SSC20-V-04

Overview of ESA's Earth Observation upcoming small satellites missions

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ABSTRACT

The "New Space" paradigm, has enabled the creation of many new opportunities in the space sector like the development of a large number of missions based on small and nano-satellites.
The European Space Agency (ESA) is supporting these new development approaches and technology advancements, including use of Commercial-Off-The-Shelf (COTS) components to enable missions based on small and nano satellites. ESA's Earth Observation Programmes Directorate (ESA-EOP) is already involved not only in the implementation of technologies exploiting the capabilities offered by small and nano-satellites as a complement to the EOP scientific and application-driven flagship satellites, but also in the quick validation of new approaches like A.I, super resolution or more in general in orbit data processing. ESA-EOP developments in the area of small and nano satellites are spread in three different programmatic lines, each with its own objectives: Scout and Φ-sat Missions and the InCubed Programme.
This paper presents the overall ESA-EOP small missions strategy providing a brief insight on the genesis of each programmatic line and their selection processes including an update of the status of the first initiatives and missions under development or study.

INTRODUCTION

In the last two decades, the advent of the so-called "New Space" paradigm, allowed the creation of many new opportunities in the space sector like the development of a large number of small missions based on micro and nano-satellites. The feasibility of this approach has already been proven successfully several times and new ways to exploit the potential benefits are currently being evaluated. Among the most interesting ideas we can highlight high revisit time constellations implementable thanks to less costly satellites, either to complement traditional single state-of-the-art institutional satellite missions or to monitor high dynamic/large scale phenomenon. These relatively new ideas complement the more consolidated fast in-orbit demonstration of new technologies.

In the context of Earth Observation (EO), many examples, both in the institutional and commercial sector, of successful implementations demonstrate the benefits of small satellites and the need to consolidate their current roadmaps and to further invest on future developments.

The European Space Agency (ESA) is supporting these new approaches, in particular through the Fly Element of the General Support Technology Programme (GSTP) that enables new missions based on small and nano satellites, which make use of a growing portfolio of readily available technologies to European entities

ESA-EOP VISION ON SMALL AND NANO SATELLITE

ESA's Directorate of Earth Observation Programmes (ESA-EOP) benefits from those generic technologies and from the "New Space" approach and throughout the years, ESA-EOP has matured comprehensive and well-established ideas specifically targeting EO applications.

The advantages of small satellite missions rely on different aspects like the generally relaxed requirements due to the short lifetime, the components standardization, and the rideshare launches that together concur to simplify the overall mission lifecycle. These immediately translate in an overall cost reduction, allowing to fly more frequently or in constellation increasing temporal resolution and coverage.

When correctly exploited, these advantages can guarantee a fast access to space balancing the higher risks with the ability to test new technologies in space, but more importantly in the case of EO to:

1. Perform in-orbit verification of new EO techniques;
2. Implement established EO techniques using new approaches like the deployment of small constellations or the use of enabling technologies such as Artificial Intelligence (AI)

The first case is typical of techniques where on ground validation or simulation are not possible and hence full system in flight implementation is necessary.

The latter can be the solution to different needs such as: high revisit time to either complement traditional institutional single satellite missions or to monitor high dynamic large scale phenomenon in which high resolutions are not always required.

Small and nano-satellites represent not only an excellent complement to the EOP scientific and application-driven flagship satellites, but also a way to quickly validate new approaches and technologies like AI, super resolution or more in general in orbit data processing and in orbit autonomy.

ESA-EOP PROGRAMMES WITH SMALL SATELLITES

ESA-EOP develops world-class Earth observation (EO) systems particularly with European (e.g. European Union, EUMETSAT) and global partners to address the scientific challenges identified in the Living Planet Programme (SP-1304)[8] and other societal challenges.

The key principle is that all these missions are user driven. They are centered on two broad components:

- Research missions[7] cover primary scientific objectives of ESA's EO Science strategy for demonstrating innovative EO techniques
- Earth Watch missions, typically driven by operational services, are developed with and for partners such as EUMETSAT for meteorological missions and the European Commission (EC) for Copernicus missions.

Within these broad component lines the European Space Agency (ESA) has specifically designed and put in place missions to support the use of small and nano-satellites for specific Earth Observation mission.

In particular, ESA-EOP has identified three EO mission lines to boost the using of small satellites to rely on a reduced budget, with different objectives in each of them:

1. **Scout missions:** As part of Research missions, to demonstrate novel Earth Observation techniques in Earth science and related non-commercial applications;
2. **InCubed missions**: As part of Earth Watch, to invest in industrial innovation, including the development of end-to-end mission aimed to support and increase the European companies competitiveness;
3. **Φ-sat missions**: to develop missions for fast demonstration of EO new technique and enable capability of innovative/disruptive technologies such as AI.

Hence this portfolio of initiatives cover the three main lines for small satellites: low budget/mainly constellation driven scientific missions; Commercial mission to support European company business; EO technique demonstration enabled by disruptive technology/AI.

SCOUT MISSIONS

The Scout Missions are the first ESA-EOP Research missions, thus driven by scientific objectives, based on reduced budgets (30Meuro), hence the interest on small satellites. The study of the first set of Scout missions has been initiated in 2019. The Scout mission(s) consist of one or several small satellites for rapid prototyping and demonstration purposes of novel Earth observation techniques in Earth science and related non-commercial applications. Small satellites (possibly in constellation) could be applied to demonstrate disruptive sensor techniques or incremental science, while retaining the potential to be subsequently scaled up to larger missions or implemented in future ESA Earth Observation programmes.

The Scout Mission development consists of two steps:

- Step 1 – "Scout Mission Concept and System Consolidation Studies". Four mission concepts have been financed for 6 months consolidation study in the first months of 2019
- Step 2 – upon completion of the consolidation study one or maximum two mission concept(s) will be financed for implementation. The implementation of this second step is based on the following conditions for mission selection:
  - technical and scientific merit / outcome of the studies;
  - selection of the mission concept(s) at programmatic level further to recommendation on scientific merits

Here below we present the four missions undergoing Step 1 i.e: HydroGNSS, Tango, NanoMagSAT and ESP-MACCS.

HydroGNSS

Essential Climate Variables (ECVs) are key parameters of the Earth system identified by the Global Climate Observing System (GCOS) to help understand and predict climate change, to guide mitigation measures, and to assess risks, in association with the united nation Convention of Climatic Change (UNFCCC), Intergovernmental Panel on Climate Change (IPCC) and World Meteorological Organization (WMO). Soil Moisture, Biomass and Permafrost are some of the key terrestrial ECVs identified by GCOS, the ESA EO Science Strategy and the ESA Climate Change Initiative (CCI) programme[6] for their relevance to understanding the global hydrological cycle.

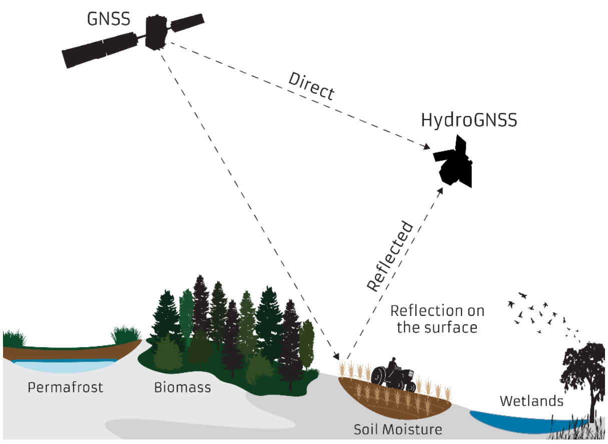

Figure 1: HydroGNSS ECV Targets

Figure 1 illustrates the four ECV targets for HydroGNSS. GNSS reflectometry (GNSS-R) is a remote sensing technique consisting of using L-band GNSS signals (from GPS, Galileo, etc.) as bi-static radar sources to sense geophysical parameters on the ground. Measurements are collected and processed by the instrument into a "Delay Doppler Map" (DDM) that can be corrected and inverted into Level 2 products such as ocean wind speed, as demonstrated on UK TechDemoSat-1 (TDS-1) and CYGNSS[8] missions. Data from these two missions were also successfully used to prove the effectiveness for sensing parameters over ice, snow and land, hence showing the potential for the HydroGNSS target applications. The rationale for the HydroGNSS ECV targets is described below:

- Soil Moisture – both indicator and driver of land-air interface processes, important for climate, agriculture and weather forecasting. Due to its criticality, a number of current and future missions also target hydrology, such as MetOp, SMOS and SMAP, Biomass, and Sentinel satellites, but more measurements are still required to meet ECV targets. HydroGNSS offers the special advantages of GNSS-R to provide complementarity with cost efficiency that lends itself to long-term continuous monitoring.
- Inundation/Wetlands – their status affects run-off and flood evolution. Allows assessment of wetland environments health, source of methane production.
- Freeze/Thaw – the timing of the freeze/thaw cycle of the permafrost active layer has a major effect on methane release and CO2 uptake.
- Biomass – influences climate and is a vital parameter affecting CO2 uptake, particularly in higher latitude forests.

HydroGNSS comprises of a constellation of two small satellites.

GNSS-R is a remote sensing technique that uses navigation satellite signals as a source for forward scattering allowing L-Band bistatic radar performance from a small satellite.

HydroGNSS builds upon orbit-proven GNSS-R instrumentation, but it is targeted for land applications, and pioneers enhanced measurements to improve resolution and separate the ECVs from each other. These include the addition of Galileo constellation signals, dual polarisation reception, addition of coherent signal reception, and wideband E5/L5reception.

The ongoing consolidation study is carried out by a consortium led by SSTL (UK) with the support of Tor Vergata University (IT), CNR/IFAC (IT), Finnish Meteorological Institute (FI), Institut d'Estudis Espacials de Catalunya (ES), National Oceanographic Centre (UK) and the Nottingham Geospatial Institute (UK).

The space segment will be based on the novel SSTL-21 platform equipped with propulsion, star tracker and an X-Band link in a 40kg package.

Tango

The TANGO satellites work together on achieving the following goals:

- Measure and monitor moderate to strong emission of CH4 ($\geq$ 10 kt/yr) and CO2 ($\geq$ 5 Mt/yr) at spatial resolutions small enough to monitor individual large industrial facilities (300mx300m), with an accuracy to determine emissions on the basis of a single observation.
- Complement Sentinel-5 (in MetOp-SG) and Copernicus CO2M observation for the verification of the Paris agreement and global stock takes.
- Attribute surface fluxes of specific emission types based on the combination of CH4, CO2
- NO2 observations at high spatial resolution.
- Exploit the use of CO2/NO2 ratio observations to estimate CO2 emissions from offshore NO2 sources.

- Demonstrate a distributed monitoring system that can pave the way to future larger constellations allowing for enhanced coverage and temporal resolution.

The TANGO mission will enable industry and policy makers to monitor greenhouse gas emissions, as well as assess the effectiveness of mitigation strategies, for sources that constitute 40% of the global emissions in key sectors such as power and energy. This is of particular importance for CH_4, as it offers the most significant potential for near term emission reduction to meet the global warming target of below 2°C.

The data from TANGO will provide input to the Copernicus Atmospheric Monitoring Service (CAMS)[4] on anthropogenic CO_2 and CH_4 emissions.

The ongoing consolidation study is carried out by a consortium led by ISIS with the participation of TNO, SRON and Royal Netherlands Meteorological Institute.

The TANGO observing technique is based on two push-broom Spectrometers (Figure 2), each flying on ISIS 16U CubeSat platforms. The 25kg spacecraft platforms are agile and can use slewing maneuvers to map off-nadir targets areas, in order to provide the most responsive monitoring of emission sources.

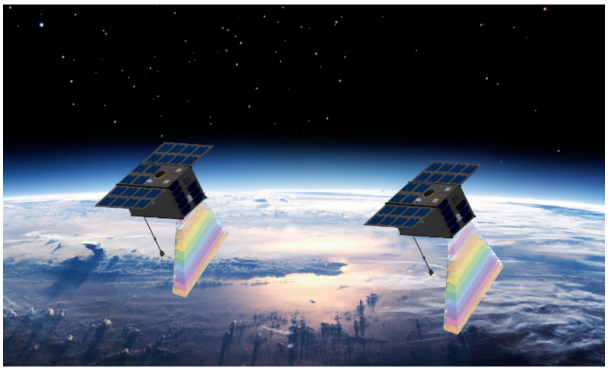

Figure 2: TANGO operational scenario

NanoMagSAT

Building on the experience drawn from the ongoing ESA SWARM mission, NanoMagSat intends to permanently monitor the Earth's magnetic field and ionospheric environment with unprecedented spatial and temporal resolution[2].

The three overarching objectives of the NanoMagSat mission are:

1. to allow the international community to further improve the survey and long-term monitoring of the many components of the geomagnetic field as well as of the ionospheric environment,
2. to address key open science questions and societal-related issues, only partly or not addressed by previous missions so far,
3. and to demonstrate the possibility of using low-cost nanosatellite constellations to achieve such goals on a permanent basis.

It will more specifically aim at:

- Better monitoring, investigating and predicting the Earth's main field for science and societal applications,
- Improving our knowledge of the Earth's lithospheric field for science and societal applications,
- Improving our knowledge of the Earth's ionospheric and magnetospheric currents for space weather science and applications, as well as for sounding the electrical conductivity of the deep Earth (Figure 3),
- Monitoring the state of the ionospheric environment for space weather science and applications, also investigating Extremely Low Frequency (ELF) whistlers produced by lightning in the neutral atmosphere,
- Investigating the impact of incoming magnetospheric currents on the physical state of the ionosphere and thermosphere,
- Recovering the signal of oceanic lunar tides for sounding the electrical conductivity of the deep Earth as well as for global warming studies.

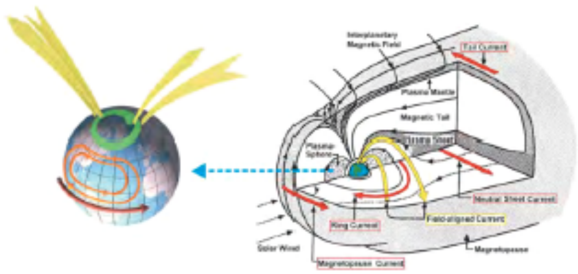

Figure 3: Earth magnetic field and magnetosphere

The SCOUT-NanoMagSat mission is a space network of geomagnetic observatories. It uses the following instruments to monitor the Earth's magnetic field:

- A Miniaturised Absolute Magnetometer (MAM) co-located with 2 Star trackers at the tip of a deployable boom situated on top of the satellite.
- A High Frequency Magnetometer (HFM) located within the satellite body
- 4 Needle Langmuir probes which deploy at the bottom of the satellite along the nadir face
- Dual-frequency GNSS data (the GNSS itself is considered part of the platform due to its dual use)

The ongoing consolidation study is carried out by a consortium led by Open Cosmos with the participation of IPGP and CEA LETI.

NanoMagSAT mission is based on a constellation of 3 low-cost, 16U Cubesats (Figure 4). To fulfil the scientific objective of temporal resolution the constellation will be deployed on three different orbit planes, one inclined at 87deg and the other two at 60deg with a delta RAAN of 90deg.

Figure 4: NanoMagSAT space segment preliminary concept

ESP-MACCS

ESP-MACCS main scientific objective is to understand and quantify processes in the upper troposphere, study its variability and contribute to trend analysis in its composition and effects on climate.

EPS MACCS focuses on the observation of the tropical latitudes of -30 to 30 degrees latitude, to retrieve key radiative important gases (H2O, CO2, CH4, O3, N2O) as well as aerosol and air mass (Figure 5).

The lifetime of 2 years is derived from the need to cover more than one full annual cycle, while the target mission extension to 4 years is required to sample the El Niño Southern Oscillation and the quasi-biennial oscillation.

EPS-MACCS aims at addressing a number of highly relevant scientific questions, which require specific observational capability of a limb sounding mission, namely:

- how water vapour in the upper troposphere and stratosphere (UTS) responds to and interacts with climate change
- how the chemical composition in the UTS responds to increasing emissions
- how estimates of surface greenhouse gas (GHG) emissions can be improved through better knowledge of GHG and ozone in the UTS
- how climate change affects stratospheric ozone and its recovery

The space segment consists of a constellation of three 12U Cubesats embarking a Thermal InfraRed (TIR) spectrometer (HIROS) and a Visible Near IR (VNIR) Hyperspectral Solar Disk Imager (HSDI) flying on low inclination orbits at 550 km altitude.

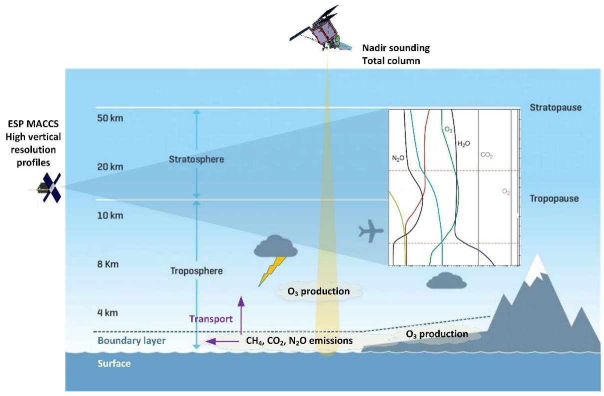

Figure 5:ESP-MACCS reference operative scenario

The ongoing consolidation study is carried out by a consortium led by GomSpace (DK) as prime contractor with Rutherford Appleton Laboratory (RAL-SFTC, UK) as sub-contractor.

INCUBED PROGRAMME

InCubed (Investing in Industrial Innovation) is an element of the ESA Earth Watch Programme. The main objective of the programme is to improve European industry competitiveness in the Earth observation global market, supporting (through a co-funding scheme) the realization of high-risk/high-potential industry led product developments.

The programme in particular supports developments of Earth observation space and ground systems as well as data products and end-to-end solutions. Flight items developments include payload, platforms, and entire satellites as stand-alone missions or as in-orbit demonstration of constellations.

Established large space industry and small medium enterprises (SMEs) playing in the New Space scenario are the target for the programme.

Two examples among the first InCubed mission concepts that under study are provided: MANTIS and Sat4EOCE.

MANTIS

MANTIS will be a demonstration mission to jointly develop, build, launch and operate an innovative nanosatellite platform, flying a high-resolution Earth Observation camera.

The requirements of the natural resources sector for remote sensing products are generally very demanding both in terms of data quality and coverage/revisit time. The MANTIS mission (Mission and Agile Nanosatellite for Terrestrial Imagery Services) fulfil those requirements using a compact and agile nanosatellite (12U CubeSat system).

This first MANTIS satellite is particularly suitable for applications in the energy and mining sector. Companies in these sectors are increasingly carrying out more complex and expensive projects in search of resources, where up to 60% can be found in more remote and hostile regions around the world. In addition, two thirds of major projects fail (i.e. over-budget or delayed) due to unforeseen risks and hazards as a result of inadequate upfront due diligence, planning and prior knowledge of the challenging operating environments. Actionable intelligence is of key importance and essential to be able to increase safety and be able to better plan and mitigate the risks of projects run by these industries.

The MANTIS satellite will address these challenges with periodic statistical reports on activity in the regions of interest, computed through the latest data processing and machine learning techniques on top of other data sets, such as those derived from the EC/ESA Copernicus Programme. The satellite will obtain images to feed these data processing algorithms in a revisit pattern that is optimised for specific areas of interest. The high resolution of these images will be complementary to lower resolution data that is already available from the Copernicus Programme.

The space segment is composed by the Open Cosmos 12U spacecraft platform hosting the Satlantis Microsats SL iSIM-12U (integrated Standard Imager for Microsatellites), an innovative high-resolution optical payload for Earth Observation missions.

iSIM-12U is a compact binocular telescope specifically designed to fit within a volume of 8U, and thus ideal for 12U CubeSat standard platforms. The design relies on the integration of four key technologies: a binocular diffraction-limited optical system working at visible and near-infrared wavelength; a high precision, robust and light structure; a set of innovative COTS detectors with 2D CMOS sensors; a high-performance and reconfigurable processing unit with Super-resolution algorithms implemented on-board.

The downstream heart is represented by Terrabotics' object recognition and change detection algorithms which will enable the processing of data on ground using the latest machine learning techniques. The overall MANTIS infrastructure is shown in Figure 6.

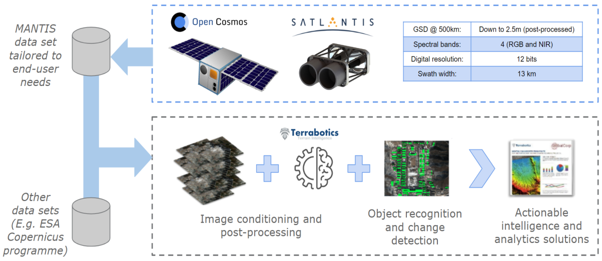

Figure 6: MANTIS overall infrastructure

SAT4EOCE

The SaT4EOCE initiative represents a peculiar exploitation of the InCubed programme; Sat4EO+ (Figure 7) is a complete End-to-End Earth Observation System[5] including all its segments (i.e. User, Mission, Flight and Ground) for which its prime contractor, DEIMOS Group, has defined a series of self-standing sub-products that InCubed is actively supporting, specifically: a COTS AOCS subsystem for mini-satellites and an Image Product Chain (IPC).

The AOCS Product is an innovative AOCS COTS subsystem solution for the smallsat class with performances enabling ~50 cm ground resolution imaging, very high pointing stability, accuracy, agility, autonomy and high duty cycle imaging.

The Image Product Chain (IPC) is composed of three products: the EO imager, the Instrument Processor and the cloud based Exploitation Platform. The main innovation of the IPC is that it is a fully integrated end-to-end system, providing access to very high resolution (VHR) imagery and cloud based analytic solutions. It enables ~50 cm ground resolution VNIR imaging in the mini-satellite class, with masses up to 300kg.

The VHR VNIR imager is an electro-optical imaging system providing a compact EO Imager compatible in terms of mass, volume and power consumption with the smallsat class. The new payload being developed by Surrey Satellite Technology Ltd brings on advanced manufacturing techniques and a new approach required to address the price and schedule targets for SAT4EO+ missions. The payload boosts a state of the art multiband on chip time delay integration (TDI) sensor provided by Teledyne e2v. Thus, it enables (~50 cm) optical VHR imaging to new customers, new satellite mass ranges, and is suitable for future large constellations;

The targeted Customers are both privately owned companies, deploying small satellite missions to provide commercial services from EO applications and institutions or governments of countries with small satellites initiatives aiming at having their own high performance and reasonable cost EO system.

The activity commenced in January of 2020. The project is currently in a design and commercial consolidation phase having already reached some major steps by passing through requirements and architectural reviews. The new design, processes and techniques required to address the changing VHR EO market demands will see the first payload of the IPC ready for test early 2021, and the AOCS qualified in late 2021.

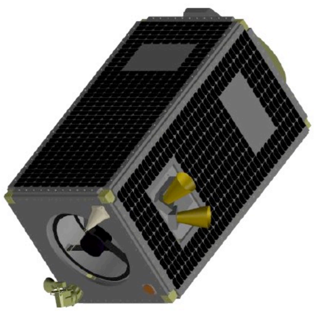

Figure 7: SAT4EO+ Space Segment Concept

Φ-SAT MISSION CLASS

As part of its initiative to promote the development of radically innovative technologies such as Artificial Intelligence (AI) capabilities onboard Earth Observation (EO) missions, the European Space Agency (ESA) initiated a project aimed to solicit the EO community to design Cubesat-based mission to demonstrate the enabling capabilities of AI for Earth Observation.
The first Φ-sat mission[3] is an experiment enhancing the FSSCAT mission winner of the Copernicus Master Programme while the second mission, Φ-sat-2 will be used to demonstrate the AI enabling capability for new useful innovative EO techniques of relevance to EO user communities. The overall Φ-sat-2 mission objective is to address innovative mission concepts, fostering novel architectures or sensing that enable to meet user-driven science and/or applications by means of onboard processing. The latter will be based on state-of-the-art AI techniques and onboard AI-accelerator processors.

Φ-sat-1 mission experiment

Φ-sat-1 is the results of the enhancement with artificial intelligence (AI) technology of an advanced hyperspectral and thermal infrared imager called HyperScout-2 from Cosine B.V (NL) aimed at detecting clouds on the images and removing the cloudy pixels reducing the prohibitive amount of data to be downloaded. (Figure 8).
The AI cloud detection experiment is aimed at validating the performance of an on-board inference engine based on a machine learning (ML) algorithm for cloud detection. This is the first time such an experiment will be conducted in space. The inference engine will run on a vision processing unit (VPU) embedded in the hyperspectral instrument and it will aim to improve the content of the downloaded data. In fact, one of the key issues for hyperspectral instrument embarked on a small satellite/Cubesat mission is lowering cost, both economically and in terms of reducing on-board resources (power, mass, contact time etc.), vs information in the downloaded data. Whilst, a hyperspectral mission produces an incredible amount of information from any observed scene, in many cases for land, hydro and cryo-sphere observations, the data are not exploitable due to the presence of clouds. For instance, in the case of Sentinel-2, more than 30% of the image content is clouds.
This experiment will demonstrate that an inference engine based on ML can significantly reduce the number of cloudy images with negligible loss (<1%) of significant data.
The experiment will be run using the images acquired by HyperScout®-2 and for this IOD phase both the inferenced images and the original images will be downloaded to verify the effectiveness of the algorithm.
The Φ-sat-1 experiment has been developed by a consortium lead by cosine B.V. with the participation of University of Pisa, Sinergise and the collaboration of Ubotica.
The Φ-sat-1 experiment is due to be launch on June 19th 2020.

Figure 8 Φ-Sat-1 mission experiment on board FSSCAT

Φ-sat-2 mission

A Call for the second mission of the Φ-sat class has been issued end of 2019 seeking new ideas and innovative approaches to EO exploiting onboard AI. The selected concepts are expected to be implemented and ready for launch within a maximum of 16 months after selection and confirmation of the winning candidate.

The overall development will be implemented in two-phases:

- The first phase (Mission Concept Phase), led by instrument and AI innovators, will consolidate the instrument and overall mission concept;
- The second phase (Mission Development Phase), led by a mission integrator, will be dedicated to the design and development of the space and ground segments, launch, in-orbit operations, data exploitation and distribution.

The first phase has a 4 month duration and concludes with a Readiness Review, where the Agency expects that the selected consortium will have a representative Breadboard Model (BBM) of the instrument able to demonstrate the overall performance and the AI capabilities, as well as an update of the plans and any other relevant documents for the following phase.

The Mission Development phase will be activated, upon successful completion of the Readiness Review. This second phase, devoted to the Mission Development shall include satellite Flight Model (FM) development, procurement of launch service, in-orbit operations (Launch and Early Orbit Phase, commissioning, nominal operations for one year and provisions for end-of-life disposal), payload data downlink, data processing and data distribution. The schedule for the development of the mission shall last a maximum of 12 months from the start of the Mission Development Phase up to the satellite readiness for delivery to the launch service provider.

The contractor shall abide to a free and open data policy for the distribution of the data.

The Kick Off for the Φ-sat-2 is expected in the 3rd quarter of 2020.

CONCLUSIONS

This paper presents a comprehensive overview of ESA-EOP current and future activities involving small and nano-satellites. In particular, the activities aim to support the role in the ESA-EOP vision for small and nano-satellite in the portfolio of opportunities that the agency offers to the user community. In particular the three-main initiative presented in the paper have been activated aiming to support and incentivize the science capability in the case of Scout missions, business development in the case of Incubed missions, and in orbit demonstration (IOD) of disruptive technology (e.g. AI) capabilities with small and nano satellites for EO remote sensing.

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