension of the Ascending Node
RMSE	Root Mean Square Error
ROI	Region of Interest
SDK	Software Development Toolkits
SNR	Signal to Noise Ratio
SSO	Sun Synchronous Orbit
TBC	To Be Confirmed
VIS	Visible
VNIR	Visible and near
VPU	Vision Processing Unit

2. ΦSAT-2 MISSION

The selected Φsat-2 concept will provide a combination of on-board processing capabilities (including AI) and a medium to high resolution Visible to Near Infra-Red (VIS/NIR) multispectral instrument able to acquire 8 bands (7 + Panchromatic). These resources will be made available to a series of dedicated applications (hereafter called App) that will run onboard the spacecraft that have been partially pre-selected during the initial phases of the mission design (4 out of 6 to be tested in the operative phase). The remaining 2 Apps will be selected via a global competition open to the AI and EO communities.

2.1. Consortium Composition

This ESA mission is supported by the following industrial consortium:

- Open Cosmos Ltd (UK), the mission overall prime, providing the OpenSat 6U platform and in charge of the overall satellite integration with COTS elements together with their OBCs, managing the end-to-end space mission (satellite, launch, ground segment)
- CGI (IT) managing one AI app development (street detection), BBM verification, Software Development Toolkits, and data dissemination and science operations
- DEIMOS (ES) managing onboard pre-processing steps (from L1A to L1C)
- Kplabs (PL) managing one AI app development linked to Cloud Detection
- GEO-K (IT) managing one AI app development linked to Deep Compression
- Ceiia (PT) managing one AI app development linked to Maritime Awareness
- Simera Innovate GmbH (CH), managing the optical sensor development
- Ubotica Technologies Ltd (IE), providing the AI chip and integrating the BBM hardware.

2.2. Space Segment

The Φsat-2 spacecraft is composed of:

- The payload chain, consisting of:
    - Multiscape 100 Optical Imager supplied by Simera Innovate GmbH (CH), that acquires images of the tasked area, performs radiometric correction and first order, open-loop band co-alignment of the acquired images. It offers 4.75m

resolution, 19.4km swath width in 7 multispectral bands (plus a panchromatic band) at the reference altitude of 500km.
    - Primary On-Board Computer (OBC), that combines functionalities of the payload and platform computer. As part of the payload chain, the primary on-board computer will host the SDK (so called NanoSat MO Framework) with AI Apps.
    - Secondary OBC, that is interfaces with the primary on-board computer and runs the image pre-processing algorithms
    - CogniSat AI processor supplied by Ubotica Technologies Ltd (IE), that hosts AI model and performs inference.
- **Spacecraft platform** responsible for providing all necessary services: host and command the payload as required by the Mission Operations and the Payload Operations Centres and download the payload and housekeeping data to the ground stations.

2.2.1. Orbital Parameters

According to the baseline launch service and to ensure the required Sun illumination conditions, the parameters of the reference orbit used for the Φsat-2 design purposes are reported in the following table.

Launch Date	Q4 2023/Q1 2024
Baseline Orbit Altitude	500 km
LTDN	11:00 PM
Inclination	97.404 deg (SSO)
Eccentricity	0
RAAN	-111.75 deg

Table 1 Φsat-2 Orbit Parameters

2.2.2. Spacecraft Platform

The spacecraft is a 6U CubeSat based on the standard Open Cosmos OpenSat 6U platform. Φsat-2 spacecraft in deployed and stowed configurations are shown in Figure 1 and Figure 2, respectively.

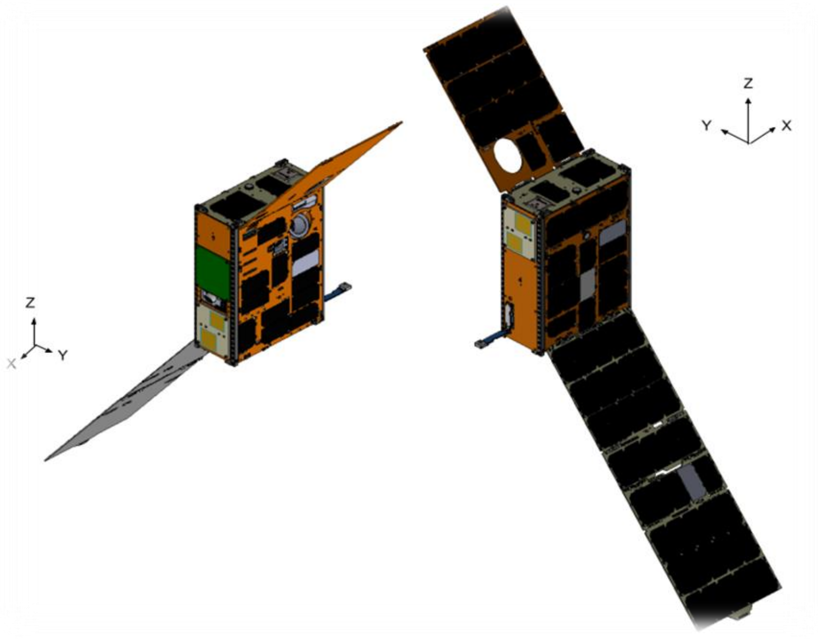


Figure 1 Φsat-2 Deployed Configuration

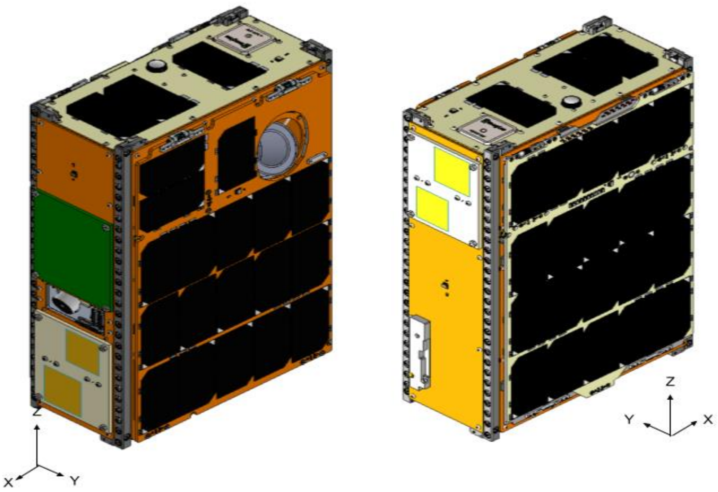


Figure 2 Φsat-2 Stowed Configuration

Its reference frame is defined with respect to the orbit:

- **+X**: Velocity vector
- **+Y**: Orbital angular momentum
- **+Z**: Zenith

Beyond the mechanical and thermal subsystems, the platform is composed by the following main subsystems:

- **Electric Power Subsystem**

  The power subsystem is composed by:
    - Solar Panels, that consists of a double deployable solar panel, a single deployable solar panel and six body mounted panels, with a total of 89 cells
    - Two Electrical Power System Assembly, which 1) provides the interface to the solar arrays, battery charging, and power distribution thanks to 3.3V and 5V power out lines, and 2) provides batteries and battery cell management, with a nominal energy storage of ~46 Wh.
- **On-Board Data Handling**

  The On-Board Data Handling consists of a microprocessor that acts as a central data processing unit, acting as the central authority for system-wide data handling operations. This includes inter-subsystem communications, data storage and management of automated operations. The On-Board Data Handling also physically contains the GNSS receiver which is functionally part of the Attitude and Orbit Determination and Control Subsystem.
- **Communications**

  Communications subsystem is subdivided in:
    - Telemetry, Tracking and Command Communication based on S-band transceiver. It acts as interface between the space and ground segments, enabling telecommand and software update functionality from the ground, and telemetry transmission from the satellite.
    - High Data Rate Communication, based on X-band transmitter and a patch antenna array, enabling high-speed payload data transmission from the satellite.
- **Attitude and Orbit Determination and Control Subsystem**

  The Attitude and Orbit Determination and Control Subsystem is a subsystem highly tailored to the mission requirements and configuration. Specifically, it is composed of 1) a dedicated computer, that includes 3-Axis MEMS rate sensors, 2) a set of sensors, which are magnetometers, Sun and Earth horizon sensors and one star tracker, 3) a set of actuators, which are primarily 4 jitter-stabilized reaction wheels and magnetorquers, required for detumbling, sun-spin mode and desaturation of the reaction wheels and 4) GNSS receiver and antenna

2.2.3. Payload

MultiScape100 instrument from Simera Innovate GmbH (CH) is a push-broom imager. The imager provides continuous line-scan imaging in 8 spectral bands in the visible and near-infrared (VNIR) spectral range. A push-broom instrument obtains the images by scanning along the ground track as the spacecraft is orbiting the Earth (see Figure 3 below). The scan is done for each spectral band separately.

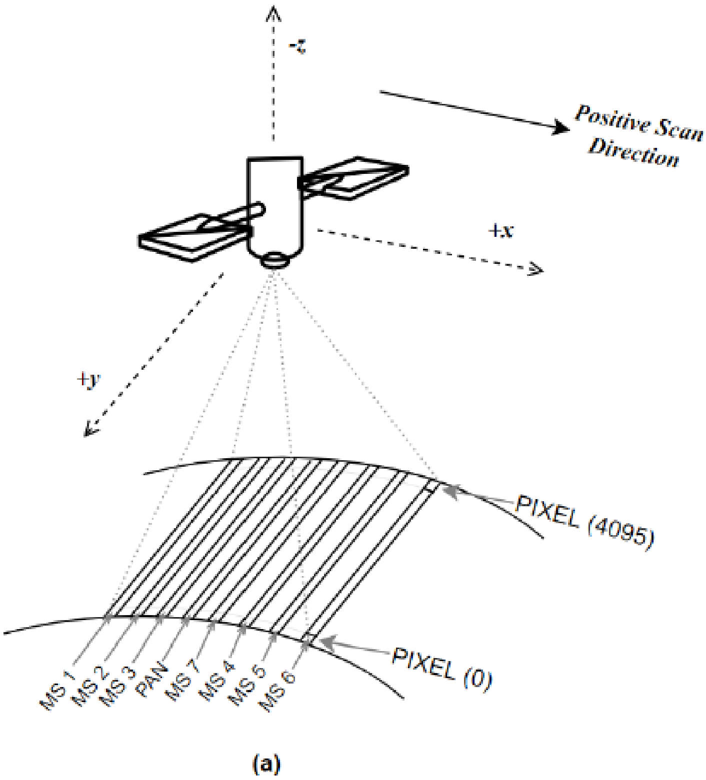


Figure 3 Φsat-2 Imager Ground Projection

In Table 2 below information on each spectral band including its line number on detector plane is provided.

Band	Centre Wavelength (nm)	FWHM Bandwidth (nm)	HPP Cut-On (nm)	HPP Cut-Off (nm)	Approximate Sensor Line Number
#0: PAN	625	250	500.0	750.0	1536
#1: MS 1	490	65	457.5	522.5	2176
#2: MS 2	560	35	542.5	577.5	1964
#3: MS 3	665	30	650.0	680.0	1748
#4: MS 4	705	15	697.5	712.5	1108
#5: MS 5	740	15	732.5	747.5	896
#6: MS 6	783	20	773.0	793.0	680
#7: MS 7	842	115	784.5	899.5	1324

Table 2 MultiScape100 Spectral Bands

The ground sampling distance (GSD) for each band from 500 km orbit is 4.75 m. The modulation transfer function (MTF) for separate spectral bands is expected to be between 3.9% and 7.2% at Nyquist Frequency. The SNR is expected to be between 54 and 129 for the multispectral bands. The expected SNR for the PAN band is 256. Further details cannot be provided at this stage.

The images of each spectral band are retrieved by the on-board computer and stored in its internal memory. The images are then radiometrically corrected, the spectral bands are co-registered, and pixels are geo-located. The data is then ready to be used by AI applications.

By default, the roll angle will be set to 0. The spacecraft is capable of capturing images with at least 15 degrees roll angle while keeping pitch at 0 degrees. No pitch manoeuvres are planned to be used during imaging.

Unless specified by the end user, the spacecraft will only capture images when the Solar Zenith Angle is between 0 and 90 degrees, i.e., when the Earth’s surface is illuminated by the sun.

2.2.4. Data products

Φsat-2 products available onboard for App are listed in Table 3. As of today, the production of L2A “Bottom of Atmosphere Reflectance in sensor geometry, fine geo-referenced, fine band-to-band alignment” is not foreseen onboard by default. However, the use of third-party AI model such as DTACS (see [RD01]) is encouraged in case the atmospheric correction is detrimental to retrieve geo- or bio-physical parameters.

Name	High Level description
L1A	Top of Atmosphere Radiance in sensor geometry, no geo-referenced (~400 m RMSE over land), no band-to-band alignment
L1B	Top of Atmosphere Radiance in sensor geometry, fine geo-referenced, fine band-to-band alignment (<10 m RMSE).
L1C	Top of Atmosphere Reflectance in sensor geometry, fine geo-referenced, fine band-to-band alignment (<10 m RMSE). As opposed to Sentinel-2 nomenclature, this product level is not orthorectified.

Table 3 Φsat-2 onboard product level

Upon interest from the community, this feature may be offered as an App service (like the Cloud detection service – see below).

2.2.5. Payload chain: CogniSat AI processor

The Ubotica CogniSAT-XE1TM CubeSat Board (Figure 4) brings the power of Edge CV and AI compute acceleration to a PC/104 form-factor for SmallSat and CubeSat missions. It is built around the Intel® Movidius™ Myriad™ 2 Computer Vision (CV) and Artificial Intelligence (AI) COTS VPU whose 12 vector cores provide high-performance parallel and hardware accelerated compute within a low power envelope.

CogniSat™ combines the power efficient compute of the Myriad 2 VPU with a wide range of interfaces and peripherals, providing broad flexibility for integration into satellite platforms.

Either Gigabit Ethernet or USB2.0/3.0 can be used as the primary control and data interface to the board, enabling data rates sufficient to handle many CV and AI applications at near-streaming throughput.

Common NN frameworks (e.g., TensorFlow, PyTorch, Caffe) can be used for NN model development and training, with the model subsequently imported into Intel®'s OpenVINO™ toolkit for targeting to the Myriad device. CogniSat™ leverages the broad range of pre-qualified models and layers available within OpenVINO™.

Custom Computer Vision pipelines can easily be deployed and executed on CogniSat™ using the CVAI Toolkit™ software toolkit. The software supports application-specific CV and ISP pipelines that utilise a combination of the power-efficient Myriad 2 streaming hardware blocks and software filters implemented on the vector engines. Deployment to the hardware platform involves the transfer of only a single configuration file, and runtime updates enable the updating of pipelines without requiring application re-compile or system reboot.

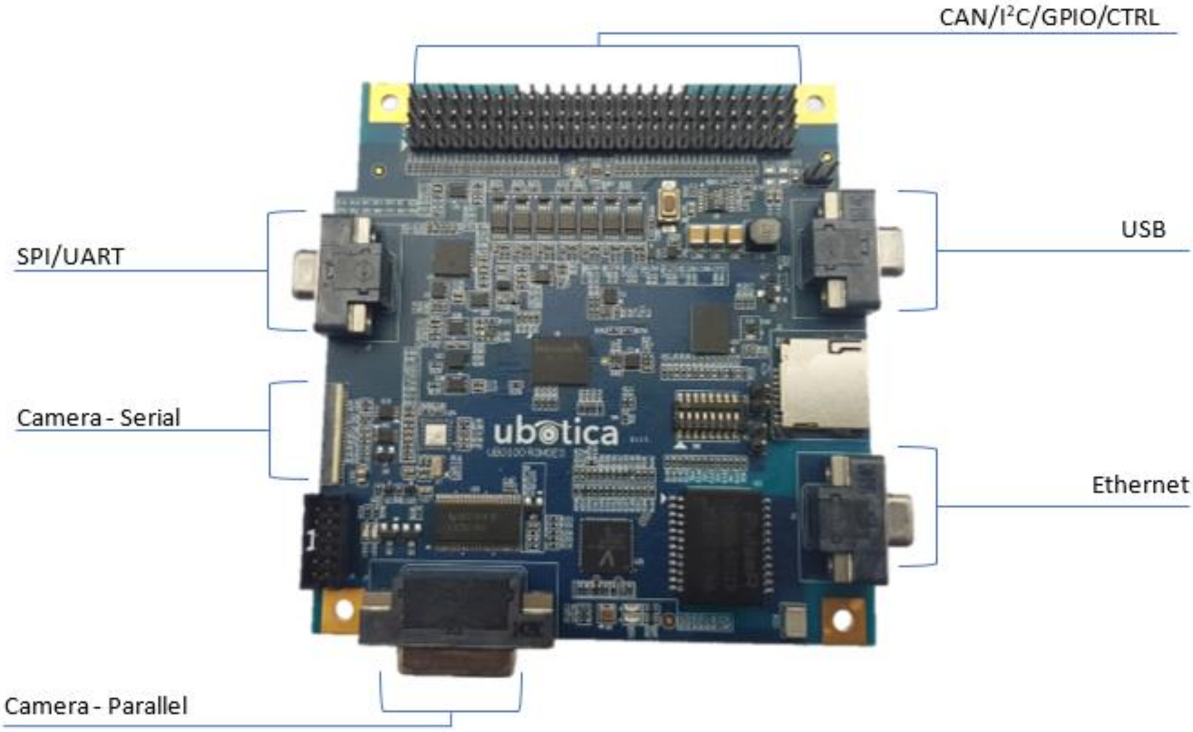


Figure 4 Ubotica's CogniSat™ Platform

2.2.6. Pre-selected A.I Applications

Four AI applications are already pre-selected for Φsat-2 mission: Sat2Map App, Cloud Detection App, Vessel Detection App, Compression App.

- **Sat2Map App:** The objective of this application is to demonstrate how the exploitation of AI on board will enable the generation and delivery of "near real time" to the ground. Sat2Map App - Transforms a satellite image to a street map using Artificial Intelligence. The APP will rely on Cycle-Consistent Adversarial Networks (CycleGAN) deep learning technique to do the transformation from the satellite image to the street map.
- **Cloud Detection App**: Cloud detection feature is essential in EO satellites focused on on-board data processing. Although the concept is well-established in on-ground processing pipelines and even demonstrated aboard satellites for bandwidth reduction,

the Φsat-2 is taking the next step and proposes a novel application-agnostic deep learning-powered cloud detection service. The App will demonstrate the APP chaining on board showing how the output of different applications can be exploited by others directly on board. The other App can then use cloud mask as input (including as well semi-transparent cloud, shadow)

- **Vessel Detection App**: The Autonomous Vessel Awareness experiment (AVA) is an application which aims to demonstrate in Φsat-2 the capability to autonomously develop awareness about vessels in the maritime domain using Artificial Intelligence (AI). The AVA app will exploit latest deep neural network techniques to perform not only vessel detection but also vessels classification.
- **Compression App**: The Deep Compression application aims at demonstrating that AI processing on-board can reduce the amount of data to be stored and sent to the ground with a limited information loss enabling other APPs to reconstruct the image on the ground exploiting directly the compressed image (e.g., for object detection). The app exploits a Deep Autoencoder to perform image compression.

2.3. Mission Timeline

The Φsat-2 spacecraft is designed for a 14-month lifetime from launch with potential extension up to 2 more years. Figure 5 shows the nominal top-level timeline of the mission, and Table 4 Summary of Mission PhasesTable 4 provides a description of the activities undertaken during each phase.

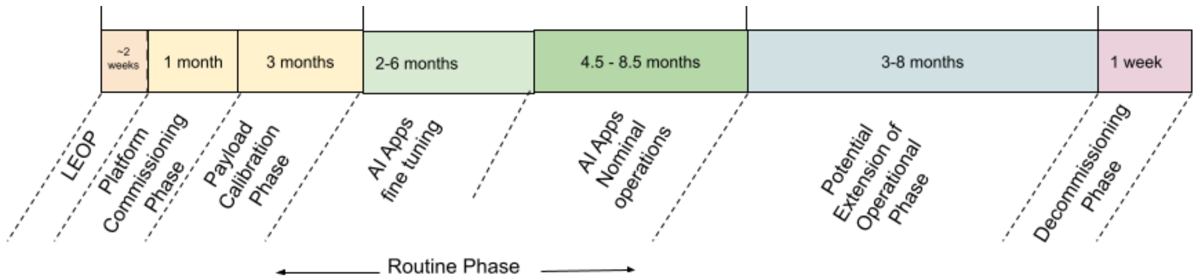


Figure 5 Mission Timeline

Phase	Duration	Activities
Launch and Early	2 weeks	• Launch and separation

Operations Phase (LEOP)		• First acquisition of signal • Satellite detumbled and stabilised attitude achieved • Orbital knowledge/determination • Initial health checks of the platform
Platform Commissioning Phase	1 month	• Platform & Payload commissioning
Payload Calibration Phase	3 months	• Payload calibration • On-board L1B image processing chain commissioning
Routine Phase	10.5 Months	• Fine tuning of AI apps • Uplink of two additional AI apps (TBC if not embarked at launch) • Nominal spacecraft operations • Spacecraft maintenance
Potential Extension of the Operational Phase	3-8 months	• Depending on the spacecraft orbital decay and spacecraft health status nominal operations can be extended for another 3-8 months
Decommissioning Phase	1 week	• Acquisition of end-of-life attitude • Spacecraft decommissioning

Table 4 Summary of Mission Phases

For the sake of calibrating the imager payload, the following calibration sites will be monitored as regions of interest (for the description of the sites can be found in [RD02]):

Site name	**Number of opportunities***
Algeria 3	10
Algeria 5	8
DEMMIN	3
DomeC	7
Egypt1	6
Geometry - Pueblo Range	4
Geometry - Sioux Falls Range	10

Site name	**Number of opportunities***
Lake Tahoe	4
Libya1	10
Libya2	10
Libya3	6
Libya4	5
Mali	5
Mauritania2	10
Mauritania1	10
Namib Desert 1	4
Niger 3	3
Niger 1	8
Niger 2	3
Salton Sea	2
Sudan 1	6
Taklamakan	3
Uyuni Salt Flats	3
Total:	**140, including 14 geometry sites**

** daylight opportunities only with SZA below 65°. Images are not expected to be longer than 100km due to the size of calibration sites. Mauritania1 and Mauritania2 sites due to their proximity to each other can be captured as one longer strip.*

Table 5 Summary of simulation results performed for in-orbit calibration phase during a 90-day interval

2.4. Observation capacity and strategy

After the system has been successfully commissioned and confirmed to be operating nominally, the activities are predominantly driven by scheduling imaging opportunities.

Upon image acquisition requests, the objective is to provide multispectral imagery to the AI Apps, images will be acquired once the spacecraft reaches the selected Region(s) Of Interest (ROI) both during APP fine tuning phase but also App operation phase.

Simulation shows that the revisit period highly depends on the location. The selected orbit on average offers global access to any area of the world every 15 days and allows imaging of any area in quasi-nadir conditions, i.e., with an off-nadir (roll) angle lower than 10 degrees. With a 5 off-nadir (roll) angle the average revisit period increases to 23 days.

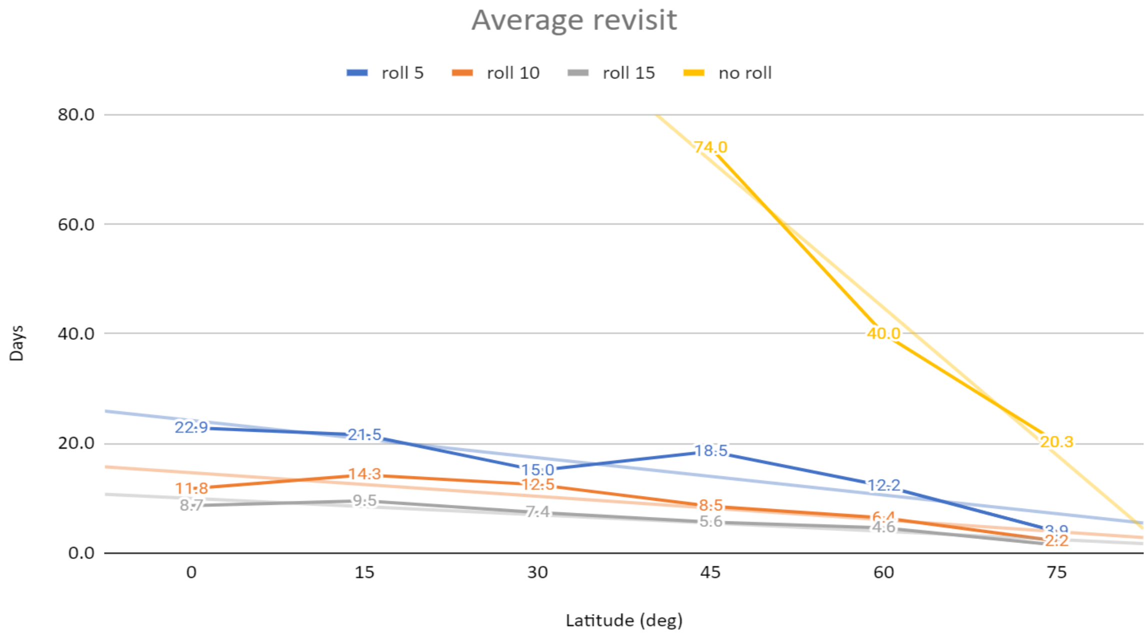


Figure 6 Spacecraft average revisit vs agility at different altitudes (as a result of 365 days simulation)

The mission will be providing global coverage (excluding north poles) as shown in Figure below.

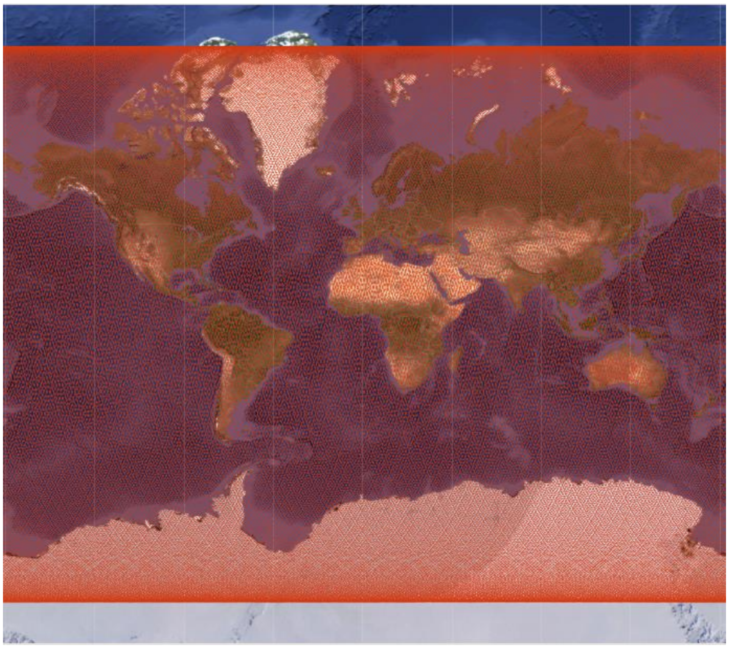


Figure 7 Φsat-2 coverage

The following regions are already identified as areas of interests for different AI apps.

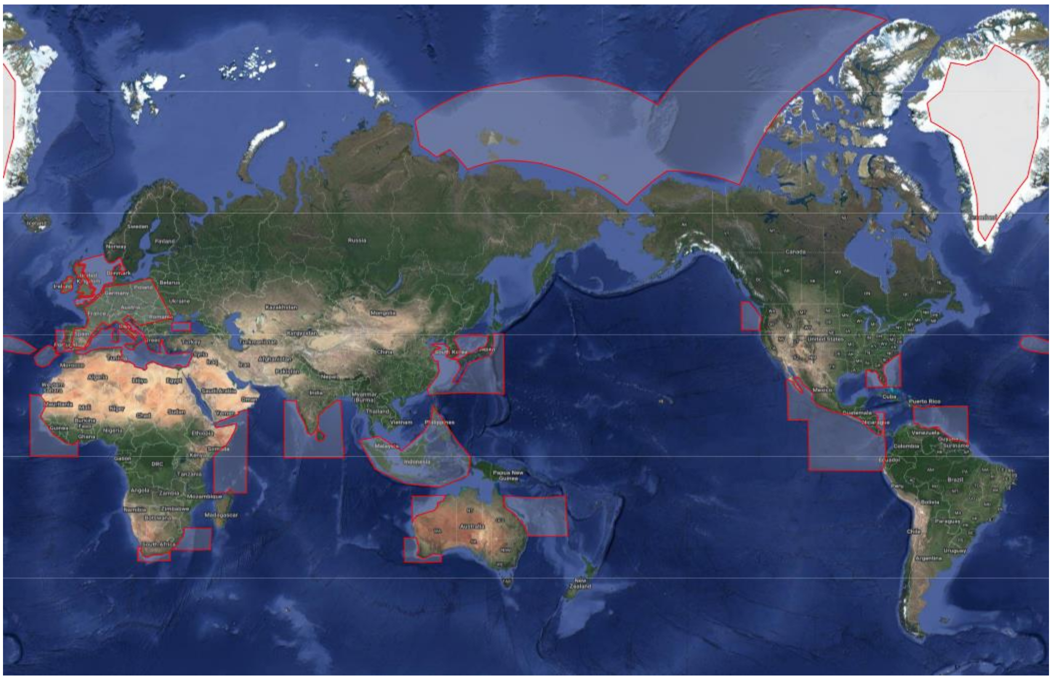


Figure 8 AOIs for the Compression, Vessel Detection and Cloud Detection Apps

The summary of the coverage/revisit simulation results for these selected AOIs can be found in the table below.

Site name	Number of opportunities	Average image capture duration (min)	Corres. average image length (km)	Corres. number of square images it can be split into (length_av / length_sq* opportunities)	Number of square images assuming only 50% of opportunities are actually scheduled*	Number of square images assuming only 10% of scheduled are useful for the needs of AI Apps
Europe Mainland	114	1.9	806	4,736	2,368	237
Greenland	78	3.1	1315	5,287	2,644	264
United Kingdom	28	0.8	339	490	245	24
Indonesia Region	103	4.7	1994	10,585	5,293	529
Ireland	17	0.6	255	223	112	11
Northpole	175	3.0	1273	11,480	5,740	574

Site name	Number of opportunities	Average image capture duration (min)	Corres. average image length (km)	Corres. number of square images it can be split into (length_av / length_sq* opportunities)	Number of square images assuming only 50% of opportunities are actually scheduled*	Number of square images assuming only 10% of scheduled are useful for the needs of AI Apps
region						
Portugal Coastline Region	21	0.9	382	413	207	21
Portugal Sea Region 1	24	1.2	509	630	315	31
Portugal Sea Region 2	35	1.1	467	842	421	42
Black Sea Region	20	0.7	297	306	153	15
East African Coastline	64	3.2	1357	4,478	2,239	224
South African Coastline 1	40	1.5	636	1,312	656	66
South African Coastline 2	33	0.8	339	577	289	29
West African Coastline	52	2.8	1188	3,184	1,592	159
Indian Coastline	67	3.7	1570	5,421	2,710	271
Japan and South Korean Coastline 1	43	1.1	467	1,034	517	52
Japan and South Korean Coastline 2	101	2.3	976	5,079	2,540	254

Site name	Number of opportunities	Average image capture duration (min)	Corres. average image length (km)	Corres. number of square images it can be split into (length_av / length_sq* opportunities)	Number of square images assuming only 50% of opportunities are actually scheduled*	Number of square images assuming only 10% of scheduled are useful for the needs of AI Apps
Mediterranean Sea	133	1.2	509	3,490	1,745	174
North America Coastline 1	47	1.4	594	1,439	719	72
North America Coastline 2	22	1.6	679	770	385	38
North America Coastline 3	107	4.4	1866	10,295	5,147	515
North Sea	70	1.0	424	1,531	765	77
North West Australian Coastline	36	1.3	551	1,023	512	51
East Australian Coastline	57	3.2	1357	3,988	1,994	199
South West Australian Coastline	39	1.2	509	1,023	512	51
South American Coastline	52	2.6	1103	2,956	1,478	148

** assuming that some orbits will be used for ground station passes or other activities*

Table 6 Summary of simulation results performed for fine-tuning phase for Compression, Vessel Detection and Cloud Detection

Based on the results presented in the table above, it is considered that the proposed approach will provide enough images to fine-tune Compression, Vessel Detection and Cloud Detection applications within 2 months. In addition to the above AOIs, another fine-tuning phase simulation is foreseen for Sat2map focusing on specific local areas in Southeast Asia prone to extensive flood events.

3. APP DEVELOPMENT

As part of the open competition, there is no requirement for AI model integration within the On-Board application environment (described in Section 3.2), however:

1. it is strongly recommended to challenge participants to check the following website [RD03] as **Cognisat supports OpenVINO 2020.3**.
2. we strongly encourage the challenge participant to **consider only Tensorflow v1** (for instance 1.15). Tensorflow v2 and Pytorch frameworks should not be used.
3. **we impose the size of the model should be less than 250 MB**.

3.1. Φsat-2 Basic Simulator

As part of the OrbitalAI challenge, a Φsat-2 basic simulator is provided in order to help the challenge participants to create realistic App.

In order to create this simulator, the main requirements were to provide the user with an easy-to-use tool, allowing to simulate in a relatively realistic way the different products generated on board, without geographical or temporal coverage constraints. Even if the COTS elements of the 6U CubeSat Φsat-2 mission have been the subject of specific studies on their intrinsic performances, as well as once integrated in a FlatSat and Engineering Model configurations, the actual performances of the mission once in orbit cannot be fully simulated.

Moreover, the possibility of simulating any AOI, without constraint of cost or commercial license, imposes this simulator to use as input the Sentinel-2 data. Indeed, the spectral and spatial characteristics of Sentinel-2 represent a very good starting point for Φsat-2 even considering the notable differences in spatial resolution. This simulator is therefore provided with all its limitations.

The possibility to acquire image with different roll angles (up to 15 degrees) is not integrated as part of the provided simulator.

Id	Spatial Res [m]	Central Wavelength [nm]	Bandwidth [nm]	Id	Spatial Res [m]	Central Wavelength [nm]	Bandwidth [nm]
Sentinel-2				Φsat-2			
2	10	492.4	66	MS 1	4.75	490	65
3	10	559.8	36	MS 2	4.75	560	35
4	10	664.6	31	MS 3	4.75	665	30
5	20	704.1	15	MS 4	4.75	705	15
6	20	740.5	15	MS 5	4.75	740	15
7	20	782.8	20	MS 6	4.75	783	20
8	10	832.8	106	MS 7	4.75	842	115
				PAN	4.75	625	250

Table 7 High level comparison between multispectral Sentinel-2 and Φsat-2 payloads (Considering an orbital height of 500km, the GSD is equal to 4.75m for all 8 bands.)

The different steps of this simulator are introduced in the following subsections.

3.1.1. Computing an equivalent PAN band

The additional panchromatic band of Φsat-2 payload is simulated by a linear combination of Sentinel-2 multispectral bands, since there is a substantial spectral overlapping between Φsat-2 PAN band and Sentinel-2 multispectral bands (B2 to B6).

The PAN band value is estimated by combining the multispectral bands from Sentinel-2 at each pixel as:

$$PAN = \frac{\alpha_2}{\alpha_P} \cdot B2 + \frac{\alpha_3}{\alpha_P} \cdot B3 + \frac{\alpha_4}{\alpha_P} \cdot B4 + \frac{\alpha_5}{\alpha_P} \cdot B5 + \frac{\alpha_6}{\alpha_P} \cdot B6 \quad \text{(Eq. 1)}$$

Where α_2, α_3, α_4, α_5, α_6 are the areas under spectral response function curves for each band limited by the panchromatic SRF and $\alpha_P = \sum_i \alpha_i$.

3.1.2. Spatial resolution

A bicubic interpolation method is foreseen for this step to reduce interpolation artifacts. As an alternative, bilinear interpolation can be considered in case of stringent performance requirements. In both cases, a two-dimensional regular grid with a 4.75m pixel spacing is used for interpolating data points. In bicubic interpolation, the intensity value assigned to the *i-th* point (x,y) is obtained using the knowledge about sixteen nearest neighbor of the *i-th* pixel, in terms of function values and their derivatives. More specifically, the interpolated surface is defined as:

$$p(x,y) = \sum_{i=0}^{3}\sum_{j=0}^{3} a_{ij}x^i y^j \quad \text{(Eq. 2)}$$

where the sixteen coefficients a_{ij} are determined solving the linear system of 16 equations in 16 unknowns arising from the considered 16 adjacent pixels. In general, bicubic interpolation can be accomplished using well-known Lagrange polynomials, cubic splines or cubic convolution algorithms.

As a possible improvement to the current baseline, more advanced image fusion techniques can be explored in order to up-scale geometrical features yielding to an augmented spatial resolution, while fully preserving the image radiometry thus limiting the spectral distortion.

3.1.3. SNR

Assuming an errorless input dataset $L_{in}(i,j)$, the computation of the sensor's specific noise is implemented starting from the provided SNR specifications. More specifically, for each band of the sensor, the equivalent noise is evaluated using the reference radiance at the ToA and the respective SNR, as follows:

$$noise(b_n) = \frac{L_{ref}(b_n)}{SNR(b_n)} \cdot rand_{sampl} \quad \text{(Eq. 3)}$$

where:

- L_{ref} is the reference radiance used to generate the specific SNR (i.e., *Spectral Radiance at Aperture* (W/m^2/sr/um) in the previous table);
- SNR is the Signal to Noise Ratio for each sensor band;
- $rand_{sampl}$ is a random number obtained from a standard normal distribution *N(0,1)*, i.e. mean equal to zero and standard deviation equal to one.

The previous step (Eq. 3) is performed once for each pixel in the input image $L_{in}(i,j)$. Then, the $noise(b_n)$ is added to the input radiance, as:

$$L_{out}(i,j) = L_{in}(i,j) + noise(b_n,i,j) \quad \text{(Eq. 4)}$$

N.B.: Eq. (4) assumes that the input data is expressed as a ToA radiance in *W/m^2/sr/um* units, i.e., accordingly to L_{ref} units.

It is worth noting that the proposed workflow does not account for sensor- and/or product-specific error sources statistically affecting the input dataset, i.e., the intrinsic level of noise characterizing the input data (for instance S-2) is not corrected.

3.1.4. Band-to-band misalignments

3.1.4.1. For Level 1A

Due to the pushbroom acquisition mode, the various bands over a given area are not acquired at the time. As such, they suffer from platform attitude stability during the various acquisition times (the misalignment due to velocity is compensated onboard by the payload). This micro-vibration analysis treats along- and across-track directions equally.

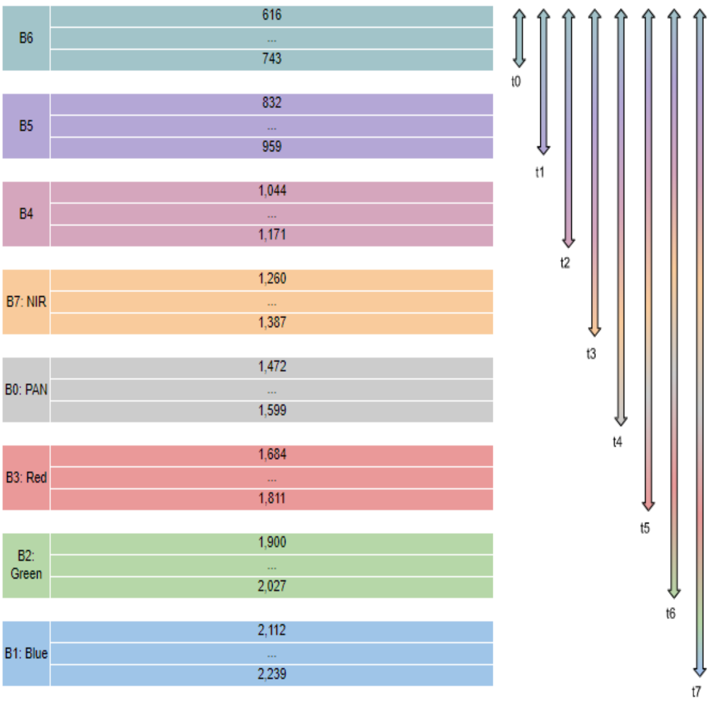


Figure 9 Sketch of band acquisitions for the Φsat-2 multispectral pushbroom payload

This effect characterizing Level 1A products is simulated in the following way:

For each subsequent acquired band MS5, MS4, MS7, PAN, MS3, MS2 and MS1 (MS6 as a reference):

- The misalignment direction of a given band (compared to its previous band) is determined by extracting a fully random direction (from 0 to 2π);
- Its magnitude is computed by adding a random offset, extracted from a normal distribution $N(0{,}0.4)$, to a constant contribution with respect to the previous acquired band (see the following table)

Description	MS5 - MS6	MS4 - MS5	MS7 - MS4	PAN - MS7	MS3 - PAN	MS2 – MS3	MS1 - MS2
Misalignment error (pixels)	1.105	1.046	0.943	0.837	0.717	0.55	0.44

Table 8 Relative misalignment error between subsequent bands due to stability performance

- The computed total shift vector is projected along x and y axis.
- Since the misalignment error vector accumulates from band MS5 to band MS1, the total band shift is summed to the total shift of the previous band and applied to the band under consideration. The process is repeated for the subsequent band, considering the previous one as the reference.

3.1.4.2. For Level 1B and above

A fine band-to-band alignment process is operated to adjust and compensate for the above effects. Considering a reference band (here red, MS3), the process operates via features detection for each band independently. Once the features are detected, a transformation is computed and applied to map the band under consideration onto the reference band. No shift is then accumulated across bands. A random error with respect to the reference band (red, MS3) is considered, assuming the difficulty to detect the same features across different spectral bands (depend on the scene content and presence of features/edges…).

The following steps have been implemented:

- The amplitude value follows a normal distribution $N(0,1)$ over land and $N(0,6)$ over full ocean surface scene. If the scene contains both land and sea, the default is 1 pixel. The possibility to use standard deviation equal to 6 pixels is a user-defined parametrization.
- The misalignment direction is defined by drawing a fully random direction (from 0 to 2π);
- The associated X and Y values are computed from the amplitude/angle and applied in an independent manner to all the bands (except for MS3).

3.1.5. MTF / PSF

To account for the system MTF (payload + platform), the proposed approach consists in the convolution of the input image with a filter function representing the system specific Point Spread Function (PSF).

It is worth noting that to emulate in a meaningful way the impacts due to optical/detector characteristics, the input image upon which apply MTF-related effects should be the one defined in the actual acquisition geometry of the considered sensor. Indeed, taking into account the system MTF aims at simulating the spatial domain of the image (i.e., emulating the signal recorded by the instrument detector element), which is then strictly correlated with the instrument characteristics (i.e. pixel size, system F-number, etc.). To this end, an input data defined in the native sensor geometry instead of ground-projected is deemed more appropriate for this task. On the assumption that sample data acquired by a different sensor (e.g., S-2) are used as input for this step, the eventual additional knowledge about S-2 PSFs could be used to remove spatial-blurring effects in the native dataset, before adding contributes of the system to be simulated.

According to the aforementioned limitations and understanding of the topic, the following assumptions have been adopted. In the current approach, the provided MTF specifications are used to build the bidimensional Modulation Transfer Function, assuming that the same trend is applied in both along-track and across-track directions (then applied here in vertical and horizontal directions). The exact values of the full MTF are not given here, being confidential information from the payload provider.

The corresponding Point Spread Function, computed as Inverse Fourier Transform of the MTF, provides the 7-by-7 kernel to be used for convolving the input image. This operation is performed for each band independently.

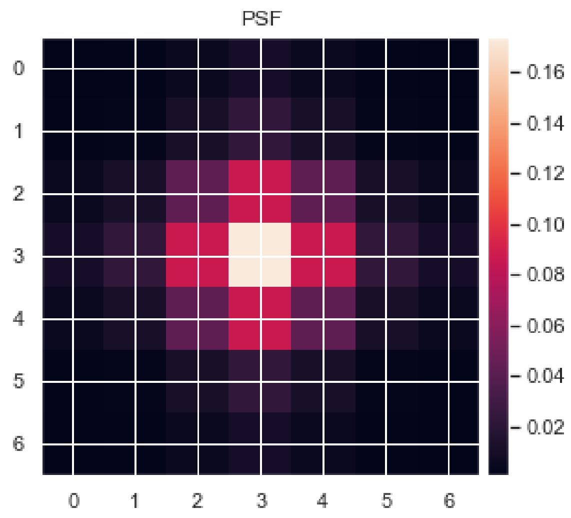


Figure 10 Example de PSF

During the filtering operation, two discrete real-value matrices (i.e., the input image `pixIN(x,y)` and the convolution kernel `PSF_kernel(x,y)`) are ingested as inputs, and the center of the kernel is *shifted* along each pixel in the image in a *sliding-window* approach. To obtain the output value at each pixel $pix_{OUT}(x,y)$, the kernel is multiplied point-wise with all the pixels it covers, and the sum of these products is used to replace the original pixel value, according to the following formula:

$$pix_{OUT}(x,y) = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} pix_{IN}(i,j) \cdot PSF_{kernel}(i,j) \qquad \text{(Eq. 5)}$$

where:

- *m*: size of PSF in the vertical direction,
- *n*: size of PSF in the horizontal direction,
- $pix_{IN}(i,j)$: is the *m-by-n* subset of the input image centered at *(x,y)*

3.1.6. Conversion from Radiance to Reflectance for Level 1C

For each hyperspectral pixel at spatial position (i,j) and corresponding to band n , the radiance to reflectance conversion is performed by applying a multiplicative factor computed from the following equation:

$$\rho(i,j,n) = \frac{\pi d^2}{E_{SUN}(n) \cdot \cos\theta_S(i,j)} \cdot L(i,j,n) \qquad \text{(Eq. 6)}$$

With $L(i,j,n)$ the pixel radiance value, d the Earth-Sun distance, $E_{SUN}(n)$ the Sun irradiance captured by band n and $\theta_S(i,j)$ the Sun-Zenith angle. The Sun irradiance, the Sun-Zenith angle and the Earth-Sun distance are extracted from Sentinel-2 metadata. Since the spectral characteristics of Sentinel-2 are quite similar to the ones of Φsat-2, no Sun irradiance adjustment is needed.

For the simulated PAN band, the corresponding Sun irradiance value is evaluated through a weighted average of the irradiance values at overlapping Sentinel-2 multispectral bands (with weights already evaluated as the areas under the spectral response function curves for each band limited by the panchromatic SRF).

3.1.7. Tiling process

The last step is to provide a tiling of the 4096x4096 pixels.

Even if during training it is not necessary to use an eventual overlap between tiles, it should be considered for a potential validation at image level. A tiling service will be provided on board Φsat-2

3.2. On-Board Application Environment

The following information are provided for information purposes only.

3.2.1. Nanosat MO Framework

The NanoSat MO Framework (NMF) is a software framework for CubeSats based on CCSDS Mission Operations services [RD 3]. It facilitates not only the monitoring and control of the nanosatellite software applications, but also the interaction with the nanosatellite platform. This is achieved by using the latest CCSDS standards for monitoring and control, and by exposing services for common peripherals that are available in nanosatellite platforms, such as, GPS, Camera, ADCS, and others. Furthermore, it is capable of managing the software on-board by exposing a set of services for software management [RD 4].

In simple terms, the NanoSat MO Framework introduces the concept of apps in space that can be installed, and then simply started and stopped from ground. Apps can retrieve data from the nanosatellite platform through a set of well-defined Platform services. Additionally, the framework includes CCSDS standardised services for monitoring and control of apps. An NMF App can be easily developed, distributed, and deployed on a spacecraft. Just like Android and iOS, ESA made a software framework for flight and ground software of CubeSats which allows flight software to become Apps that run in space.

The main objective of the NanoSat MO Framework is to facilitate the development of software for small satellites and to simplify its orchestration. For example, new software can be easily deployed in a satellite just by starting and stopping Apps.

The core functionalities of the framework are:

- Monitoring and control of AI applications
- Easy access to platform peripherals via services
- Simple on-board software management: Deploy and run AI applications
- Updating AI applications and AI models
- Deleting AI applications and AI models

In the Φsat-2 Mission the NMF will provide the possibility to integrate models developed by the AI experts, wrapping the AI models and enabling them to:

- Deploy a model on the CogniSat AI processor
- Retrieve image from the camera
- Apply the model in prediction on the acquired image

The NanoSat MO Framework allows the AI App developers to make their App using well-defined interfaces and APIs that allow the App to reach the on-board devices via a set of services. The framework by itself will also prevent conflict when different Apps will compete to access a resource (e.g., imager) which in any case will be scheduled via the Payload Orchestrator Center.

NanoSat MO Framework and AI applications will operate in a dedicated memory space allocated specifically for them, which will not intersect with the rest of the software running on the OBC. In case of NanoSat MO Framework and any of the AI apps malfunction, OBC flight software will not be affected.

3.2.2. Towards the Incubation phase

During the Incubation phase, the provided AI models (in python) may be further checked by the Φsat-2 team including:

- run on generic GPU
- tested in targeted hardware Intel® Movidius™ Myriad™ 2 on Neural Compute Stick with OpenVINO (2020.3)
- tested with FlatSat in real configuration.

3.2.3. Application Lifecycle

The main App activities during routine operations are described below:

- Define AOI. The corresponding image will be acquired depending upon duty cycle and various constraints.
- Depending on the readiness of the App (from low to high):
    1. Dataset consolidation, on ground fine tuning (retraining)
        - Download raw Image and payload data to the ground segment: activity to be performed as often as necessary during the visibilities over the ground stations to allow the maximum use of on-board storage capacity and provide data to the users and developers.
        - On ground, fine tune the parameters of AI Apps to improve their performance (if required).
        - Upload newly developed AI applications and AI models and test performance. The AI Apps and AI models can be updated in orbit after fine tuning is done with real images on the ground.
    2. App validation
        - Run App inference onboard and download Image, payload data, and App outputs
        - On ground, validation of the AI apps.
    3. App operation
        - Run App inference onboard, and download App outputs
        - On ground, dissemination of the Apps outputs

The NanoSat MO Framework will support software updates. When a new software update is created by the developers on ground, the new or updated libraries will be packaged into an NMF Package. The NMF Package containing the software updates will then be transferred to the spacecraft and installed.

For all the above steps, the selected winners will be fully supported by the Φsat-2 team. The participants will be in charge of:

- providing general requirements for image acquisition such as AOIs
- eventual fine tuning of the AI models
- scientific validation of the AI apps.