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Multi-Asset New Observing Systems Flight Demonstration

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Abstract

NASA's New Observation System (NOS) program seeks to "involve the coordination and integration of various instruments located at different vantage points from NASA and non-NASA sources, including in orbit, airborne and even in-situ sensors to create a more dynamic and complete picture of a natural physical process." This can be seen as an evolution of prior programs in "Sensorwebs" which used data from a number of sources (space, air, in-situ, marine) to direct further sensing to most effectively track dynamic scientific phenomena such as wildfires, flooding, volcanic activity, algal blooms, and more. Concurrently, the European Space Agency (ESA) **Φ**-Lab is initiating a "virtual constellations" initiative with similar goals.

JPL is leading an effort to demonstrate these concepts leveraging the proliferation of commercial platforms in Low Earth Orbit. We describe the capabilities that we wish to demonstrate, initial progress in demonstrations, and future demonstration plans.

Keywords: remote sensing, observation scheduling, artificial intelligence, multi-agent systems, constellation operations

1. Introduction

Recent developments in the space sector are bringing new capabilities to space as well as reducing cost of said capabilities. These capabilities include:

1. proliferation of Low Earth Orbiting (LEO) platforms to improve temporal and spatial coverage and reduce cost of observation services;
2. edge computing (including "AI processors") to immediately process acquired data into knowledge;
3. improved software environments onboard spacecraft – flight of common distributions of Linux as to "spacecraft virtual machines" in which software is deployed as a container with access to well defined spacecraft interfaces and even tested in the cloud on Virtual Machines; and
4. satellite communications link to enable 24/7 low data rate on demand communications to and from the ground to enable both (a) rapid dissemination of observed events or features and (b) rapid tasking from the ground.

JPL is leading an in-space flight demonstration of NOS technologies [1] leveraging existing commercial assets from satellite providers such as: Open Cosmos, Loft, Planet, Aptos, and D-Orbit to demonstrate in space the NOS concepts. This effort includes other collaborators such as Ubotica, Hyspace and others. This demonstration will show the value added in emerging in-space capabilities including the following:

1. onboard analysis of acquired data, leveraging available onboard edge compute;
2. onboard rapid self-response, leveraging the knowledge generated from the onboard analysis to direct/reconfigure sensors on the same platform;
3. rapid notification of the ground or other assets, leveraging the knowledge from onboard analysis and 24/7 satellite communications link;

4. rapid cross-tasking of other assets, wherein insights derived on one spacecraft are used to drive tasking of another spacecraft; and
5. multi-agent systems technology to orchestrate user defined workflows across both flight and ground and also across multiple spacecraft operated by different providers.

The aspirational goal of the FAME project is to demonstrate each of the above use cases routinely for an extended period of time (e.g. 1+ year) across multiple science use cases, satellite platforms, and satellite providers. Key to this concept is a service-oriented approach to Earth Observation that enables users to request desired service workflows that are fulfilled by space providers seamlessly without direct contact required. This is enabled by a federated multi-agent systems architecture where no centralized coordination exists because operational responsibility for each set of assets lies with different institutions [2, 3] (see Figure 1).

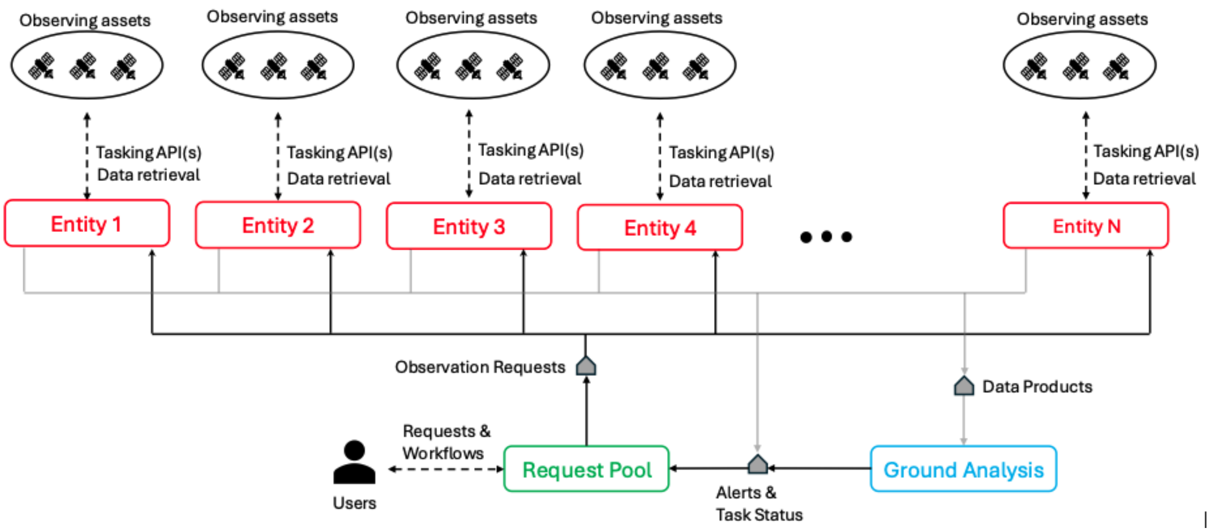

Fig. 1. Overview of a federated observation system. Operating entities get allocated requests to schedule for their observing assets based on a federated scheduler. The federated system interfaces with requests through several channels such as users, alerts, and task status and manages workflows on behalf of users.

2. Capabilities

In our demonstration, we aim to highlight a number of emerging capabilities.

Onboard Analysis includes deep learning and spectral analysis onboard processing algorithms for a range of science applications [4]. In these applications a major limiting factor is that most spacecraft have only visible spectral range imagers with a few extending in the Very Near Infra-red (VNIR) spectrum.

While flying off-line learned classifiers has significant (2004) heritage [5,6], dramatic improvements in edge computing mean that much more sophisticated onboard analysis is now possible [4]. For example, hyperspectral unmixing onboard ASE/EO-1 took hours to execute [7], now with dedicated AI/CNN hardware, CNN inference can be performed in 10s of seconds or faster. Deep learning applications include [4]: cloud screening, surface water extent (flooding/hydrology), algal bloom/ocean color, and land use. Thermal analysis for detection of volcanic activity and wildfires is also an important application although without a higher wavelength (e.g. VSWIR or TIR) such analysis is susceptible to red-edge confusion [8].

Spectral signature detection approaches [4] include spectral angle mapper, matched filters, and spectral unmixing both using deep learning / CNN hardware and traditional means such as Sequential Maximum Angle Convex Cone (SMACC). Spectral anomaly detection schemes include Reed-Xiaoli.

These key capabilities enable the spacecraft to interpret the acquired imagery onboard to glean knowledge from the imagery and therefore enable quicker action.

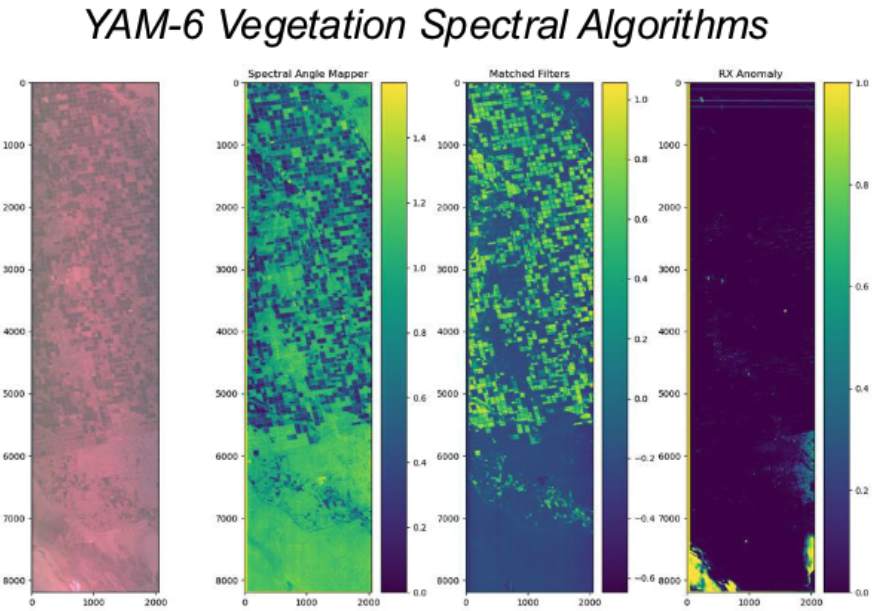

Figure 2: Examples of potential onboard analysis enabled by space edge computing. Shown is imagery acquired by the Loft YAM-6 spacecraft (visible mapping of imagery at left) with spectral analysis algorithms from left to right: Spectral Angle Mapper (vegetation signature), Matched Filters (vegetation signature), and Reed-Xiaoli Anomaly Products.

Dynamic Targeting is a capability in which a single spacecraft uses onboard analysis of acquired data to configure or direct sensing on the same spacecraft [9] within the same overflight. In Low Earth Orbit with a ground track velocity of 7.5km/s at 500 km altitude a 45-50 degree lookahead requires a response timeline of 30-60 seconds. Such capability is already in operations on JAXA's TANSO-FTS instrument onboard the GoSAT2 mission [10] and has also been proposed for hunting deep convective ice storms as part of the SMICES mission concept [11] and also for study of planetary Boundary Layer (PBL) phenomena [12]. A particularly intriguing concept is where a satellite directly receives data continuously broadcast by other satellites (as is common for weather satellites) [13]. Such a concept could allow for lookahead significantly in advance of the satellite orbit.

Cross-tasking aka Sensorweb is a capability where data from one sensor (satellite or other) is analyzed to drive tasking of another satellite [14]. Sensorwebs have proven effective for volcanology [15], flooding [16], wildfires [17] and even using commercial assets [8]. The NOS demonstration will demonstrate sensorweb technologies made even more effective by edge computing and intersatellite links that will make notifications more rapid.

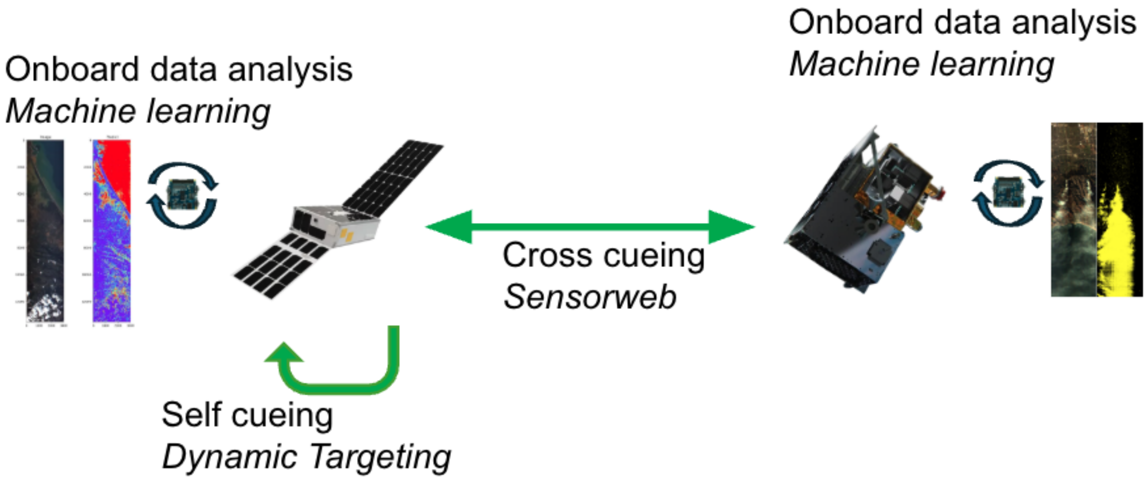

Figure 3: Onboard Analysis, Self cueing (Dynamic Targeting), Cross cueing (Sensorweb) are all key elements in the New Observing Systems (NOS) flight demonstration.

Federated Scheduling is a capability in which service requests can be made at a service portal and a distributed scheduling protocol negotiates allocation of said service (e.g. an observation or series of observations) with multiple satellite providers transparent to the end user. For more details on this approach see the companion paper in these proceedings [18]. Figure 1 above highlights how Federated Scheduling enables greater access to space services by extending access seamlessly to multiple providers. Figure 4 shows how automated federated scheduling allows for service requests that may correspond to multiple observations to be handled by the scheduler(s). Figure 5 highlights how federated scheduling automatically handles outcomes such as specific observations not executing (for reasons such as pre-emption, operations anomalies, or even weather) and automatically issues replacement requests.

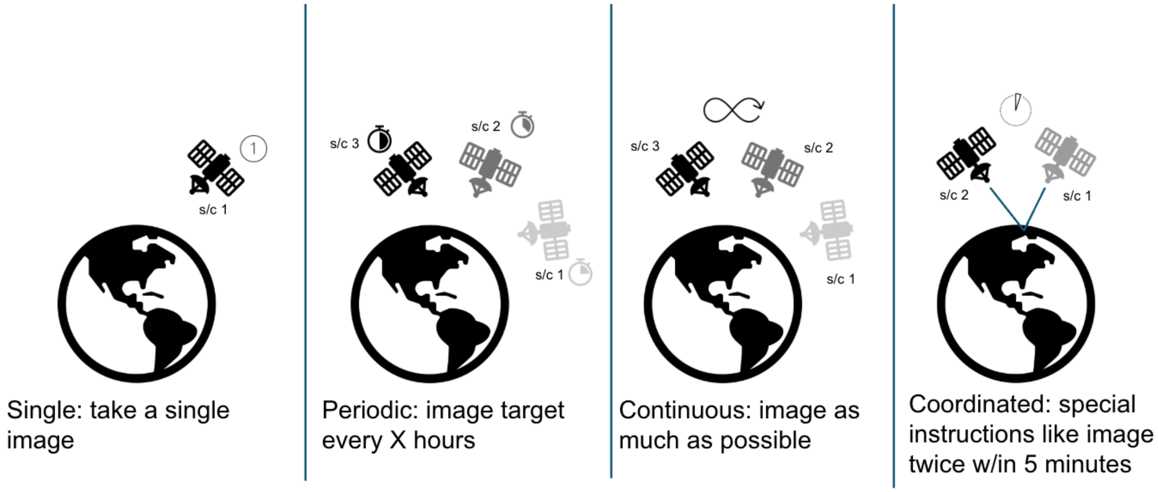

Figure 4: Campaign requests - aggregations of individual observations

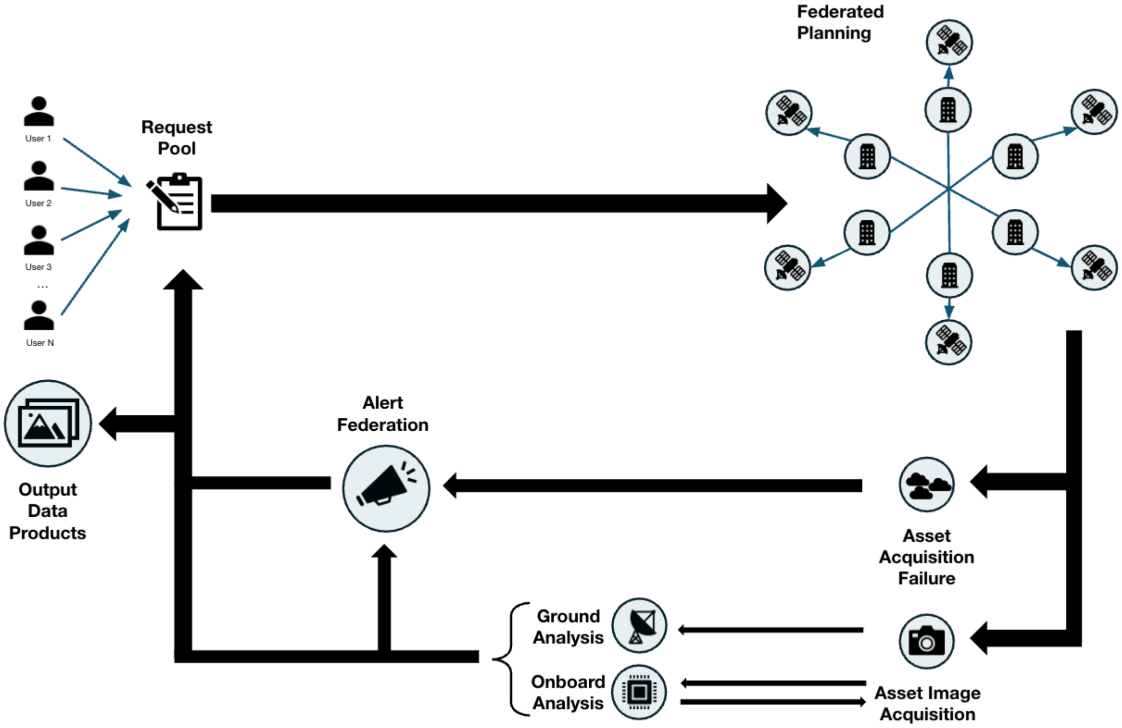

Figure 5: Federated Scheduling abstracts space observation to service fulfillment

Workflow Orchestration is a capability tightly linked to federated scheduling in which workflows (e.g. acquisitions, processing of said acquisitions, issuance of alerts, triggering additional observations contingent on results of said processing, combinations of observations periodic observations etc.) can be submitted to a service portal and the service portal automatically manages the workflow distributing the lower level activities (service requests) to appropriate satellites and computation (either onboard or ground) and ensures timely delivery of end user products. Figure 6 illustrates a science workflow for detecting volcanic activity, acquiring data from satellite observations, and generation of science measurements. Such a workflow can monitor reported activity from multiple sources, initiate observation requests (including aggregate requests as indicated earlier), robustly re-request if needed, and execute processing from direct measurements to derived quantities, delivering science data products to end users. These are the types of workflows used in [8,15,16,17] the advancement would be to enable specification in standard tools such as Jupyter notebooks [19].

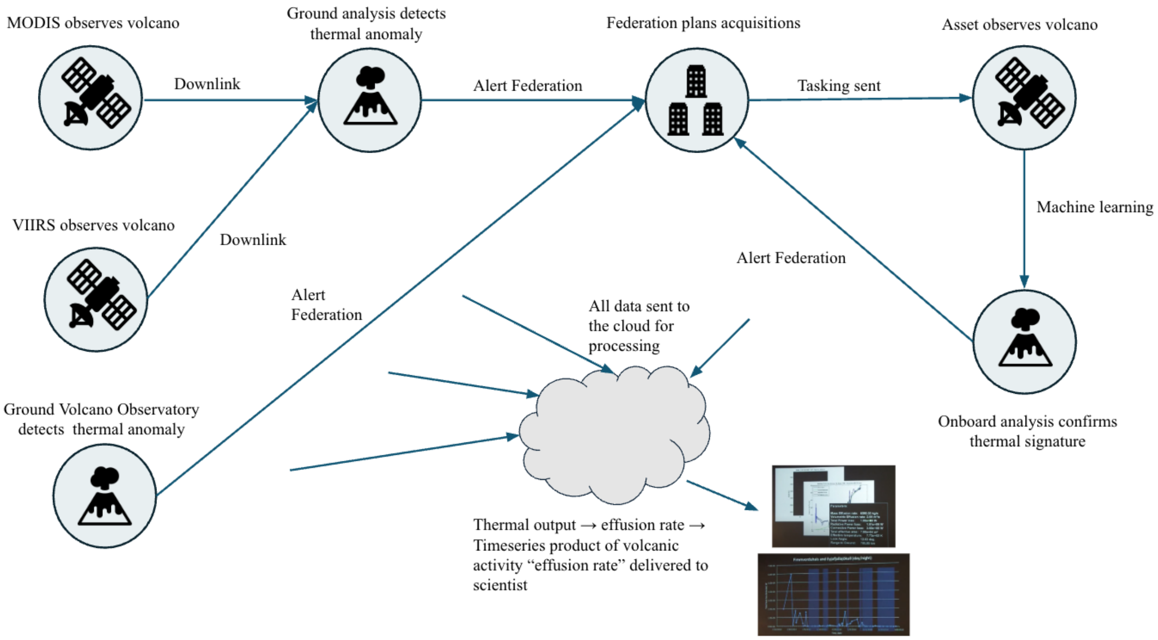

Figure 6: Sample Workflow – Detection of volcanic activity → thermal output timeseries → effusion rate timeseries

3. Science Use Cases

Another goal of the NOS flight demonstration is to demonstrate as many science use cases as possible. The principal limitation on science use cases is that most commercial satellite platforms with edge computing have primarily visible range sensors (e.g. not VSWIR or SAR). However we plan to engage VSWIR and SAR instruments likely as “task only” without onboard processing/analysis. Likely VSWIR assets would include EMIT and Planet’s Tanager and SAR assets would include commercial assets such as Capella, ICEye, and Umbra.

Cloud screening and avoidance (Applicable to many). Cloud screening is a key DT application because many observation types are compromised due to cloud obstruction. Onboard cloud screening is already in use for AVIRIS and EMIT [20] reactively and TANSO-FTS-2 [10] proactively. We will train VIS cloud detectors for most assets, as well as VIS + TIR models that leverage more information to improve cloud detection performance when possible. Many atmospheric retrieval missions (e.g. TANSO-FTS-2) are particularly vulnerable to cloud contamination. For example, OCO-3 retrievals in certain regions and seasons are less than 10% [21] and some areas (e.g. Amazon, Central Africa, Borneo) in cloudy seasons for large size pixels retrieval rates are closer to 1%. Indeed, the frequency of clouds can dramatically hamper atmospheric retrievals for large pixels because as the size of pixels increases the chance of cloud free pixels drops dramatically [22]. Agile, intelligent cloud avoiding sensors [23] offer the potential to improve such yields.

Storm targeting (Atmosphere). Here clouds can serve as a proxy for ice clouds and storms of interest or more complex features can be extracted from satellite and other data sources like GPM-IMERG [9]. An exemplar DT application is the SMICES mission concept [11]. Further work will study onboard analysis for cloud structure and convection.

Algal bloom (Carbon & Ecosystems, Oceans). Numerous water quality and science applications exist that can be studied with VIS sensors. We will create VIS detectors to monitor algal blooms, relevant to water resources, human health, and species management.

Thermal analysis (Atmosphere, Earth Surface & Interior) [15, 17]. This application will detect and measure volcano eruptions and wildfires. VIS only measurements are limited in utility, but several assets will have VIS+TIR and VSWIR for greater utility.

Flooding/surface water extent (Flooding Multiple Use Cases) [16]. This will be useful for many hydrology applications, such as monitoring disasters due to hurricanes, storms, and severe rain and snow. We will use both VIS (with cloud cover issues) as well as X-band SAR for study.

Planetary Boundary Layer (PBL) science (Atmosphere). We will work to refine use cases for inclusion in the DT flight demonstration [12]. Although available instruments are limited for PBL science, we will investigate learning models that could predict phenomena of interest (e.g., convective mass flux) using the available sensors.

We will develop algorithms to broadly detect and characterize anomalies in imagery and spectral data. This will be achieved through the fusion of multiple data sources with varying spatial and temporal resolutions. To address "anomalous" events we will develop domain agnostic saliency mining capabilities at different levels to consider spectral, morphological, and when available, multi-temporal features. The algorithms will be resilient and generalizable to the presence of different conditions (e.g., solar zenith angle).

4. Status

We are currently in implementation for demonstration with three (3) spacecraft: CogniSAT-6/HAMMER (Ubotica/Open Cosmos) [24], ION SCV-004 (D-Orbit/Hyspace), and YAM-6 (Loft/Hyspace). Shown below are early results with classification onboard CogniSAT-6 and spectral algorithms onboard D-Orbit ION-SCV 004.

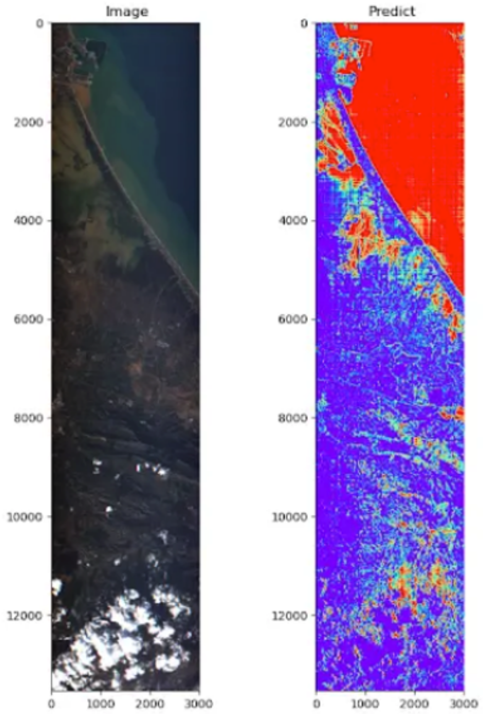

Figure 7: 02 November 2024 Surface Water Extent (SWE) from Flight on CogniSAT-6
(left) color image (Ubotica Imagery All Rights Reserved)
(right) SWE: Red = water, purple = non-water

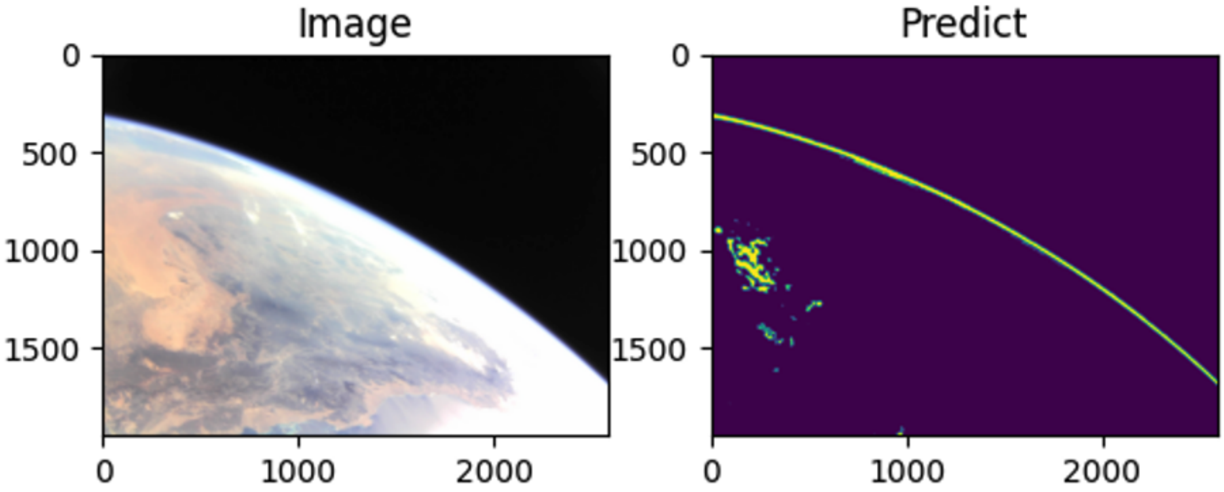

Figure 8: February 2024 Reed-Xiaoli Anomaly Detection from ION SCV 004 (D-Orbit, Skyserve.ai) (left) color image (Imagery D-Orbit All Rights Reserved.) (right) anomaly score where yellow = high anomaly

We are in earlier stages with additional spacecraft and providers: Aries SN1 (Ubotica/APEX), Kanyini (Smartsat Cooperative Research Center), SOWA(SmartRev, Hyspace), multiple (Aptos, Cryptosat) and Phi-Sat-2 (ESA, Open Cosmos).

We are also integrating the above with additional earth observation assets as part of a longstanding "sensorweb" effort. This includes several missions and constellations: ECOSTRESS, EMIT, and Planet (Dove and Skysat are currently integrated with Tanager and Pelican anticipated). Large scale mapping missions/instruments such as NASA: MODIS and NOAA VIIRS and ESA Sentinel-2 are also incorporated.

5. Conclusion

We have described an effort in progress to demonstrate New Observing Systems (NOS) capability for Earth Science. NOS seeks to leverage advances in space capabilities such as proliferated spacecraft, edge computing, intersatellite link, as well as information technologies such as artificial intelligence, machine learning, and multi-agent systems to enable unique and cheaper measurements. We have described preliminary results as well as additional spacecraft demonstrations in terms of scale/assets and capabilities.

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