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## Abstract

Earth Observation spacecraft play a pivotal role in various critical applications impacting life on Earth. Historically, these systems have adhered to conventional operational paradigms, namely the “mow-the-lawn” and “bent pipe” approaches. In these paradigms, operational schedules are formulated on the ground and subsequently uploaded to the spacecraft for execution. Execution involves either systematically acquiring vast amounts of data (mow-the-lawn) or targeting specific areas of interest as defined by end users or operators. We aim to depart from these traditional methodologies by integrating onboard Artificial Intelligence, near real-time communication, and new observing strategies in one system called CogniSAT-6. These innovations will amplify the amount, speed, and quality of the information yielded by such a system by up to an order of magnitude. This paper provides an overview of the current state of the art in autonomous Earth Observation spacecraft and the application of onboard processing in Earth Observation spacecraft. An overview is given of the CogniSAT-6 mission, its concept of operations, system architecture, and data processing design. In addition, the first results of our in-orbit functional tests are presented. Since we believe that the technology presented here will have a significant impact on society, an ethical framework for such systems is presented. Finally, the benefits of the technology and implications for Earth Observation systems going forward are discussed.

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# The Next Era for Earth Observation Spacecraft: An Overview of CogniSAT-6

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**Abstract**—Earth Observation (EO) spacecraft plays a pivotal role in various critical applications impacting life on Earth. Historically, these systems have adhered to conventional operational paradigms, namely the “mow-the-lawn” and “bent pipe” approaches. In these paradigms, operational schedules are formulated on the ground and subsequently uploaded to the spacecraft for execution. Execution involves either systematically acquiring vast amounts of data (mow-the-lawn) or targeting specific areas of interest as defined by end users or operators. We aim to depart from these traditional methodologies by integrating onboard artificial intelligence, near real-time communication, and new observing strategies in one system called CogniSAT-6. These innovations will amplify the amount, speed, and quality of the information yielded by such a system by up to an order of magnitude. This article provides an overview of the current state of the art in autonomous EO spacecraft and the application of onboard processing in EO spacecraft. An overview is given of the CogniSAT-6 mission, its concept of operations, system architecture, and data processing design. In addition, the first results of our in-orbit functional tests are presented. Since we believe that the technology presented here will have a significant impact on society, an ethical framework for such systems is presented. Finally, the benefits of the technology and implications for EO systems going forward are discussed.

**Index Terms**—Artificial intelligence (AI), Earth Observation (EO), new observing strategies (NOS), onboard processing, real-time insights.

## I. INTRODUCTION

SATELLITES have been utilized as remote sensing systems since the very beginning of spaceflight itself with the launch of Sputnik in 1957 [1]. Spacecraft have evolved to smaller form factors and incorporate increasingly capable communication links and sensors. Nevertheless, the operational paradigm of Earth Observation (EO) spacecraft has largely remained the same. Generally, these spacecraft operate following the bent pipe principle: commands are sent up, executed on spacecraft, and results are sent down.

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With the advent of intersatellite communication links as well as onboard processing, it is now feasible to break with this operational paradigm. By including new processing capabilities on spacecraft, payload data can be interpreted in-orbit. This allows the spacecraft to react to its environment and make autonomous decisions based on what it “sees.” In addition, with the inter-satellite link (ISL) information can be exchanged with the ground segment without requiring line of sight with a ground station. Combining this capability with onboard processing enables end-to-end delivery of information on ground in near real-time, which we define as within 5 min from image acquisition in this context. The availability of space-based EO information within minutes for end-users can have significant benefits for use cases such as disaster response. Since the persistent communication link is bidirectional, new operational paradigms are possible that require low-latency tasking and interaction with the platform. The combination of these capabilities can increase the return of valuable information from these systems by up to an order of magnitude [2].

CogniSAT-6, a joint mission by Ubotica Technologies and Open Cosmos shown in Fig. 1, is the first mission specifically designed around this new operational paradigm of autonomous and collaborative robotic remote sensing systems that leverage onboard intelligence to interact dynamically with their environment. The spacecraft is a 6U CubeSat launched in a Sun Synchronous Orbit at around 500 km altitude in March 2024 on SpaceX Transporter 10. It carries a Simera Sense HyperScape100 hyperspectral imager as well as an ISL communication payload. In addition, the spacecraft carries the CogniSAT-XE2 artificial intelligence (AI) and computer vision edge computing processor. This processing board allows the system to perform inference using neural networks on board the spacecraft as well as complex computer vision tasks.

This article first presents a comprehensive overview of related work. Next, an overview of the mission and the concept of operations of CogniSAT-6 is provided as well as an overview of the onboard data processing architecture. Since the authors believe that the technology presented here will have a significant impact on society and autonomous agents such as CogniSAT-6 are moral agents that could encounter ethical dilemmas, a starting point for an ethical framework for such systems is presented. In the next section, early results from our mission are presented, verifying many of the onboard functionalities. Finally, the implications of the technology integrated into CogniSAT-6 on EO systems are discussed.

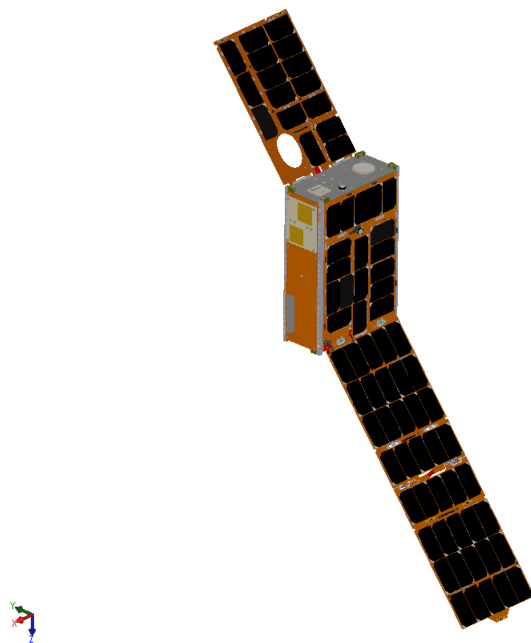


Fig. 1. CAD drawing of CogniSAT-6.

## II. RELATED WORK

The limitations of bent pipe architectures have been well documented in literature. Denby and Lucia state: “*Limits on downlink bitrate prevent bent pipes from scaling to accommodate the extreme data volumes of large constellations and create a need for a new system architecture less reliant on communication*” [3]. Furano et al. [4] described the inefficiency of the classical paradigm. The authors propose applying AI to prefilter data on board, increasing the efficiency of the end-to-end system and moving away from the first-in-first-out bent pipe paradigm.

In addition to limitations, alternatives to the classical EO paradigm have also been described in literature. Chien et al. [5] proposed the use of EO spacecraft in a “SensorWeb,” where multiple air, space, and ground-based sensors are leveraged in coordination to enable more valuable observations. This system architecture has been used to demonstrate the automatic cross-tasking of spacecraft based on measurements from other spacecraft and autonomous tasking based on in-situ measurements of sensors on the ground, showing an increase of event capture by up to an order of magnitude versus blind monitoring by EO spacecraft [6], [7], [8]. The concept of SensorWebs fits within the wider context of new observing strategies (NOS), which has the following goal as defined by Le Moigne and Cole: “*to dynamically optimize measurement acquisition using many diverse observing capabilities (space, air, and ground), collaborating across multiple dimensions and creating a unified architecture.*” [9]. NOS demonstrations on CogniSAT-6in collaboration with JPL are in preparation [10].

Previous work has described elements required to enable NOS as incorporated in a number of missions. An overview is given here of related works on onboard processing for EO spacecraft, autonomous scheduling capabilities on EO spacecraft based on onboard interpretation of captured data, near real-time insight

delivery (RTID) capabilities for EO systems, and integration of EO spacecraft in networked sensor systems.

One of the first EO missions to incorporate onboard autonomy was ESA’s project for onboard autonomy (PROBA). This spacecraft was launched in 2001 and included onboard payload operational scheduling [11]. The system utilized a constraints solver and optimizer on board the spacecraft to optimize for mission data return but did not interpret captured imagery on board the spacecraft.

The Bispectral InfraRed Detection (BIRD) mission was one of the first spacecraft to incorporate hardware-accelerated neural network-based payload data processing [12], [13]. Launched in 2001, the purpose of this 94-kg spacecraft by DLR was to detect hot spots using a stereo line scanner and an infrared sensor system. The spacecraft flew a “neuro-chip” called the “Recognition Accelerator NI1000.” In addition, radiometric and geometric preprocessing steps such as image coregistration were performed on board. In June 2002, an onboard experiment was executed segmenting water from land and detecting a hotspot in an acquired image.

The EO-1 mission demonstrated onboard decision-making algorithms that modified the operational schedule of the spacecraft to maximize the scientific output of the system in 2004 [14], [15]. The system, called Autonomous Sciencecraft (ASE), processed captured data to analyze its content and modify the mission plan based on the analysis result with an advanced onboard planner called continuous activity scheduling planning execution and replanning (CASPER) [16]. ASE ran on the EO-1 mission until the end of the mission in 2017 [17].

Tactical Satellite-3 (TacSat-3) launched in May 2009. This military smallsat flew the Advanced Responsive Tactically-Effective Military Imaging Spectrometer (ARTEMIS). The design for the spacecraft featured an onboard processing capability that enabled it to send data products directly to personnel on ground within 10 min from image capture and allowed tasking by warfighters in the field, leveraging tactical ground stations [18].

PROBA-2 was launched in November 2009 and includes autonomous navigation capabilities [19]. These capabilities included a low complexity numerical orbit propagator, allowing the spacecraft to accurately determine its location even under GPS outages. In addition, the spacecraft can prioritize images based on detected image quality and perform image feature detection on board for coronal mass ejections [20].

PROBA-V was launched in May 2013 and includes an algorithm that predicts land visibility [21]. These predictions are used to autonomously switch the payload on and off. In these autonomous operations, additional constraints based on observation locations and predicted Sun illumination are also taken into account. Arguably, these operations can be considered a form of an “optimized mow-the-lawn” paradigm.

Launched in December 2013, the 1U CubeSat Intelligent Payload Experiment (IPEX) demonstrated autonomous operations [22]. Like EO-1, the spacecraft was also equipped with CASPER. This system demonstrated the use of machine learning for processing payload data onboard.

The successor to the BIRD mission consisted of two spacecraft and was called the FireBird mission [23]. One of these

spacecraft, BIROS, was launched in July 2016. The spacecraft had an experimental ISL relay and onboard processing capabilities that enabled it to directly alert ground users of detected hotspots. These capabilities were verified on ground [24], but due to technical problems with the satellite could not be verified on board [25].

On OPS-SAT, a 3U CubeSat by ESA launched in 2019, several relevant experiments have been performed. An autonomous planner was developed and tested on a ground setup to autonomously reschedule operations based on the output of a classification neural network [26]. NOS-related experiments involving dynamic targeting [27] based on interpreting look-ahead image data using onboard processing have been planned for deployment on OPS-SAT [28]. In addition to these experiments, a range of onboard applications involving processing of captured image data has been performed [29], [30]. The spacecraft also demonstrated the use of “apps” by abstracting the lower-level implementation requirements from the platform away for app developers [31]. OPS-SAT was operational until May 2024 [32].

An onboard planning system called MEXEC has been developed by JPL [33]. MEXEC was tested in 2020 on the ASTERIA CubeSat [34]. Although this experiment did not use information collected from payload data in its operational planning, it did demonstrate that highly capable planning software may be integrated into a restricted platform like a CubeSat.

Giuffrida et al. [35] described the  $\Phi$ -Sat-1 mission. This 6U CubeSat launched in September 2020 included a dedicated AI accelerator [Intel Movidius Myriad 2 Vision Processing Unit (VPU)] on board and utilized a neural network-based pipeline to detect clouds in captured hyperspectral images.

DLR has developed the autonomous real-time detection of moving maritime objects (AMAROs) system, a feasibility study of a near real-time alert system detecting ships by processing EO images on board EO platforms [36]. The system utilized the Iridium satellite communication network to transfer alerts in near real-time from the platform to the end user. The system was verified in an aircraft flight campaign over the North Sea in 2018, but not on spacecraft.

Kerr et al. [37] described a novel system architecture for EO satellites generating rapid civil alerts in . The authors proposed the use of onboard processing in combination with an ISL to provide near real-time insights to end users, with a latency below five minutes globally and below 1 min in certain cases. It is shown that this architecture is both feasible for optical and synthetic aperture radar (SAR) payloads [38]. The proposed system was developed up to TRL 4/5.

In June 2021, Loft Orbital’s YAM-3 spacecraft was launched on SpaceX Transporter 2. This spacecraft featured a Simera Sense MonoScape100 panchromatic imager, with a ground sampling distance (GSD) of 4.75 m at 500 km as well as a payload data processor and a GlobalStar ISL [39], [40]. It hosted a third party neural network-based ship detection demo, implemented on a field programmable gate array (FPGA) [41].

Also launched on Transporter 2 was D-Orbit’s ION-MK02 Dauntless David SCV-003 (the “Wild Ride” mission). This carrier vehicle hosted a number of payloads, among which an onboard computing subsystem called the “Cloud Computing in

Space module” and a low-resolution webcam-like camera [42]. The computing subsystem (Unibap’s SpaceCloud iX5-100) included a quad-core x86 64-bit CPU, a Microsemi SmartFusion2 FPGA, and an Intel Movidius Myriad X VPU. Mateo-Garcia et al. [42] performed an onboard flood segmentation experiment on board this spacecraft leveraging the Myriad X accelerator and the onboard camera. After initial deployment, the authors retrained their model on ground on acquired spacecraft imagery and reuploaded the trained model to spacecraft, demonstrating the ability to update models “on the fly.”

Similarly, launched in January 2022 on Transporter 3, D-Orbit’s ION SCV-004 Elysian Eleonora (the “Dashing Through The Stars” mission) combines a Unibap compute unit with a hyperspectral imager [43]. Few-shot onboard training of a variational auto-encoder (VAE) was for the first time demonstrated on this spacecraft in 2023 [44]. In addition, onboard processing experiments of captured image data using AI have been planned for this spacecraft [45].

Some onboard processing experiments were performed by software company Palantir on Satellogic’s NewSat-27 EO spacecraft (launched April 2022), demonstrating a ship detection pipeline [46]. This spacecraft flies a Nvidia Jetson TX-2i, a multispectral imager with sub-meter GSD and a 29-band hyperspectral imager. While details on the performed experiments are limited, Imig and Rehman [47] performed a preprocessing pipeline on raw imagery, including image registration on board the spacecraft . The authors note some challenges in their processing systems: power limitations cause the onboard edge AI to have a practically achievable runtime of only minutes, and the authors implemented a checkpoint system to recover the Jetson processing state in case of an unexpected processing interruption, presumably due to radiation effects.

HYPISO-1 was launched in January 2023 and includes onboard processing algorithms such as CCSDS123 compression [48]. The spacecraft is reconfigurable in flight and includes onboard processing capabilities. Software for target detection and classification on captured hyperspectral data is planned to be uploaded to spacecraft [49].

In June 2023, OroraTech’s FOREST-2 6U CubeSat was launched. The goal of this spacecraft is to monitor wildfires and alerting stakeholders as soon as possible after discovery of a fire [50]. To this end, the spacecraft features two infrared imagers and one visual imager, an Nvidia Jetson Xavier NX processing unit, and an ISL. The spacecraft uses a single-channel thresholding algorithm for its onboard fire detection. The spacecraft successfully demonstrated the downlinking of fire detections through a ground station, but ISL relay has so far been unsuccessful due to unreliable coverage [50].

Intuition-1 was launched in November 2023 and includes a hyperspectral instrument and onboard processing capabilities [51]. This spacecraft utilizes its onboard processing to extract information and reduce the bandwidth required for downlink yet relies on a bent pipe architecture and line of sight communication with a ground station.

Also launched in November 2023, MANTIS is a 12U CubeSat that features a 3.5-m GSD imager and onboard AI capabilities. This spacecraft incorporates a CogniSAT-XE1 processing board.

An experiment demonstrating cloud detection using onboard AI has been performed [52].

In April 2024, the Hyperspectral Thermal Imager (HyTI) CubeSat was deployed from the ISS. This 6U hyperspectral mission incorporates a Unibap Deep Delphi iX5 heterogeneous computer platform with CPU, GPU, and FPGA processors [53]. The spacecraft also features a Globalstar ISL, which is used as a beacon and a backup communication link. The onboard processing capability is used to perform L2 processing on board, as well as demonstrate the derivation of L2 products onboard and low-latency delivery of those products. Processing of the anticipated raw data volumes per pass to calibrated datacubes takes an estimated two orbits (i.e., several hours) after acquisition.

Launched on SpaceX Transporter 10 in March 2024 was the SONATE-2 spacecraft. This 6U CubeSat features an Nvidia Jetson Xavier NX processing platform, featuring both a CPU and a GPU, and four NIR and RGB image sensors [54]. The spacecraft will demonstrate image segmentation, object detection, and anomaly detection onboard using convolutional neural networks (CNNs), auto-encoders, and generative adversarial networks (GANs). The spacecraft will also be used to train models on board using captured imagery. As stated above, similar experiments have previously been performed on D-Orbit's ION SCV004. At the time of writing, SONATE-2 has demonstrated onboard training of an auto-encoder using preloaded Sentinel 2 data but not on images captured by the spacecraft itself [55].

Also launched on Transporter 10 was Loft Orbital's YAM-6 spacecraft. This smallsat features an Inmarsat ISL communication subsystem, several high-performance compute resources, including CPU and GPU modules, and a 10-m GSD, 150-band visual range hyperspectral imager [40]. The spacecraft will host a range of third-party demonstrations that involve AI processing of data captured by the spacecraft and ISL relay of results [56], [57]. An onboard radio frequency signal detection experiment using AI has been completed by the company Helsing [58].

Examples of recently launched missions include the 6U Kanyini CubeSat, which flies a HyperScout-2 hyperspectral imager and onboard AI acceleration for AI-based early fire smoke detection [59], and  $\Phi$ -Sat-2, a 6U CubeSat that allows developers to run AI apps using the same abstraction framework as implemented on OPS-SAT [60]. Several applications are planned to be deployed to this spacecraft [61].  $\Phi$ -Sat-2 includes the CogniSAT-XE1 AI accelerator, which incorporates the Intel Movidius Myriad 2 and a MultiScape100 multispectral camera [62], [63]. Both Kanyini and  $\Phi$ -Sat-2 have been launched in August 2024.

Clearly, there is an increasing prevalence of AI-enabled EO spacecraft. The rate at which these EO spacecraft are launched is also increasing, a testament to the traction of this technology. However, the actual deployment of this technology in a long-term operational system beyond limited demonstrations has not yet been achieved. Most of the announced missions will consist of further technology demonstrations, but some commercial companies are already either investigating the use of AI onboard proprietary spacecraft for particular use cases or have plans to deploy AI. Examples include Orbital Sidekick [64] and Planet Labs [65].

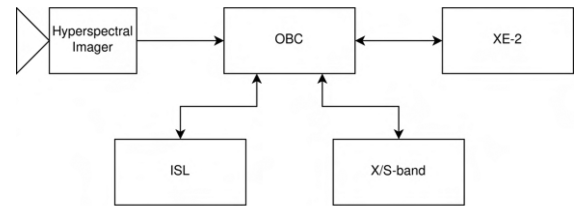


Fig. 2. Simplified system diagram for the space segment of CogniSAT-6.

To the best of the knowledge of the authors of this article, no previous mission has successfully combined hardware-accelerated AI processing on hyperspectral imagery, near RTID over ISL, and autonomous scheduling in one spacecraft system, let alone a CubeSat. While elements of the dynamic, intelligent, and interconnected EO system paradigm presented here have been discussed and in some cases demonstrated in previous work, CogniSAT-6 is the first system to integrate these elements into one platform.

### III. MISSION OVERVIEW AND CONCEPT OF OPERATIONS

As previously stated, CogniSAT-6 has three payloads: the Simera Sense HyperScape100 hyperspectral imager, a near real-time communication payload in the form of an ISL, and the CogniSAT-XE2 AI and computer vision edge computing processor.

The HyperScape100 is a pushbroom imager that can capture up to 32 spectral bands (selectable from over 1000 bands available) with a GSD of 4.75 m at 500 km [66].

The CogniSAT-XE2 processing board is built around the Intel Movidius Myriad X VPU, which has been verified for use in space applications in previous work [67], [68], [69]. CogniSAT-XE2 is further described in Section IV-A. All payloads, as well as the X- and S-band communication subsystems, interface to the main On Board Computer (OBC). A simplified system diagram is presented in Fig. 2.

The mission objectives are as follows.

- 1) To deliver near real-time and persistent insights of value created using onboard AI applications applied to EO data collected in LEO.
- 2) To autonomously schedule operations onboard spacecraft based on the output of AI-based data interpretation.
- 3) To interact with the spacecraft from a consumer device in near real-time.
- 4) To provide a validation platform for new onboard AI and non-AI applications.
- 5) To provide a platform for offering commercial services to paying customers.

These mission objectives have been addressed by our Concept of Operations (CONOPS), which will be explained in this section. Note that objective 5, providing commercial services, is left out of scope for this article and will be described in future work.

The initial neural network-based application that has been developed for CogniSAT-6 to execute these CONOPS is a ship detection application, based on a segmentation model. This

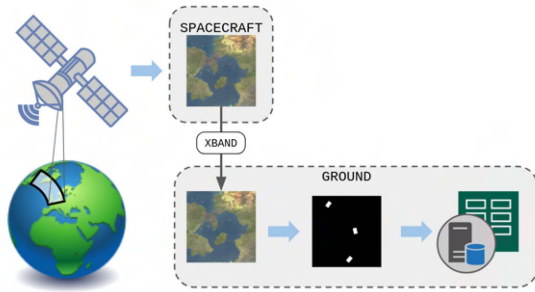


Fig. 3. Concept of Operations for nonreal-time delivery of EO-based insights for current EO systems.

application is not detailed here, as it should be considered that the system is application agnostic and can be adapted to any feature detection pipeline compatible with the chosen sensor. The authors intend to develop and upload other feature detection applications throughout the mission in addition to the ship detection application and test these applications within the CONOPS presented below. Furthermore, the operational paradigm presented here can be applied to other sensors and spacecraft, therefore the utilized platform is only described at a high level.

#### A. (Near) RTID

As previously established, current EO spacecraft require a line of sight of a ground station to establish a communication link. Furthermore, this ground station needs to be available to the spacecraft. These constraints can lead to significant latency between image capture and delivery to ground (depending on the number and location of ground stations). Furthermore, these systems do not scale to constellation scale [3], and cannot accommodate the rapid increase of data generated by modern EO imagers [4]. Clearly, this type of system does not meet the first mission objective: insights of value are neither delivered in near real-time nor can this solution deliver persistence by scaling the number of spacecraft in a constellation to sufficient numbers.

The current method of alert creation by EO systems is shown in Fig. 3. After image capture, data are downlinked to the ground when possible, where this data is processed to extract relevant information. This information is stored in a database for distribution to end users.

CogniSAT-6 changes this paradigm by moving the data processing operations onboard the spacecraft and utilizing near real-time communications to distribute the extracted information. This CONOP is shown in Fig. 4. Information is extracted from raw data and stored on board in a database. Since this information has orders of magnitude smaller data volume than raw data, an ISL can be used to transmit information to ground. These data links are typically very limited in bandwidth but have the (near) continuous availability required for near real-time delivery of information during operations.

Delivering near real-time insights of value from EO data is a topic that has been frequently covered in literature recently. Examples of valuable near real-time alerts are: wild-fire detection [70], [71], ship detection and extreme weather

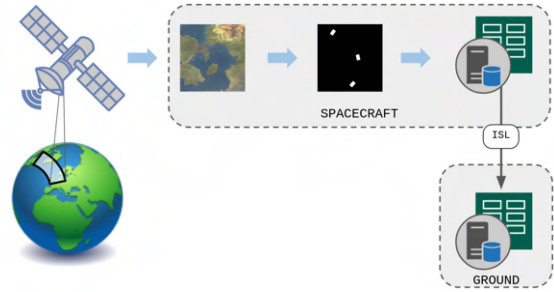


Fig. 4. Concept of Operations for delivery of near real-time EO-based insights for AI-centric EO systems.

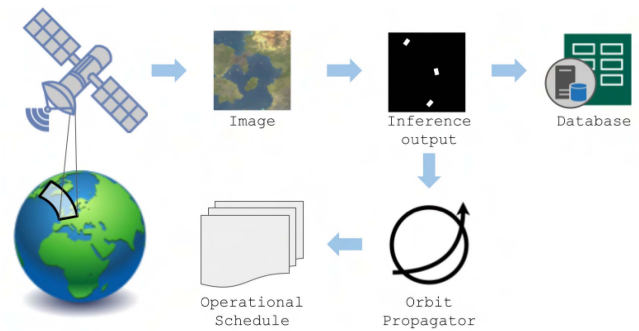


Fig. 5. Functional flow for autonomous scheduling CONOP for CogniSAT-6. Note that all steps presented here are performed on spacecraft.

monitoring [72], flood mapping [42], [73], oil-spill detection [74], detection of Harmful Algal Blooms (HABs) [75], methane emission detection [76], volcanic eruption detection [77], and change detection for disaster management [78].

As stated above, the initial operations of CogniSAT-6 will leverage Ubotica's ship detection application. Output from this application will provide geolocated coordinates of identified ships in an Earth reference frame (longitude, latitude), alongside details on length, width, orientation, and detection confidence. CogniSAT-6 has been designed to deliver insights within 5 min from image capture to an end user.

#### B. Autonomous Scheduling (ASCH)

To meet our second mission objective, CogniSAT-6 will autonomously schedule acquisitions based on the detection of features of interest without the need for intervention from ground operators. This operational concept has been previously expounded in [2]. A visual representation of the functional flow of this concept is provided in Fig. 5.

The concept of operations for this capability can be summarized as follows:

- 1) The spacecraft flies over a predefined region of interest.
- 2) An image is captured at the scheduled location using the planned system state.
- 3) The image is processed on board the spacecraft to detect and subsequently geolocate features of interest (e.g., ships).
- 4) If a feature of interest is found, results are stored and an orbit propagator is called. If no feature of interest is found, no action is taken and results are stored.

- 5) [Optional] If a feature of interest is found, this feature is sent over the ISL directly to the ground to inform mission control.
- 6) The propagator determines the next opportunity to capture the location of the feature of interest and the required spacecraft attitude.
- 7) A follow-up image acquisition is scheduled, including the required spacecraft attitude and time of acquisition.
- 8) The follow-up image acquisition is executed.
- 9) [Optional] The follow-up image is processed on board the spacecraft to detect and subsequently geolocate features of interest (e.g., ships).

As with RTID, in the initial operational phase, a ship detection application is used. The system will pass to the onboard orbit propagator the location of the largest detected ship, determined from a single acquisition with a confidence level exceeding 80%. In addition to feature detection applications that detect features other than ships, subsequent operational phases envisage more intricate acquisition logic including sophisticated operational constraints like location-based filtering (e.g., monitoring specific areas), ship orientation-based filtering, ship concentration-based filtering, and others.

While the utility of ASCH is arguably limited with one spacecraft due to limited revisit rates, the proposed system can extend to a SensorWeb scenario. In this setup, coordinates of the identified feature of interest are sent via ISL to CogniSAT-6. These coordinates are used as input for its onboard orbit propagator, expediting the acquisition of this location. Such demonstrations would validate the utility of this concept, and such demonstration opportunities are under investigation by the authors.

### C. Interactive Satellite (ISAT)

For the third mission objective, the ISAT application will utilize the ISL to enable duplex communication between a ground node (such as an end-user device) and the spacecraft. An operational duty cycle for this CONOP starts with the invocation of the ISAT application on spacecraft. Upon starting, the application commences with the downlinking of messages containing a high-level description of the features detected in the latest imaging sessions. For example, in the ship detection use case, the initial ISL transmission will encompass a summary of onboard inference results, categorized by the port from which they are obtained. The on-ground system operates as an always-on system, enabling continuous retrieval of messages.

When a user connects to the on-ground server with a device, the downlinked messages transition from being stored to being displayed on the graphical user interface (GUI) on the user's device. Next, the end user can request additional information directly from the spacecraft. When a ground-based request is received by the spacecraft, additional information can be returned to the end user detailing features per image acquisition and providing comprehensive information about a specific feature.

This application will demonstrate a communication interface that enables many use cases besides near real-time user interaction, such as rapid tasking (which in certain cases requires a persistent communication link) or SensorWeb use cases. The

demonstration will verify our API's for communicating with CogniSAT-6, persistently in both uplink and downlink direction. These API's can be used to build additional capabilities for the spacecraft, which will be detailed in future work.

### D. Validation Platform

In addition to the specific CONOPS above, CogniSAT-6 is intended as a validation platform for future technologies. A key system characteristic required for the validation of new technologies is the ability to a) enable developers to test and iterate on new software for the system and b) apply maintenance to the system by updating existing software and uploading new software.

By developing a representative on-ground flatsat that is remotely accessible to developers, iterative development, and verification of operational software is possible throughout the mission lifetime without risk to the spacecraft. In addition to this flatsat, development of AI and CV pipelines is enabled by a cloud-based hardware testing platform, allowing third-party developers to develop and verify custom neural networks and computer vision pipelines on engineering hardware. Data budgets of the system allow the regular uplink of new software and neural networks.

Several novel onboard experiments have been planned for execution on the spacecraft, which will be published in future work.

## IV. DATA PROCESSING OVERVIEW

CogniSAT-6 is a data processing system that requires novel hardware and software to meet its requirements. These novel elements are described in this section.

### A. CogniSAT-XE2

CogniSAT-6 flies the CogniSAT-XE2 high-performance AI compute engine, which performs all onboard AI inference for the mission. This platform is a PC/104 form factor board (0.15U) that is ideally suited to the 6U form factor of CogniSAT-6. Weighing 65g, the platform provides Ethernet, Universal Serial Bus (USB), Controller Area Network (CAN), and general-purpose input/output (GPIO) communications interfaces to support data communications, command and control, and critical issue identification, respectively. All onboard computations on the XE2 are performed on an Intel Movidius Myriad X VPU. This is a low-power System on Chip (SoC) with application-specific hardware blocks to accelerate layer computations within inference, and 16 Very Long Instruction Word (VLIW) vector engines for layer compute offloading during inference. The peak power consumption of the XE2 during inference with the ship segmentation network used in the mission is 3.5 W, and in low-power standby mode, the board draws only 15 mW. The CogniSAT-XE2 engineering model is shown in Fig. 6.

A custom enclosure provides mechanical mounting and an element of radiation protection. The payload power interface is a 5 V switched and payload-software-controllable supply from the satellite Electrical Power System (EPS) supplied via dual redundant connections to the PC104 header array on the XE2.

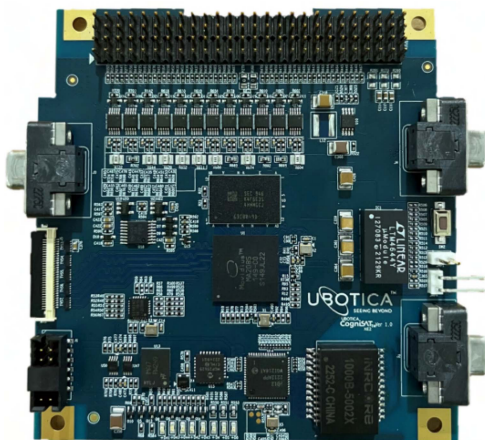


Fig. 6. Engineering model of CogniSAT-XE2.

The XE2 is controlled via an application, CogniSatApp, which executes on the OBC. This software manages all inference requests, operating in a client–server architecture, wherein the XE2 operates as an inference server that responds to inference requests from the OBC.

On power-up, the XE2 boots from onboard flash memory, automatically loading a secondary bootloader that configures the Ethernet interface and waits to receive the inference application from CogniSatApp. Once received over Ethernet, the application firmware is booted and the board is ready to receive a neural network or Pipeline Configuration Descriptor (PCD), and subsequent inference requests.

Health monitoring is implemented via CubeSat Space Protocol (CSP) status commands over CAN, with lower-level status information acquired through the OBC monitoring of a 1 Hz logic-level heartbeat signal from the XE2. Board errors, for example due to single event effects (SEEs), are managed via an XE2 reboot. A logic level, dual redundant, active high enable signal can be pulled low via the payload software running on the OBC to hard reset the Myriad X on the XE2. This same signal is used to place the XE2 in a low-power mode. Overcurrent thresholds were carefully determined per rail by monitoring current levels on the XE2 power rails during ground testing and adding margin. Overcurrent functionality can be dynamically enabled and disabled during board operation via CSP messages from the OBC. Overcurrent events are automatically handled via onboard power cycling, with repowering timed from a monostable multivibrator. Any such overcurrent events are logged by the OBC through monitoring of a dual redundant and logic level active high output straight from the XE2.

### B. Software Functional Flow

The data processing software is controlled by a software orchestrator called a manager. This manager is invoked by flight software, as shown in Fig. 7. The manager is in charge of orchestrating the different functional blocks of the application pipeline. The manager is written in Python and invokes optimized and compiled C++ applications that perform onboard data processing. In addition to orchestrating the operations of the data

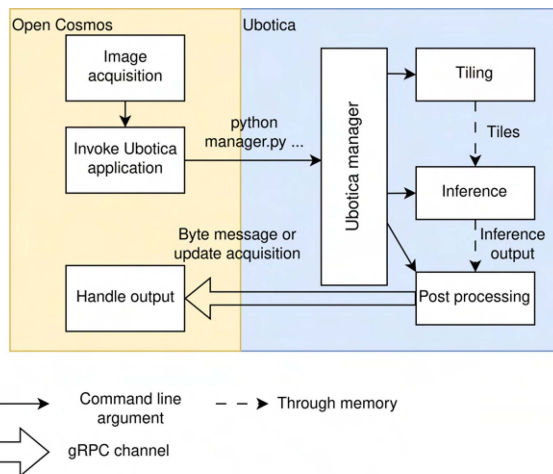


Fig. 7. High-level software architecture depicting both flight software and data processing software.

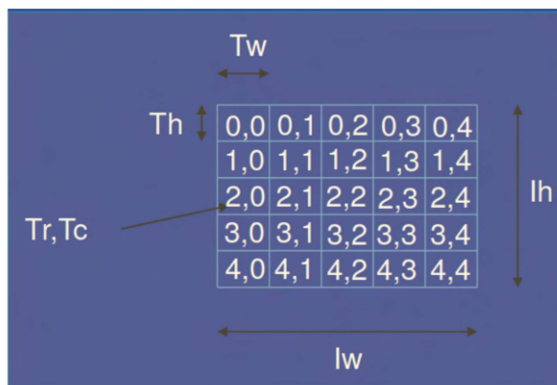


Fig. 8. Mapping of an image to individual tiles.  $T_w$  indicates Tile width,  $T_h$  indicates tile height,  $T_r$  indicates tile row,  $T_c$  indicates tile column,  $I_h$  indicates image height, and  $I_w$  indicates image width.

processing flow, the manager also handles errors returned from the invoked applications.

The software functional flow has been designed to be modular by reusing functional blocks that are shared between CONOPS. Depending on the application, tiling and postprocessing may run on the OBC or CogniSAT-XE2.

The software flow begins with the image acquisition by the spacecraft, using the hyperspectral imager. After image acquisition, the manager is invoked, triggering the tiler. The tiling application parses and tiles the raw incoming image data from a hyperspectral imager into the expected image format, complying with the input size limitations of the pipeline. Parameters like tile height, width, bit depth, and the number of bands are specified via a JSON file passed to the tiling application. The mapping of an image to individual tiles is shown in Fig. 8.

The CogniSAT-XE2 board is controlled by CogniSatApp, an application running on the OBC that enables the execution of AI inference and image processing operations. A visual representation of the input to CogniSatApp and the outputs generated is shown in Fig. 9.

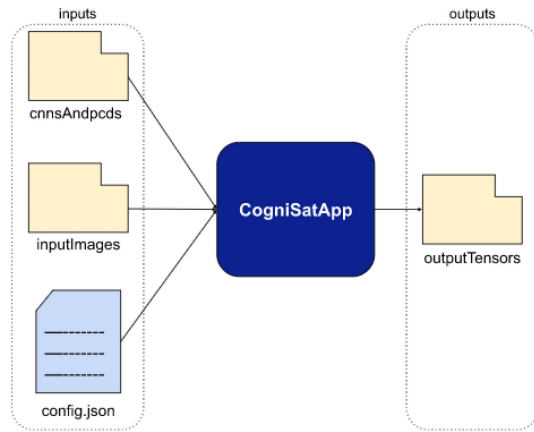


Fig. 9. Visual representation of CogniSatApp dataflow.

CogniSatApp makes use of JavaScript Object Notation (JSON) configuration files to allow for easy deployment of new applications without the need to write/alter any code, and without the need for any compilation. The design of the CogniSatApp addresses pre- and postprocessing generically, allowing for zero or multiple pre- and postprocessing operations to be deployed in hardware.

Image processing pipelines to be executed require a PCD file that describes the pipelines in binary format with the extension. pcd. Similarly, each neural network to be executed requires a binary file describing that network. Neural network binary large object (BLOB) files are generated by the Intel OpenVINO tool and have the extension. unn. At least one. pcd file or one. unn file is required to execute CogniSatApp.

The postprocessing of the output tensors is performed in parallel with inference to speed up execution times. Depending on the CONOP that is performed, the postprocessing software block optionally initiates the ISL connection. Once output tensors start arriving at the postprocessing software block output files are immediately handled to improve latency.

For RTID, an ISL downlink is issued immediately when sufficient data is available, reducing the latency induced by waiting for full inference output. The postprocessing uses a gRPC channel interface with flight software to queue generated ISL messages for transmission.

For ASCH, after the completion of inference on the entire acquisition, the most relevant feature is chosen as a target for the next acquisition opportunity. As previously stated, for initial demonstrations the most relevant feature is set as the largest detected ship, with a confidence level exceeding 80%. The next acquisition opportunity is autonomously determined by the onboard orbit propagator that is part of the flight software. The autonomously scheduled acquisition can be transmitted over ISL using the gRPC interface to inform mission control.

During ISAT operations, the parsing and processing of incoming and outgoing ISL messages is handled by the manager application. Since the ISAT functional flow does not require any real-time data processing but only retrieves information from an onboard database on request, tiling, inference, and postprocessing applications are not invoked.

## V. ETHICAL FRAMEWORK

Autonomous systems such as the one described here are moral agents that could encounter ethical dilemmas during their application. For example, if the system detects both a forest fire and an oil leak but can only reschedule an acquisition for either of the two features of interest, the decision made by the autonomous system needs to be made on an ethical basis. One could consider this a version of the famous trolley problem [79]. As stated by Tatem et al. in [1]: “Such a resource [near real-time EO] potentially enables revolutionary studies involving the global tracking of ocean life, animals and human movement, which could facilitate, for instance, real-time disease epidemic models, dynamic traffic control and reactive conservation, but it also raises significant security and privacy concerns.” A similar observation of the need for additional work to define a new perspective on the application of autonomous systems in space activities is made by Martin and Freeland in [80]. Hence, the ethics of these systems must be considered now.

Winfield et al. [81] identified two branches in the field of robot and AI ethics. First, AI ethics or robot ethics is concerned with the ethical application of such systems in society. Second, machine ethics is concerned with the question of how systems such as the one presented in this article can behave ethically. We will consider the former ethical branch here.

Moor defines machine ethics and methods for incorporating ethics in machines in [82]. Based on Moor’s definitions, the technology presented in this article should be considered an implicit ethical agent and used in society as such, by constraining the system operations to avoid unethical outcomes. To do so, an ethical framework is required. At a high level, unethical outcomes need to be defined to mitigate those outcomes.

Kochupillai et al. [83] defined six fundamental ethical values for the application of AI in EO systems. For each of these values, the authors define an extensive set of ethical issues and guidelines, with examples in the context of “AI4EO” based on literature and discussions with peers. These ethical values and associated examples have been used to derive an ethical framework for CogniSAT-6, which is an appendix to this article.

It should be emphasized that this ethical framework should be considered as a starting point, to be further developed and iterated upon by experts, the scientific community, and society as a whole. We expect that autonomous EO spacecraft, such as CogniSAT-6, will become widely used in society in the coming decades, and therefore stress the importance of practical and sound research to ensure the ethical application of these systems.

## VI. EARLY RESULTS AND FUNCTIONAL VERIFICATION OF RTID

At the time of writing, the spacecraft has successfully completed Launch and Early Operations (LEOP) and has been going through commissioning of its onboard systems and software. As part of these procedures, the RTID dataflow has been verified end-to-end. CogniSAT-6 has acquired a full 32-band hyperspectral image of roughly 1000 km<sup>2</sup> at Galveston, Texas, USA, processed this image onboard the spacecraft and sent the generated insights over ISL to ground. The image and the



Fig. 10. Raw (Level 0) CogniSAT-6 image of Galveston, Texas, USA. Red boxes indicate ship detections received on ground. Since this is raw data with enhanced contrast for visualization purposes, some image artefacts such as band-misalignment and striping are visible.

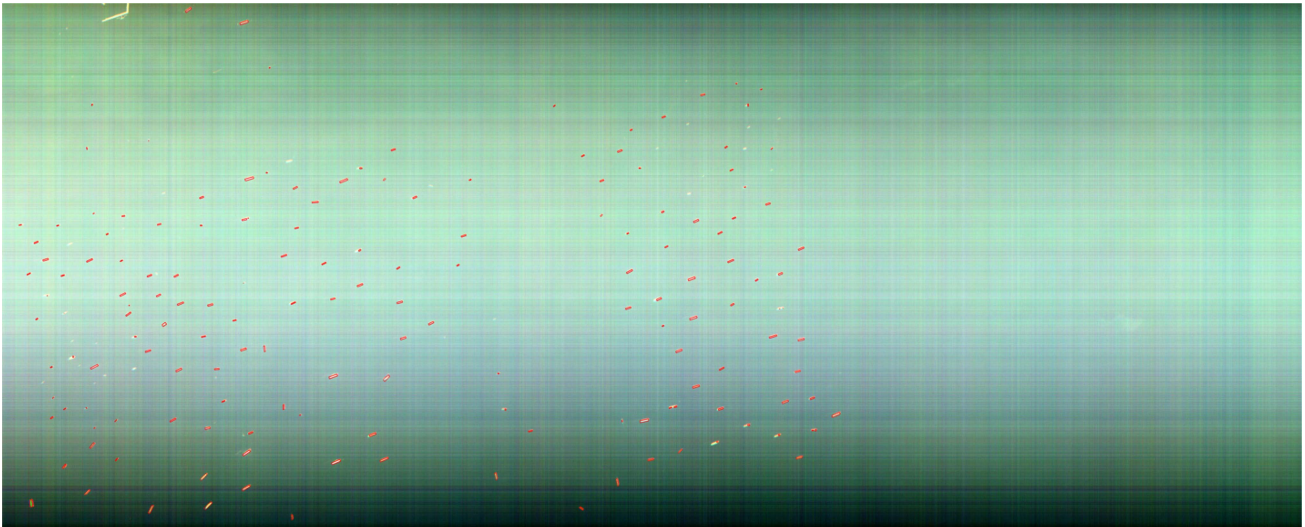


Fig. 11. Raw (Level 0) CogniSAT-6 image of Khor Fakkan, UAE. Red boxes indicate ship detections received on ground. Since this is raw data with enhanced contrast for visualization purposes, some image artefacts such as band-misalignment and striping are visible.

received detections (shown in red) are shown in Fig. 10. An additional RTID run, successfully performed a day later above Khor Fakkan, UAE, is shown in Fig. 11.

This test verifies the functionality of the spacecraft onboard data flow for the RTID CONOP. System performance in both detection capability as well as end-to-end timing will be verified further and improved where necessary over the coming months. Current processing time onboard the spacecraft for both images after image transfer to the OBC is below 120 s, well within timing budgets. Both image transfer time and ISL latency remain to be fully verified at the time of publication, as the performed tests had high system margins on both steps for testing purposes.

The performance of the current neural network remains to be improved. Some ships are not detected by the network (false negatives, see Fig. 12), and some land features are detected as ships (false positives, see Fig. 13). This is expected, as the model used in these verification tests was an early model not trained

on any data from the spacecraft itself and performs inference on level 0 (raw) data on spacecraft. The process used for training and improvement of this and other models will be covered in future work.

## VII. DISCUSSION

The technology integrated into CogniSAT-6 will transform what EO systems can do by both reducing the operating cost of these systems and increasing the amount of value provided by these systems.

The operating cost of EO systems is significantly reduced by prioritizing or filtering data on board the spacecraft. By extracting, storing, and downlinking information rather than raw data, system efficiencies are dramatically increased.

The value created by the EO system is increased by up to an order of magnitude by increasing the speed of delivery of

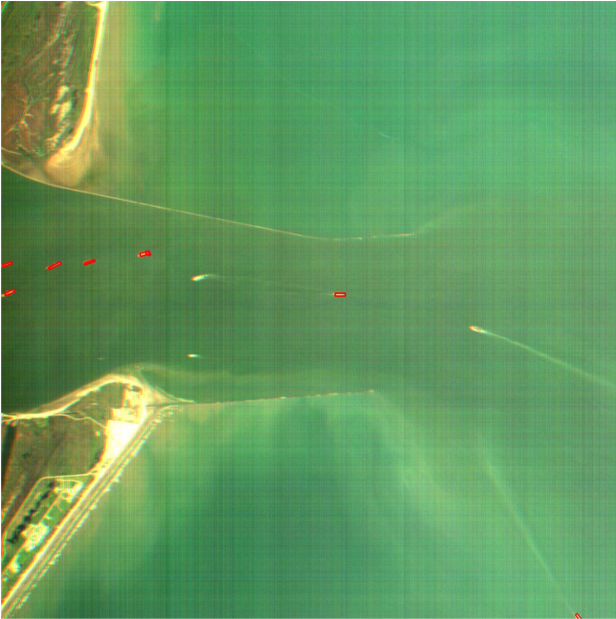


Fig. 12. Crop of the first image (of Galveston, Texas) analysed using a neural network on board with results relayed over ISL. Red boxes indicate the ship detections received on ground. Some false negative detections are visible. Since this is level 0 data with enhanced contrast for visualisation purposes, some image artefacts such as band-misalignment and striping are visible.

information, by capturing more information of higher value, and by responding more quickly to dynamic events. By delivering information to end users and responding to user requests in near real-time, the inherent value of this information is increased. For example, receiving an alert within 5 min of an otherwise undetected forest fire significantly improves the response time of authorities. Value within the captured data is ensured by applying AI to detect the presence of valuable information. Autonomous scheduling and persistent communication allow spacecraft to respond quickly to dynamic events.

In addition to near real-time insights, the technology presented here enables *persistent* insights. Persistence of insights is defined as having a minimal time between insights of a single location of interest. This can only be achieved by often repeated measurements of a location of interest, requiring multiple spacecraft. Achieving the required constellation size for persistence necessitates low unit costs per spacecraft. Second, operations need to be autonomously scheduled to enable this system scale and to decrease the effective revisit time of features of interest. CogniSAT-6 shows that these characteristics can be integrated into a low-cost spacecraft, paving the way for the low-cost constellations required for persistent insights.

An important element of the technology presented here is the maintainability and ability to improve the system in flight. To this end, the software can be updated in flight and iterative development is made possible by the availability of a flatsat. The system performance can be iteratively improved over time by updating neural networks and processing pipelines. Furthermore, within the constraints of the flown hardware, entirely new functionalities can be uploaded to the spacecraft over the mission lifetime.



Fig. 13. Crop of the first image (of Galveston, Texas) analysed using a neural network on board with results relayed over ISL. Red boxes indicate the ship detections received on ground. Two false positive detections are visible. Since this is level 0 data with enhanced contrast for visualisation purposes, some image artefacts such as band-misalignment and striping are visible.

Throughout the mission lifetime, the performance and reliability of the onboard AI will be extensively monitored and analyzed. While operations will only send down information extracted from raw data in near real-time, all acquired raw data will be sent down at a later time during ground station passes to both enable this performance analysis as well as further development of the onboard software and AI. For autonomous scheduling, AI inference results and scheduled operations will likewise be verified on the ground. By carefully monitoring performance over time, we aim to validate the use of the technologies presented here in prolonged operations. The results of these activities will be published in future work.

## VIII. CONCLUSION

EO has tremendous potential to benefit mankind and greatly enhance how we manage our environment, our security, and our economies, helping to address some of the world's greatest challenges. However, EO does not realize this potential today. Spacecraft system design has historically been limited by a lack of capable computing resources. The advent of more powerful edge computing capabilities enables several new operational concepts that were not feasible until now. While these concepts are not necessarily new, they have not been combined in one low-cost platform, nor have they been taken out of the realm of demonstration and to the reality of scalable and repeated utilization in *real use cases*. CogniSAT-6 will, for the first time, take these concepts from demonstration to utilization. The spacecraft marks the beginning of a new era of EO systems: autonomous and collaborative robots that interpret and curate data,

make autonomous operational decisions, and can communicate bidirectionally in near real-time with other spacecraft and end users. Not only will systems like CogniSAT-6 reduce costs, but they will also provide significantly more value to end users than traditional systems. As onboard computational capabilities and communication bandwidth of ISL systems further improve in the coming years, the capabilities of future systems like CogniSAT-6 will only further increase their value with respect to legacy EO systems and will finally allow a break with the current bent pipe and mow-the-lawn operational paradigms used in EO. With that, EO systems will be able to reach their full potential, improving life on Earth for all.

#### APPENDIX ETHICAL FRAMEWORK

This ethical framework has been based on work by Kochupilai et al. [83]. It should be considered a starting point and not finished work, to be further developed with all relevant stakeholders.

##### 1) Privacy

- a) The data used and generated throughout the development and operation of CogniSAT-6 shall not be tied to individual persons.
- b) Data labels shall not contain stigmatizing elements.
- c) The system shall not limit individual freedom and self-determination.
- d) Ethical risks shall be avoided with respect to privacy (e.g., by not disclosing geolocations in certain situations).
- e) The project shall comply with GDPR.
- f) Any collection, analysis, or dissemination of data must not adversely impact the fundamental human rights and welfare of people associated with or affected by this data.

##### 2) Honesty

- a) The shortcomings and limitations of the system and the accuracy of the generated predictions/insights shall be transparent to those who rely on those predictions/insights.
- b) If policy decisions are made based on the generated predictions/insights, the process to get to those predictions/insights needs to be made transparent and explainable.
- c) The accuracy and correctness of training data, underlying model presumptions and predictions/insights as well as the contextual data veracity is to be considered and tested where required.

##### 3) Integrity

- a) The system output shall have an accuracy that corresponds to claims made externally.
- b) The probability and level of error and uncertainty as well as limitations to the generated prediction/insights shall be determined and disclosed where appropriate.
- c) In the context of safety/security data governance shall be considered when making decisions as to the method, extent, and timing of publishing data.

##### 4) Fairness

- a) Appropriate measures shall be taken to ensure that *equals are treated equally*. For example, while labeling data and while making recommendations regions with similar circumstances should be treated similarly.
- b) The system shall operate in an unbiased and nondiscriminatory manner.
- c) The system data used in training algorithms shall have the appropriate diversity required for the system to function in an unbiased and nondiscriminatory manner.

##### 5) Responsibility

- a) The responsibility for ethical use of the system lies, within reason, with the operator of the system (in this case, Ubotica and Open Cosmos).
- b) Human agency and oversight shall be implemented where necessary during the development and deployment of new applications, considering the context in which these applications are to be deployed and the impact that this deployment may have on real people.

##### 6) Sustainability

- a) The development and operation of CogniSAT-6 shall limit any compromise of economic, social, or environmental sustainability. Where these sustainability prongs need to be balanced against each other, a conscious and responsible decision shall be made with respect to the implementation of this balance taking into account the ethical framework as a whole.
- b) The system shall wherever possible contribute to the achievement of the UN sustainable development goals.

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