Open-Source Software in Space Operations

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Abstract

The open-source software movement has transformed the way software is developed. It has leveraged the power of software reuse with sustainable community support to attractively develop and scale software for the benefit of all. The movement has found its way into the space domain where newer players are stepping in and adopting open-source solutions for both ground and space segments. A notable adoption driver are the recent developments in off-the-shelf compute capabilities of modern spacecraft coupled with the increasing decision-making complexity and data-generation capacity of modern satellite payloads. The latter requires ever more on-board autonomy due to communication bandwidth limitations with the ground control software and the inherent human factor limitations in decision-making. Software which was never expected or even intended to be used in the space domain is now being adopted by space players, particularly in New Space. In support of industry and academia to explore and experiment with open-source for space operations, the European Space Agency (ESA) launched the OPS-SAT Space Lab in December 2019. The spacecraft is an open innovation platform in the form of a 3U CubeSat in Low Earth Orbit (LEO). OPS-SAT has accomplished many firsts in space powered by open-source and rapid prototyping, from the first securities trade to pioneering the use of Artificial Intelligence (AI) frameworks for Machine Learning (ML) training and inferences with payload and telemetry data. This paper presents lessons learned and a suggested way forward from the perspective of two former OPS-SAT Flight Control Team (FCT) members turned experimenters, showcasing the opportunities and challenges in revisiting how spacecraft operations benefit from a rethink with open-source software as a pillar of mission design.

Keywords: open-source, space, satellite, operations

Software de código abierto en operaciones espaciales

Resumen

El movimiento del software de código abierto ha transformado la forma en que se desarrolla el software. Ha aprovechado el poder de la reutilización de software con el apoyo de la comunidad sostenible para desarrollar y escalar software de manera atractiva para el beneficio de todos. El movimiento ha encontrado su camino hacia el dominio espacial donde los jugadores más nuevos están interviniendo y adoptando soluciones de código abierto para los segmentos terrestre y espacial. Un impulsor de adopción notable son los desarrollos recientes en las capacidades informáticas listas para usar de las naves espaciales modernas, junto con la creciente complejidad de la toma de decisiones y la capacidad de generación de datos de las cargas útiles de los satélites modernos. Este último requiere cada vez más autonomía a bordo debido a las limitaciones de ancho de banda de comunicación con el software de control de tierra y las limitaciones inherentes al factor humano en la toma de decisiones. Los jugadores del espacio están adoptando ahora software que nunca se esperó ni se pretendió que se usara en el dominio espacial, particularmente en New Space. En apoyo a la industria y la academia para explorar y experimentar con código abierto para operaciones espaciales, la Agencia Espacial Europea (ESA) lanzó el Laboratorio espacial OPS-SAT en diciembre de 2019. La nave espacial es una plataforma de innovación abierta en forma de 3U CubeSat en órbita terrestre baja (LEO). OPS-SAT ha logrado muchas primicias en el espacio gracias a la creación de prototipos rápidos y de código abierto, desde la primera negociación de valores hasta ser pionera en el uso de marcos de inteligencia artificial (IA) para el entrenamiento y las inferencias de aprendizaje automático (ML) con carga útil y datos de telemetría. Este documento presenta lecciones aprendidas y un camino sugerido a seguir desde la perspectiva de dos ex miembros del Equipo de Control de Vuelo (FCT) de OPS-SAT convertidos en experimentadores, mostrando las oportunidades y desafíos al revisar cómo las operaciones de naves espaciales se benefician de un replanteamiento con software de código abierto como un pilar del diseño de la misión.

Palabras clave: de código abierto, espacio, satélite, operaciones

太空操作中的开源软件

摘要

开源软件运动改变了软件的开发方式。该运动利用软件再使用的能力和可持续的社区支持来开发和改变软件大小以造福所有人。该运动已经进入太空领域，其中新的行动者正在介入，并为地面和太空操作采用开源解决方案。一个值得注意的驱动因素是现代航天器现成计算能力的最新发展，以及现代卫星有效载荷日益增加的决策复杂性和数据生成能力。鉴于地面控制软件的通信带宽限制和决策中固有的人为因素限制，后者需要更多的机载自主权。以前从未期望或打算在太空领域使用的软件如今正在被太空参与者采用，特别是在新太空(New Space)。为了支持工业界和学术界探索和试验用于太空操作的开源，欧洲航天局(ESA)于2019年12月启动了OPS-SAT太空实验室。该航天器是一个开放式创新平台，以3U立方星的形式位于近地轨道(LEO)。在开源和快速成型的支持下，OPS-SAT在太空领域实现了多项第一，从第一次证券交易到率先使用人工智能(AI)框架进行机器学习(ML)训练，以及利用有效载荷和遥测数据进行推理。本文从两名OPS-SAT飞行控制小组(FCT)前成员的角度，介绍了所获得的经验和研究建议，展示了航天器操作如何从重新思考开源软件（作为太空任务设计的支柱）一事中获益，以及相关的机遇和挑战。

关键词：开源，太空，卫星，操作

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1. Introduction

Space operations requires resilient and high availability ground control and flight software to successfully conduct missions in Space. Many large space players and agencies use a broad range of legacy systems for their mission operations and offer these via tailored licenses to commercial entities. As a result, there is a notable reliance on legacy and flight proven software in space operations with often closed source software which makes experimentation and innovation cumbersome. Innovating in the space operations domain, both in the ground and space segments, requires testing new software with improved capabilities based on open-source software tools. Since December 2019, an open innovation lab has been in orbit to test such innovative technologies and experiments.

OPS-SAT is a 3U CubeSat launched by ESA on December 18, 2019. It is the first nanosatellite to be directly owned and operated by ESA. It is equipped with a full set of sensors and actuators including a HD-camera, Global Navigation Satellite System (GNSS) receiver, star tracker, reaction wheels, high speed S-band and X-band communication, laser receiver, Software Defined Radio (SDR), and a powerful processor with a reconfigurable FPGA at its heart. Conceived to break the "has not flown, will not fly" cycle, OPS-SAT has spearheaded many firsts. One of which is a new paradigm to on-board software by introducing "apps" in space. These apps can be "easily developed, debugged, tested, deployed, and updated at any time without causing any major problem to the spacecraft" (Coelho et al., 2017, p. 1). The Altera Cyclone V System-on-Chip with an ARM dual-core (Cortex-A9) has an 800 MHz CPU clock and 1 GB DDR3 RAM. The Linux operating system, processing power, and memory capacity makes it possible for the Satellite Experimental Processing Platform (SEPP) to re-use and run open-source software. Onboard apps can be developed in C, C++, Java, and Python 3. At the center of the experimenter operations is the OPS-SAT Community Platform hosted by the European Space Operations Centre (ESOC).

After submitting a short non-binding form describing an experiment idea, the experimenter is registered to the Community Platform ("ESA OPS-SAT Space Lab Community Platform," n.d.). From there, the experimenter is provided support through an iterative process to develop, and sometimes pivot, their idea into a flight-ready experiment. One of the interesting developments seen during the mission is the way in which experiments can interact with, or be built on-top of, other experiments. Experimenters can make remote use of two testing setups at ESOC, a small FlatSat and a larger Engineering Model (EM).

2. Openly Accessible

The spacecraft is a flying innovation platform that is easily accessible to European industry, institutions, and individuals for rapid prototyping, testing, and validation of their software and firmware experiments in space. The NanoSat MO Framework (NMF) was developed to provide a standard, open-source on-board software framework for nanosatellites that follows the Mission Operations (MO) services framework architecture (Consultative Committee for Space Data Systems [CCSDS], 2010). It facilitates monitoring and controlling the spacecraft's software applications as well as interaction with the platform and its peripherals via hardware abstraction. The NMF inherits all the advantages of the MO framework but with a special focus for nanosatellites with pre-implemented components that achieve a full end-to-end system when assembled to satisfy mission requirements. The NMF consists of a set of tools, core components, and Application Programming Interfaces (API). The core components and APIs are defined as a set of "composites" that the applications can reuse and infer. The build products are deployed across the two segments: Ground and Space.

The NMF comes in the form of open-source Java libraries and applications, allowing to quickly create applications interfacing with the OPS-SAT payloads and exposing a unified monitoring and control interface, compliant with the Consultative Committee for Space Data Systems (CCSDS) Mission Operations Monitor and Control Services standard (Coelho et al., 2017). Not only does NMF provide means to quickly develop, test and deploy onboard applications, but it also comes with a set of ground components to abstract away difficulties coming from operating a remote system with sparse live visibility. A major such component is Ground MO Proxy. Its function is to mirror the space application data model, configuration, and state in an opportunistic manner and expose them further to other ground systems. This approach ensures that the need to worry about the specifics of operating a space mission is almost completely abstracted away from the experiment developer.

The frontend application provided to the OPS-SAT experimenters is called Light-Weight Mission Control System (LWMCS), built by reusing the ESA Ground Operations System User Desktop—a selected set of user-friendly Graphical User Interfaces (GUIs) used to monitor and control Satellite Control and Operation System (SCOS) based system. These GUIs are packaged into a web application and tailored to support integration with the MO Services. The LWMCS is hosted on ESA

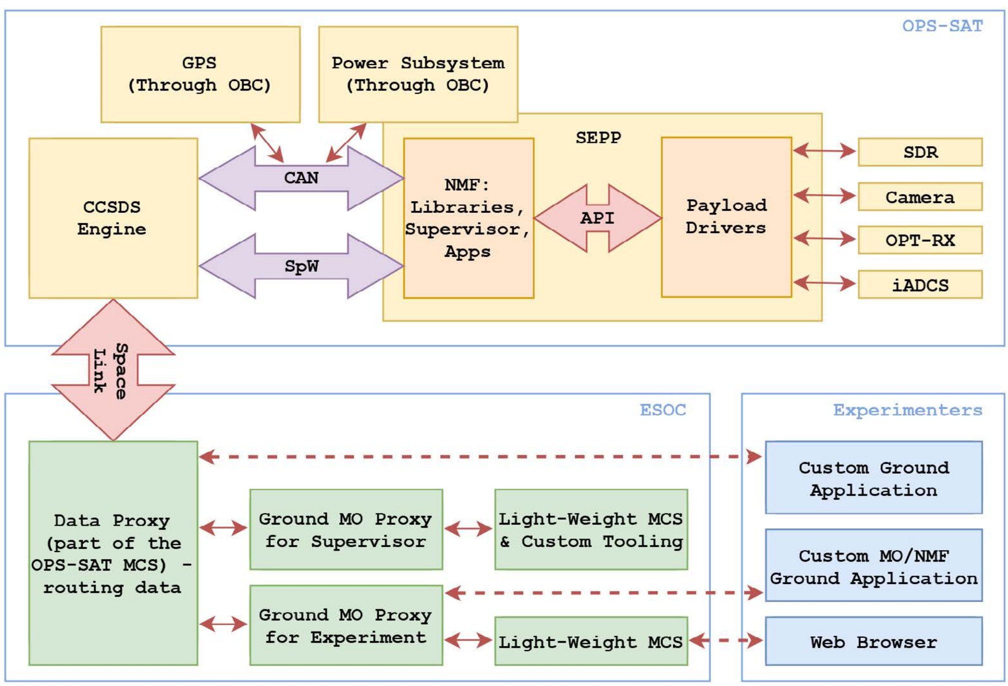

Figure 1: OPS-Space interactions between space and ground segments.

premises for operational purposes, while runnable Docker containers are also available to the experimenters, allowing them to perform in-house integration and testing.

Experimenters have a multitude of ways to send and receive data to their application running on OPS-SAT. They can interact with their NMF application through a fully-fledged Mission Control System (MCS) interface via a web-browser. This system allows for advanced features also present in ESA MCSs. These features include Activity tracking (TCV); Modifying parameters; Aggregation control and view; and Message display. Experimenters can locally prepare command stacks in the form of XML files and load them onto the ESA LWMCS server through which they connect via port forwarding, and then accessing a web page. High level technical interactions between space and ground segments are shown in Figure 1.

3. Community Outreach and Support

This section presents three case-studies on how open-source software on-board OPS-SAT has facilitated community outreach and support, effectively crowdsourcing space segment innovations. Two basic arguments are taken from Szajnfarber and Vrolijk (2018) to support extracting better solutions from the crowd than from internal experts: right-tail sampling and unearthing distant expertise. The former is illustrated in Figure 2 where the best open solution from the crowd is greater than the average closed solution from the experts. For the latter, novel solutions may be contributed by outsiders as they problem-solve with different disciplinary perspectives that are outside the context in which internal experts are entrenched.

Opening OPS-SAT to experimenters in industry, institutions, and

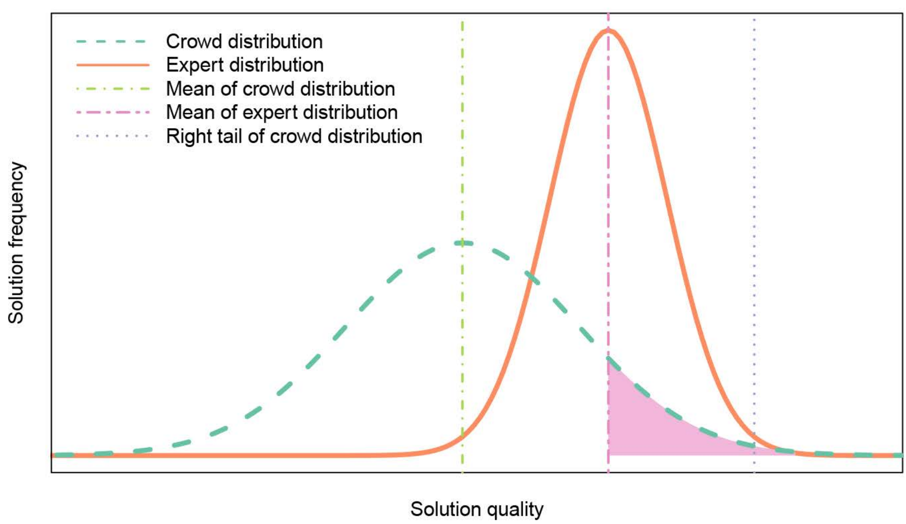

Figure 2: Right-tail sampling for better contributions from the crowd. Reproduced from Szajnfarber and Vrolijk (2018).

professionals across ESA member states is a form of innovation crowdsourcing that engages the crowds in ideating new approaches to space operations. The experiments proposed and executed by the OPS-SAT community establishes an end-to-end innovation process that creates new perspectives on spacecraft software engineering and agile development enabled by open-source technologies and the interactions with the communities supporting these technologies. As seen in Figure 3, exciting developments have been broadcast to a wider audience through media and outreach that builds on top of the openly accessible nature of the mission.

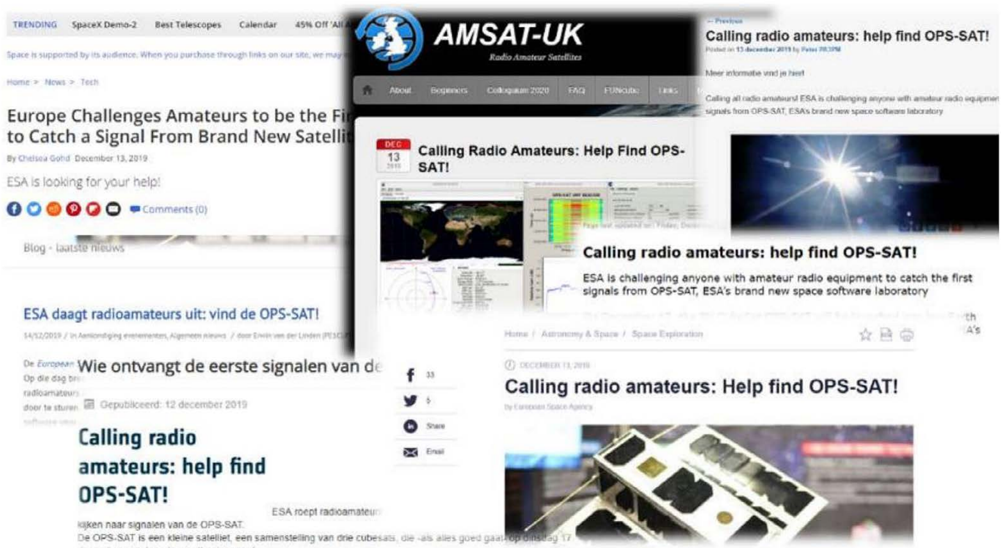

Figure 3: Amateur radio articles covering the community challenge to track OPS-SAT after separation from the launch vehicle.

3.1. Radio Amateurs Community Support

OPS-SAT communicates in the Ultra High Frequency (UHF) amateur radio band for the backup telemetry and telecommanding link. The advantage of the UHF link is the less stringent requirements on platform pointing, making it a preferred fallback channel when an on-board anomaly leads to a non-nominal attitude of the satellite. Usage of the Amateur radio UHF spectrum requires publishing all communication modulations, protocols, and frequencies that the satellite will use. This requirement by the International Amateur Radio Union (IARU) makes it possible for any radio operator to decode data from satellites in the amateur radio band for identification purposes. Using this information, the amateur radio community could prepare to track OPS-SAT. In parallel, the news of OPS-SAT was picked up by the SatNOGS (Satellite Network Operated Groundstations) team, which is an open-source project by Libre Space Foundation that connects amateur satellite-tracking antennas and stations worldwide in a single network. Finally, the FCT published a dedicated signal processing dashboard to view and plot decommutated TM parameters. As the tools are all based on free open-source signal processing software and libraries (GNU Radio), they are widely used and adopted by the community due to familiarity with other tools.

Operational use of the UHF link in nominal situations was foreseen to be limited to the Launch and Early Orbit phase (LEOP) where a detumbling phase is executed. Initial communication attempts over UHF were difficult without any acknowledged uplink packets or received telemetry beacons. Due to the community outreach and interest, many groundstations were tracking OPS-SAT and providing 3rd party signal reports which allowed the FCT to narrow down the reception issue to a groundstation configuration error. Afterwards community contribution was persistent and resulted in increased UHF telemetry coverage as seen in Figure 4.

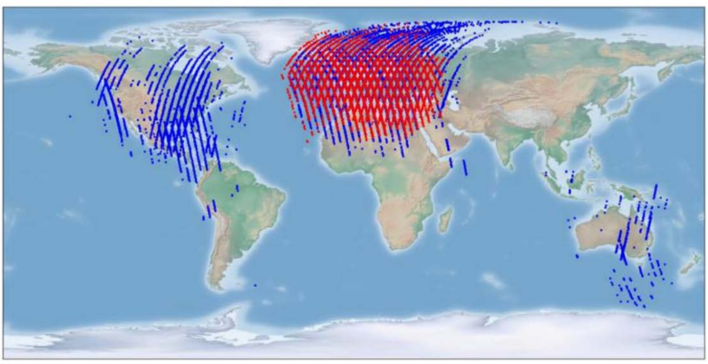

Figure 4: ESA ground station coverage of OPS-SAT (red), community coverage (blue).

3.2. Crowdsourcing Innovations in Artificial Intelligence

The SmartCam app on OPS-SAT is the first use of AI by ESA for autonomous planning and scheduling on-board a flying mission (Labrèche et al., 2022). It was originally developed to optimize downlink bandwidth utilization by autonomously discarding bad images acquired from the spacecraft's camera. The software has since developed geospatial capabilities to autonomously capture pictures when the spacecraft is above areas of interest, thus eliminating the need for operators to plan and schedule image acquisition operations. The SmartCam is presented in this section as an experiment to make space operations "openable" by means of crowdsourcing image classification problems. This is made possible with the experiment's scalable image classification pipeline designed to ingest ML models trained by third-party contributors. Image classification is a common ML use-case and a wealth of thumbnails downlinked from the spacecraft is available to experimenters as training data. The application runs an image classifier developed with TensorFlow Lite, an open-source framework to train on-device machine learning models for low-latency inferences with a small binary size (TensorFlow Developers, 2022). To the authors' knowledge, this is the first instance in which the TensorFlow framework is used for on-board autonomy. The SmartCam operationalizes on-board ML inference to provide daily support for OPS-SAT operators. Beyond this, and in line with the mission's concept, the platform seeks to extend its capability to experimenters so that space AI can be made easily accessible to industry, institutions, and individuals. TensorFlow is a powerful and versatile framework that has spearheaded countless innovations in terrestrial applications of AI by enabling rapid prototyping with easy modeling and intuitive high-level APIs. Its availability on-board a spacecraft sets the groundwork to introduce similar dynamism for space applications. Third-party Convolutional Neural Network (CNN) model files can be uplinked to the spacecraft and chained into an ML inference pipeline that sequentially classifies and subclassifies acquired pictures. Branching rules are configurable based on each model's inference output. This is illustrated in Figure 5, where an image inferred as "Bad" by Model A is an input for Model C. If Model C cannot determine whether the direction is "Nadir" or "Space" then it settles for the generic parent label of "Bad."

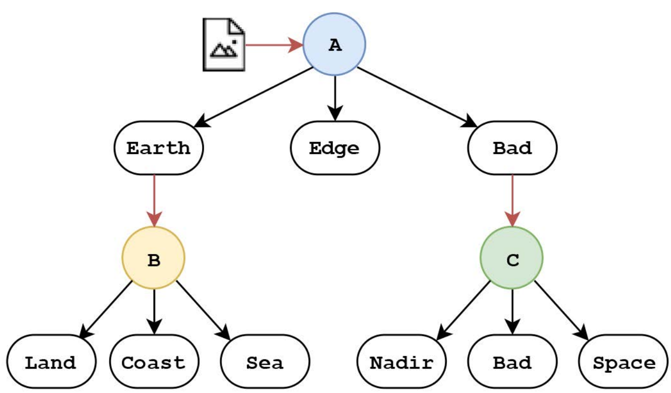

Figure 5: Simple classification pipeline (Labrèche et al., 2022). Red arrows represent image inputs and black arrows are inferences.

The pipeline is designed to scale through crowdsourced contributions of TensorFlow Lite *.tflite* model files as well as executable binaries with standard inputs and outputs. Deploying an industry standard framework—with strong industry heritage—on-board a spacecraft broadens its accessibility to AI communities established outside of the space sector. In this regard, OPS-SAT serves as a platform for synergistic development that de-risks and accelerates adopting AI in future missions. Over 200 experiments have registered to run on OPS-SAT in response to an open call and the SmartCam builds on top of this successful open innovation method to attract AI experimenters through crowdsourcing. This format also addresses latent skepticism of using open methods as an added value to spacecraft operations.

The SmartCam's approach to crowdsourcing exemplifies the productive path described in Szajnfarber and Vrolijk (2018) for extending the applicability of open methods so that a full system problem pertain to image classification and processing is decomposed into isolated "openable" subproblems along a configurable pipeline. This was demonstrated in an experiment that successfully de-risked the BeaverCube-2 mission by prototyping experimental ML algorithms on the SmartCam's image classification pipeline (Kacker et al. 2022). BeaverCube-2 is a mission jointly developed by the MIT Space Telecommunications, Astronomy, and Radiation (STAR) Lab and the Northrop Grumman Corporation which aims to demonstrate the use of an AI Computational Accelerator System-on-a-Chip (SoC) on a 3U CubeSat in LEO. BeaverCube-2 will leverage this AI accelerator to train ML models to perform in-orbit image processing to identify clouds and ocean fronts around the Cape Hatteras region of North Carolina (Felt, 2022; Kacker et al., 2022). Previous work has been conducted on producing a computer vision pipeline for this task, specifically on the cloud segmentation (Kacker et al., 2022) and front identification (Felt, 2022) models. However, deploying software that has only been tested using ground-based computing and imaging is a risk. It is desirable to test novel algorithms in a flight-like environment before deploying them for use. The image processing algorithms developed for BeaverCube-2 were thus integrated into the SmartCam's image processing pipeline as an In-Orbit Demonstration (IoD). The ML models trained for this IoD were designed to run on OPS-SAT's SEPP, and in doing so the experimenters bequeathed to OP-SAT the capabilities developed for BeaverCube-2. Some changes to the model implementations will be necessary for BeaverCube-2 to best harness BeaverCube-2's hardware, which uses a different AI Computational Accelerator SoC. The experiment thus validated cloud-segmentation algorithms on-board OPS-SAT to help understand the challenges of image processing in an in-orbit environment in preparation for further software development and deployment on BeaverCube-2.

3.3. The Kelvins Challenge

Crowdsourcing ML models to meet decomposed image classification needs is ongoing through a competition hosted on the Kelvins platform maintained by ESA's Advanced Concept Team (ACT). The submissions will serve operational needs as well as a knowledge transfer mechanism to develop new training capabilities in OPS-SAT so that on-board AI can be used to extract information to classify an image base on models trained from only a handful of images. The landing page of the challenge's website is shown in Figure 6. The submissions are ranked on a leaderboard, adding a competitive motivator to the challenge. Teams can be formed thus encouraging collaborations. The winners are invited to run their models onboard the spacecraft with full support of the FCT.

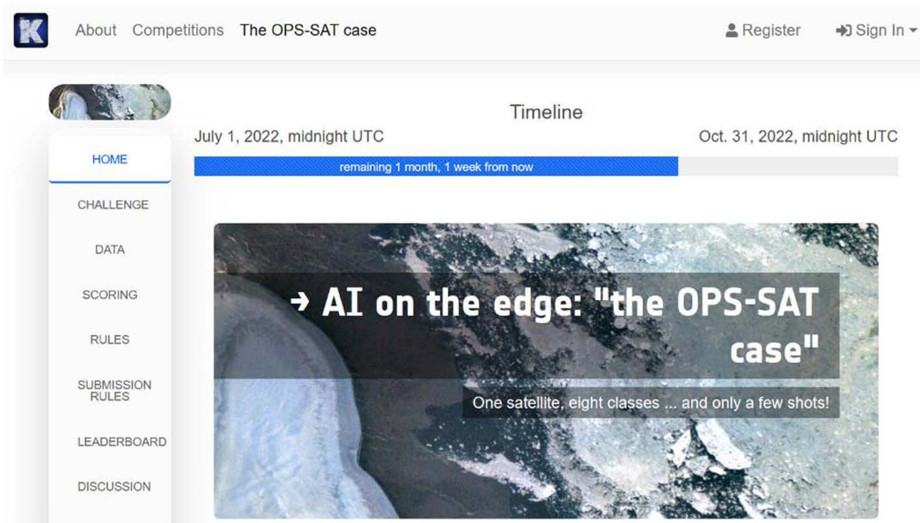

Figure 6: "The OPS-SAT case" is an Edge AI competition on the Kelvins challenge platform. This competition is created and organized by the ACT in collaborations with Phi-Lab and the OPS-SAT FCT.

4. In-Orbit Demonstrations

This section presents three in-flight case-studies of ground-breaking experiments on-board the OPS-SAT spacecraft which were developed and operationalized using open-source software.

4.1. Image Classification

Inconsistent spacecraft pointing during OPS-SAT's commissioning phase led to an unbalanced dataset of downlinked pictures. This was an inefficient use of the limited communication bandwidth with the ground station as most images that were downlinked ended up being "Bad" images at the cost of useful science data that remained onboard the spacecraft. To resolved this, a total of 4,705 thumbnail images retrieved from the spacecraft were manually labeled as either "Edge" (2.6 %), "Earth" (12 %), or "Bad" (85.4 %). Sample pictures for each label are shown in Figure 7.

A CNN model was trained with the open-source TensorFlow Lite ML framework using the labeled thumbnail images as training data. This model was uplinked to the spacecraft and is used by the SmartCam app to run on-board inferences and classify acquired images on the fly. The spacecraft autonomously recognizes and discards "Bad" images from being sent to the ground station (Labrèche et al., 2022).

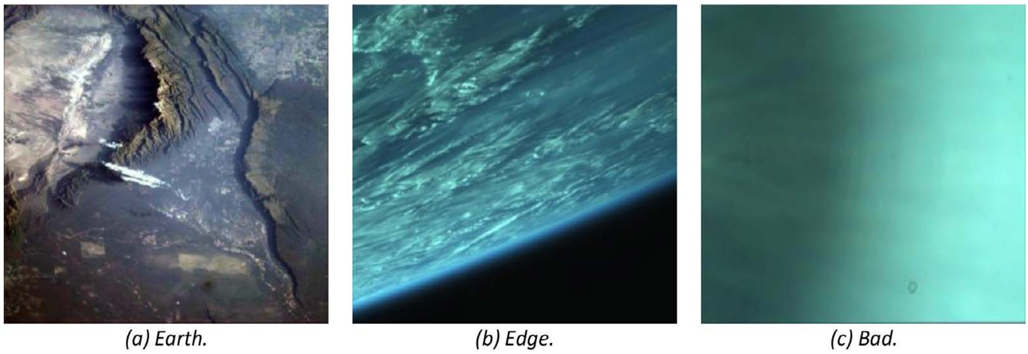

Figure 7: Sample Earth, Edge, and Bad thumbnail images acquired by OPS-SAT's on-board camera (Labrèche et al., 2022). Thumbnail (a) is white-balanced, (b) and (c) are unprocessed. Credit: ESA.

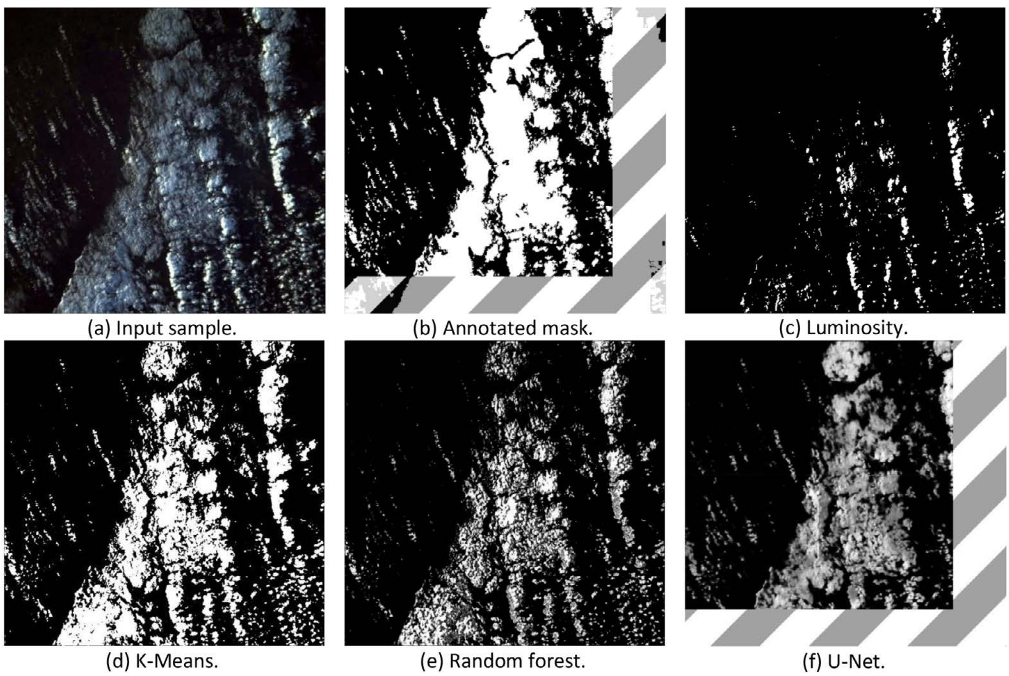

Figure 8: Comparison of the output cloud mask from each method on high contrast white-balanced sample input over ocean (Kacker et al., 2022). Mask is annotated up to 512 px width and height to match U-Net output.

4.2. Cloud Detection

Open-source cloud detection image processing algorithms adapted for MIT's BeaverCube-2 spacecraft were uploaded to and executed on OPS-SAT for in-orbit testing and validation purposes (Kacker et al., 2022). The focus was on four algorithms: a luminosity-thresholding method, a random forest method, a U-Net based deep learning method—all developed by STAR Lab for BeaverCube-2—and a k-means clustering deep learning method implemented by the OPS-SAT FCT. Each method was evaluated in terms of overall accuracy, power draw, and temperature rise on-orbit. A visual cloud mask comparison is shown in Figure 8. All algorithms were executed in-orbit except for the random forest model due to a radiation induced anomaly which corrupted OPS-SAT's filesystem. Instead, it was executed with a sample image on the OPS-SAT EM FlatSat, which has identical hardware to the flight model. Each algorithm outputs a cloud pixel percentage which can be used to autonomously discard images with a cloud factor that is above a given threshold.

4.3. Search and Rescue

A successful IoD was carried out on the OPS-SAT spacecraft using the SDR, hereafter referred to as the SDR IoD (Mladenov et al., 2022). The SDR IoD performed autonomous decoding and on-board processing of Search and Rescue (SAR) messages transmitted in the UHF 406 MHz band by Emergency Position Indicating Radio Beacons (EPIRBs) and Emergency Location Transmitters (ELTs). These devices are used in emergency situations by maritime and aeronautical platforms to transmit a UHF distress signal containing identification and ground position. The SDR of OPS-SAT is used to acquire real time baseband radio signal samples in-orbit which are processed by the GNU Radio open-source signal processing software running on-board the spacecraft. Figure 9 illustrates the concept of operations of the SDR IoD.

Decoded RF messages containing identification and GPS information are stored on the filesystem and downlinked as one or more JSON files. In parallel, the raw recording can also be downlinked to aid decoder development. The SDR IoD validated the unprecedented flexibility of a software defined Radio Frequency (RF) payload which can be deployed for multi-purpose missions such as monitoring Internet of Things (IoT) sensors, wildlife tracking, and global RF interference mapping. OPS-SAT is the first ESA spacecraft to use SDR-based in orbit signal processing using GNU Radio running on embedded Linux. The SDR can generate large amounts of data exceeding both storage and real-time downlink capabilities, hence on-board processors, detectors, and decoders are necessary to process raw data in orbit and keep downlink volumes to a minimum while ensuring relevant metadata products are delivered to the ground as fast as possible without operator intervention nor oversight.

The SDR IoD has since been further developed with the use of the open-source TensorFlow Lite framework by training and using a CNN model to identify SAR signals by using object detection on a spectrum image representation of the signals (Mladenov et al., 2022).

5. Looking to the Future

Replicating programs like OPS-SAT will allow a more community-based approach to developing software for space applications, as

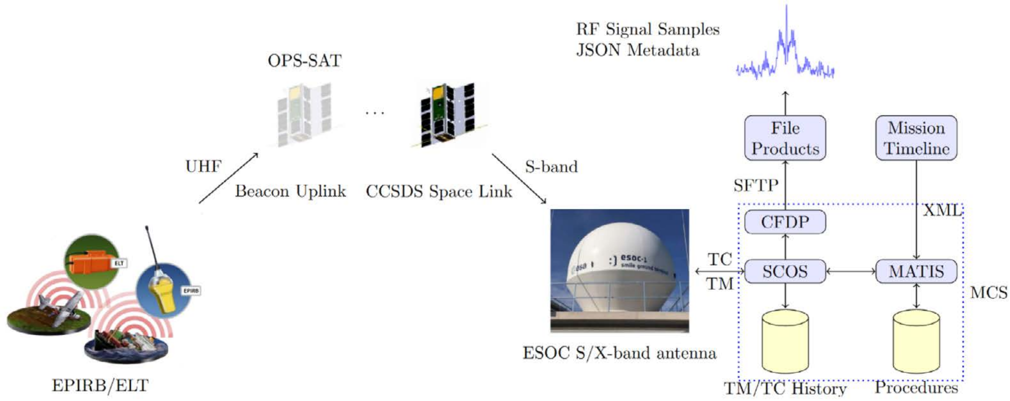

Figure 9: Overview of the ConOps involving the various Ground and Space components (Mladenov et al., 2022).

is currently the case for terrestrial-used software. The open-source approach allows a wider pool of actors to contribute to the reliability and usability of software, which has historically proven correct. Adopting modern methods such as Agile development ("Manifesto for Agile Software Development," n.d.) and DevOps flows will further drive innovation in space operations. Involving the communities both in space and ground segment software directly leverages community contributions, which advance software functionality and robustness. Satellite Platform as a Service (SPaaS) allows a community centric approach around developing and deploying applications to test out new operational concepts in space and lay the foundation for multipurpose missions by use of payload sharing. The latter also paves the way for more sustainable mission operations where multiple operators share the payloads instead of launching individual spacecraft. ESA's OPS-SAT mission has pioneered in these aspects and is the world's first satellite accessible by the public over the internet and openly available for experiments. The objective of the mission is to remove as many barriers as possible preventing experimentation involving mission critical elements. These barriers include technical, programmatic, and financial aspects. Embracing open-source technologies on-board the spacecraft has proven to be an invaluable enabler in broadening experimental access towards new paradigms of space segment software engineering.

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