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NanoSat MO Framework: Enabling AI Apps for Earth Observation

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ABSTRACT

Following the success of the first Φ-Sat mission, in 2020, the European Space Agency (ESA) announced the opportunity to present CubeSat-based ideas for the Φ-Sat-2 mission as part of its initiative to promote the development of radically innovative technologies such as Artificial Intelligence (AI) capabilities onboard Earth Observation (EO) missions. Open Cosmos and CGI submitted a joint proposal for the Φ-Sat-2 mission idea, which takes advantage of the latest research and developments in the European ecosystem. The proposed mission idea is a game-changing EO CubeSat capable of running AI Apps that can be developed, easily deployed on the spacecraft and updated during flight operations. The AI Apps can be operated from ground using a simple user interface. This approach allows continuous improvement of the AI model parameters using the very same images acquired by the satellite. The mission takes advantage of the latest research for mission operations of CubeSats and use the NanoSat MO Framework, a framework for small satellites that allows software to be deployed in space as simple Apps, in a similar fashion to Android apps. This framework was previously demonstrated in ESA's OPS-SAT mission, and supports the orchestration of on-board Apps. It fully decouples the App features from the underlying on-board hardware via an abstraction layer API in the form of services. Additionally, it includes a Software Development Kit with demo Apps, development tools, and tutorials to facilitate the development of Apps. By decoupling the data platform from the Apps, it is possible to distribute the development of specialized AI Apps to different partners within the Φ-Sat-2 mission consortium. The mission will include a set of default AI Apps that will be able to do vessel detection, high compression of images, and roadmap transformation from satellite imagery. The framework allows more than just the set of default Apps and so, third-party Apps can be included on later stages of the mission lifecycle. This paper will present the NanoSat MO Framework, introduce the AI Apps that are part of the Φ-Sat-2 mission, and how the free and open-source framework enables the creation of software-defined satellite missions via on-board Apps.

ACRONYMS

Acronym	
AI	Artificial Intelligence
CCSDS	Consultative Committee for Space Data Systems
ESA	European Space Agency
EO	Earth Observation
IPC	Inter-Process Communications
MO	Mission Operations
NMF	NanoSat MO Framework
TRL	Technological Readiness Level

1. INTRODUCTION

The recent miniaturization of space components and electronics has allowed the design of smaller satellites, which are considerably cheaper to build and launch than conventional satellites. This decrease in the total cost of a space mission has boosted a new growing market for small satellites and, as the number of small satellites keeps increasing, there is a raising demand for reusable software across nanosatellites. [1]

The NanoSat MO Framework closes that gap by using the latest technologies in software and by taking as inspiration the successful world of smartphones and tablets. It is based on the CCSDS Mission Operations concept and it is used by experiments on ESA's OPS-SAT mission which was launched in 2019. OPS-SAT is an in-orbit laboratory mission designed to test new software where no single-point of failure is allowed to exist. Therefore, in case of a system failure, the mission shall be always recoverable. OPS-SAT has provided the perfect opportunity for the first on-board validation of the NanoSat MO Framework. [2]

The successful demonstration of the NanoSat MO Framework on-board of the OPS-SAT mission has paved the way for further small satellite missions to take advantage of the same reusable concepts.

One of these is the Φ-Sat-2 mission which will be a game-changing Earth Observation CubeSat platform in space capable of running AI Apps that can be developed by its users, then easily deployed in the spacecraft, and operated from ground.

CCSDS MO services

CCSDS Mission Operations (MO) is a set of standard end-to-end services based on a service-oriented architecture, which are being defined by the CCSDS Standards Organization, and it is intended to be used for mission operations of space missions. [3]

The MO service's framework allows mission operation services to be specified in an implementation and communication agnostic manner. The core of the MO service framework is its Message Abstraction Layer (also known as MAL), which ensures interoperability between mission operation services deployed on different framework implementations.

The standardization of the Mission Operations Services offer a number of potential benefits for the development, deployment and maintenance of mission operations infrastructure, such as: [3]

- Increased interoperability between agencies;
- Re-usage between missions;
- Reduced costs;
- Greater flexibility in deployment boundaries;
- Increased competition and vendor independence;
- Improved long-term maintainability.

The deployment of standardized interoperable interfaces brings a number of benefits as each organization is be able to develop/integrate their own multi-mission systems that can then be rapidly made compliant with the spacecraft. Additionally, the on-board software development costs can be reduced by taking advantage of strict software reuse. [3]

OPS-SAT

ESA and its European industry partners generate many new and innovative ideas for advancing European space technology regarding mission operations every year, but the majority of these innovations never make it to orbit. The OPS-SAT mission provides a low cost in-orbit laboratory available for authorized experimenters to test, demonstrate and validate their developed software experiments.

OPS-SAT is the first CubeSat designed by European Space Operations Centre (ESOC) and is a safe experimental platform which is flying in a low earth dawn-dusk orbit. OPS-SAT makes available a reconfigurable platform, at every layer from channel coding upwards, which is available for experimenters that wish to test and demonstrate new software and mission operation concepts. [2]

The OPS-SAT mission was launched on the 18th of December 2019 and it uses the NanoSat MO Framework as its main software orchestration system.

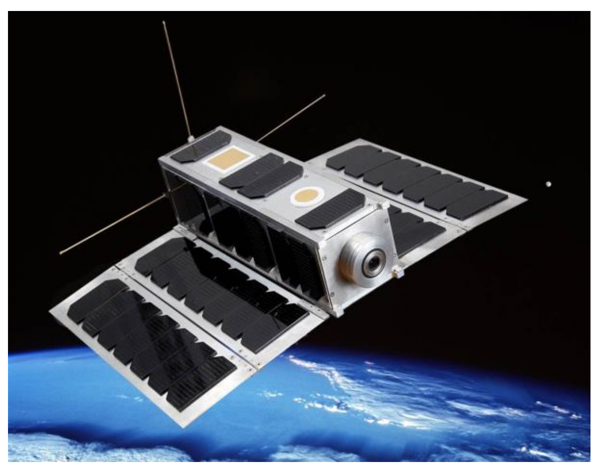

Figure 1: OPS-SAT in space

Φ-Sat-2

Following the success of the Φ-Sat-1 mission [4], the European Space Agency announced at the end of 2019, an opportunity to present CubeSat-based ideas to be assessed for a potential Φ-sat-2 mission as part of its initiative to promote the development of radically innovative technologies such as Artificial Intelligence capabilities onboard Earth Observation missions.

OpenCosmos, CGI, Simera Sense, Ubotica, CEiiA, GEO-K, and KP Labs submitted a joint mission idea for Φ-sat-2. After a review based on several criteria which looked on both the innovation of the ideas and the feasibility of the mission to demonstrate the enabling capability of artificial intelligence for new useful Earth Observation applications, this idea was selected for the implementation of the Φ-Sat-2 mission.

The mission idea is a game-changing EO CubeSat platform in space capable of running AI Apps that can be developed, easily deployed on the spacecraft, updated during flight and operated from the ground using a simple user interface.

The Mission is divided into two sequential phases:

- First phase, the Mission Concept Phase, shall demonstrate the readiness of the mission by demonstrating the innovative EO application through a breadboard validation test.

- Second phase, the Mission Development Phase, shall be dedicated to the design and development of the space and ground segments, launch, in-orbit operations, data exploitation, and distribution.

The Φ-Sat-2 mission intends to demonstrate some of the advantages of doing on-board processing, such as, reducing transmission bandwidth, and improving the information delivery timeliness. Ultimately, the improvements in delivering information rather than data to ground.

2. NANOSAT MO FRAMEWORK

The NanoSat MO Framework is an advanced software framework for small satellites based on the latest CCSDS MO services. The main objective is to facilitate the development of software for small satellites including both the ground and space segments, and also to simplify the orchestration of software. The core functionalities of the framework are: [5]

- Monitoring and control of on-board status and activities
- Monitoring and control of the platform peripherals
- On-board software management

The NanoSat MO Framework is built upon the CCSDS Mission Operations Service Framework and thus inherits the same agnosticism towards the transport layers used in the space system. This allows the conceptualization of a "multi-segment" software framework dedicated to nanosatellites that is neither limited to the space segment nor the ground segment, and instead it covers both segments simultaneously. [5]

From a spacecraft system point of view, the NanoSat MO Framework is split in two segments. First, the "Ground Segment" just like in any traditional spacecraft system. Second, the "NanoSat Segment" which is the equivalent of the space segment but because the target deployment in space are nanosatellites, it contains a more specialized name.

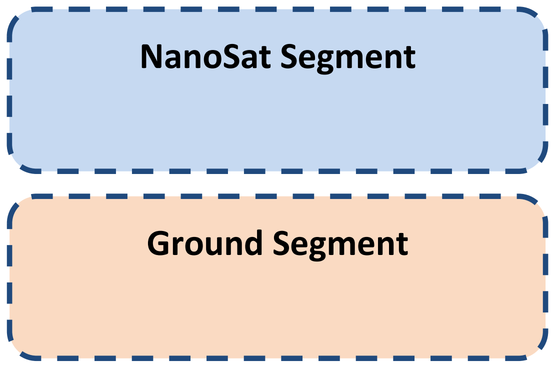

Figure 2: NMF Segments

Inside each segment a set of prebuilt components was created in order to allow quick development of new software solutions that are interoperable in end-to-end scenarios. These components were defined as the NMF Composites. [6]

The design of the NMF Composites was done in a modular and flexible manner which allows them to be reconfigured or adapted depending on the needs in the overall design of the system. This is similar to a Lego® type approach where the bricks can be recombined to form something different. [6]

The family of NMF Composites is the following:

- NanoSat MO Monolithic
- NanoSat MO Supervisor
- NanoSat MO Connector
- Ground MO Adapter
- Ground MO Proxy

The first 3 NMF Composites are supposed to run on the NanoSat segment while the last 2 are meant to run on the Ground segment. The Ground MO Adapter and Ground MO Proxy are components which are intended to be deployed on the Ground segment and when combined with the NanoSat segment part, they are capable of providing end-to-end deployment solutions.

An NMF App is developed by integrating the NanoSat MO Connector component into the software application. These NMF Apps are expected to be started, monitored, stopped, or killed by the NanoSat MO Supervisor component.

The Multiple NMF Apps Scenario consists of multiple NMF Apps running on the NanoSat segment that are connected to the Platform services of the NanoSat MO Supervisor using the NanoSat MO Connector. Figure 3 presents this scenario. [6] [7]

The NanoSat MO Supervisor includes the Central Directory service that plays an important role in this scenario as it allows NMF Apps to be found. A ground application can connect to the Central Directory service and find the right NMF App to connect to. [8]

This scenario is expected to be deployed in the NanoSat segment therefore the communications between the NMF Apps and the NanoSat MO Supervisor are expected to occur via Inter-process communication (IPC).

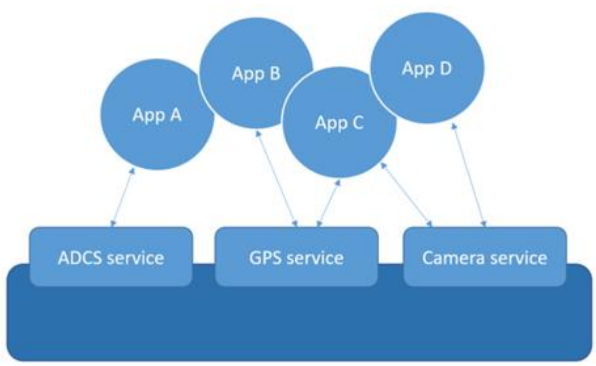

Figure 3: Apps running on-board using the different Platform services

The NMF provides a layer of Platform Services that allow Apps to monitor and control the devices on-board of a spacecraft platform (e.g. performing image acquisitions, getting GPS data, etc.). [9]

The following Platform services have been defined:

- Camera service
- GPS service
- Autonomous ADCS service
- Software Defined Radio service
- Optical Data Receiver service
- Power Control service

For the Φ-Sat-2 mission an additional service for Artificial Intelligence is intended to be defined. This will allow the exchange of data with the AI board device on the mission. The service will allow multiple Apps to concurrently query the device in a controlled manner.

3. AI APPS ON Φ -SAT-2

The Φ-Sat-2 mission will take advantage of the latest research for mission operations of CubeSats and use the NanoSat MO Framework [11], a framework for small satellites that allows software to be deployed in space as simple Apps, in a similar fashion to Android and iOS apps. This framework, was developed through ESA research and development, and demonstrated in ESA's OPS-SAT mission, supports on-board Apps upload/upgrade and orchestration. It fully decouples the App features from the underlying on-board Hardware by providing an integration API and tutorials to simplify Apps integration. This will allow distributing the development of specialized AI Apps to different partners within the Φ-sat-2 Consortium.

Φ-sat-2 will contain a set of default AI Apps, which will cover different ML approaches and methodologies such as supervised (image segmentation, object detection) and unsupervised learning (with auto encoders and generative networks). These default AI have been selected for their innovation regarding its usefulness in Earth observation user-driven applications. The Technological Readiness Level (TRL) for the various apps at project start is 4 and is expected to reach 5 at the end of the first phase and 6-7 during the project lifetime.

The set of default AI Apps that will be available in Φ-Sat-2 are the following:

- **Cloud detection App** – Since the Φ-sat-2 mission relies on an optical sensor, the availability of an onboard cloud detection App which will generate cloud masks and identify cloud free areas which can be exploited by the other Apps is not only relevant for on-board resources optimization, but also enables the demonstration of AI Apps pipeline.

- **Autonomous Vessel Awareness App** - Using machine learning techniques, in particular deep learning, the App will autonomously detect and classify vessels in optical imagery and determine which images, or subsets thereof, should be downlinked. On top of a fast detection of vessels, this App will also feature autonomous tasking (by providing relevant geographic coordinates and time slots of areas where significant features are detected), which will also be implemented during the operational phase.

- **Sat2Map App** - Transforms a satellite image to a street map in emergency field using Artificial Intelligence. The software takes advantage of the Cycle-Consistent Adversarial Networks (CycleGAN) technique to do the transformation from the satellite image to the street map. This App will enable the satellite to provide to rescue teams on ground in case of emergency (Earthquake, flood etc.) real time of still available and accessible street. It is based on a app developed by CGI for ground image elaboration. [12]

- **High Compression App** – This App aims to exploit deep auto encoders to push AI image compression on-board and on ground reconstruction. The performances of the App will not be measured only in terms of standard compression rate VS image similarity but also in terms of how the reconstructed image will be exploitable by other Apps e.g. for objects recognition. [13]

To demonstrate the huge capability of the NanoSat MO framework, the Φ -Sat-2 mission will also support third parties developed AI Apps to be uploaded and then started/stopped on demand. This concept is extremely powerful enabling future AI software to be developed and easily deployed in the spacecraft. Also this will represent an enabler for in-flight mission continuous learning of the AI networks.

In fact, in AI, the computational complexity is associated mainly with the training phase, which can be performed off-line on-ground (e.g. using actual images from the sensor). When a new/improved version of the model is generated, this can be uploaded on the satellite for improved performance. A significant effort during the operational phase will be dedicated to actually demonstrate how in real cases this can be achieved with the Φ-Sat-2 mission architecture.

4. CONCLUSION

The utilization of the NanoSat MO Framework in a space mission enables the creation of Apps that can do advanced processing on-board and easily orchestrate them together with the rest of the mission. This approach to mission operations is considerably different from the standard way of mission operations currently done by the European Space Agency and/or other space agencies. [10]

By taking advantage of cutting-edge research and using a new paradigm to mission operations, ESA will demonstrate the deployment of Artificial Intelligence directly on-board the Φ -Sat-2 mission. Thanks to this innovative concept, the NanoSat MO Framework will allow the distribution of the development of specialized AI Apps to different partners within the Φ-sat-2 Consortium.

These AI Apps will demonstrate the innovative capabilities of running Artificial Intelligence directly on-board of the spacecraft covering different ML approaches such as supervised (image segmentation, object detection) and unsupervised learning (auto encoders and generative networks), including the enormous advantages of easy in-flight, continuous learning of the AI networks.

The Φ-Sat-2 mission is not just limited to the default set of AI Apps and supports the upload of new AI Apps even after the mission is launched and flying in space.

The consortium envisages a future follow-up mission levering the concepts present in Φ -Sat-2 but extended to an EO constellation with multiple satellite nodes. This mission would be, in essence, a Constellation-as-a-Service capable of deploying AI Apps over certain areas of the world based on different criteria. [11]

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