Automated Operation of Multiple Payloads on Agile MicroSat (AMS)

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ABSTRACT

The Agile MicroSat (AMS) is a 6U CubeSat designed to operate in very low-Earth orbit (VLEO), an orbit which enables a higher ground resolution given a particular optical sensing aperture. AMS was developed by MIT Lincoln Laboratory in collaboration with Blue Canyon Technologies LLC and Enpulsion GmbH. AMS is hosting three disparate payloads: an indium field effect electric propulsion (FEEP) thruster to change and maintain orbit; a laser demonstration payload called Beacon for adaptive optics experimentation; and a camera payload for visible-spectrum imaging. In order to fully exercise the capability of each payload, the AMS operations team has developed an automated end-to-end processing pipeline which handles experiment scheduling subject to constraints, upload of commands and satellite state estimates to our mission partner BCT, and download and ingest of telemetry for operations planning and the creation of data products. An example product includes a change detection algorithm and image publication workflow, using camera images to detect disaster damage. These payload operation tools have enabled daily interleaved payload operations with minimal manual overhead since the AMS launch on SpaceX's Transporter 5 mission on May 25th, 2022. This paper will describe the architecture of our processing pipeline, mission outcomes, and lessons learned.

INTRODUCTION

Very low-Earth orbit (VLEO), defined as below 450km, has historically been an attractive orbit as it enables a higher ground resolution given a particular optical sensing aperture, thus allowing for a smaller overall sensor and smaller size, weight, and power (SWaP) as compared to a sensor deployed at a higher altitude. However, with the lower altitude of VLEO comes the challenge of significant atmospheric drag, which necessitates the use of propulsion in order to maintain altitude.[1] To date, there have been only two satellites (excluding space stations) with sustained VLEO operations: the European Space Agency's (ESA) Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)[2], launched in 2009; and the Japan Aerospace Exploration Agency's (JAXA) Super Low Altitude Test Satellite (SLATS/Tsubame)[3], launched in 2017. Both were fairly large (400kg or more) satellites. CubeSats, defined in increments of 1U (10 cm^3), have much lower SWaP requirements due to their size and thus much lower overall cost than traditional satellites.[4] The benefits of VLEO, cost savings of CubeSats, and development of CubeSat-sized electric propulsion technology led to the Agile MicroSat (AMS) mission, which is (to the authors' knowledge) the first VLEO-designed CubeSat to launch. AMS is shown in Figure 1.

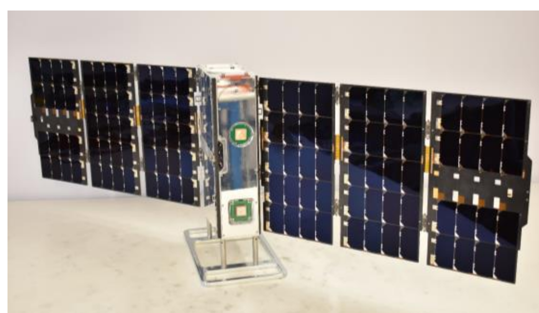


Figure 1. AMS with its solar panels deployed. AMS's panel configuration was designed such that it is able to fly in a low drag configuration which minimizes aerodynamic drag disturbance torques.

The 6U AMS bus, provided by Blue Canyon Technologies (BCT), operates as an experimental platform hosting three payloads. The first is the indium field effect electric propulsion (FEEP) thruster, developed by Enpulsion GmbH, needed to change and maintain orbit. The thruster previously underwent an on-orbit demonstration in 2018 and subsequently has been launched on over 100 spacecraft[5]; however, AMS is the first usage of the thrust vector control version of this thruster and the first intended to be used in VLEO. Automated flight software called Autopilot was developed for AMS in order to alter and maintain the desired orbit using the thruster and active aerobraking. The second payload is a laser demonstration payload, called Beacon, used in conjunction with observatories on the ground to facilitate adaptive optics experimentation. The third payload is a 3-D Plus camera for visible-spectrum imaging. The camera has been used for capturing post-disaster images and doing change detection with images from other Earth observing satellites.

Mission progress

AMS launched on 05/25/2022 from Cape Canaveral, and we were able to make first contact on the same day. BCT and the payload ops team quickly moved through commissioning, and by 06/07/2022 the bus, camera, Beacon, and onboard autopilot software were commissioned. Figure 2 shows operations following those initial steps.

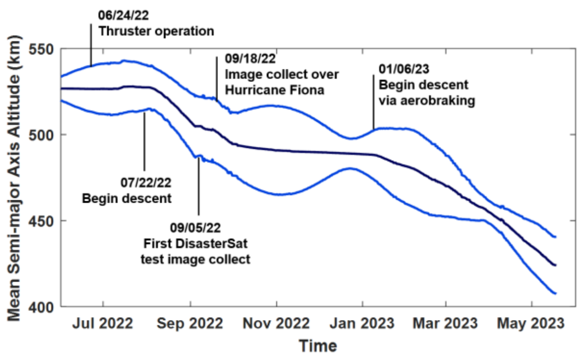


Figure 2: Altitude profile of AMS and events over time. During the entire mission we have also been collecting imagery and doing Beacon experiments.

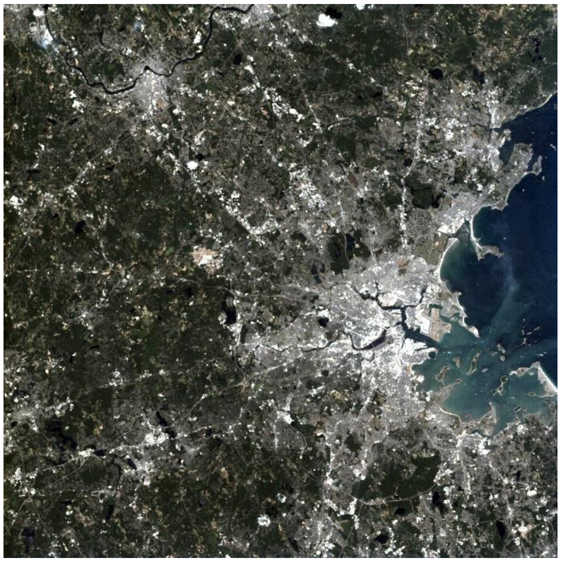


Figure 3. MIT LL and the Greater Boston Area

Since launch, the camera has been operating nearly every day and has taken over 1900 photos and counting. One such image is Figure 3, taken over the Greater Boston Area on July 10, 2022.

To operate each payload to its full potential, the AMS operations team needed to develop an automated end-to-end processing pipeline. The aim of this paper is to describe our overall ground processing architecture, development of our satellite state prediction method, payload operations and deconfliction process, and showcase an application of AMS's camera and scheduling algorithm for capturing post-disaster imagery.

GROUND PROCESSING

We will begin with an overview of the AMS payload data flow, as shown in Figure 4.

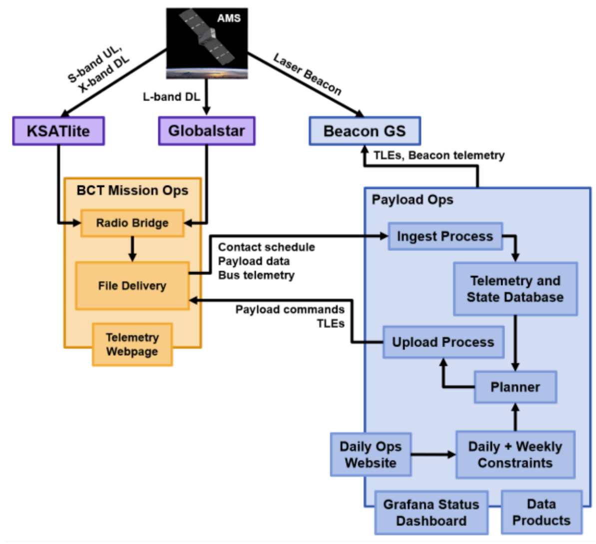


Figure 4. AMS ground processing overview with a focus on Payload Operations

The primary communications link with the AMS bus is through the KSATlite ground station network operated by Kongsberg Satellite Services (KSAT), with an S-band uplink and X-band downlink. We receive bus telemetry and payload telemetry through this network, with passes scheduled for once or twice a day (and more passes scheduled as need to facilitate troubleshooting). The AMS bus also has a Globalstar transmitter, which is a downlink-only service that allows us to receive a select set of telemetry fields with greater frequency than our main contacts. The Globalstar packet includes GPS-derived spacecraft ephemerides to facilitate orbit estimation. Data received through KSAT and Globalstar are processed by BCT and delivered to the AMS Payload Ops Center, along with daily delivery of a contact schedule file. BCT also provides an API that can be used to request bus telemetry for historical periods, as well as a telemetry webpage that can be used to view trends and export data manually.

Ingest processing in the Payload Ops Center runs whenever new data is detected. This process is responsible for parsing and storing all data within a series of tables in a MySQL database and on a networked file share. This telemetry is used for AMS state estimation, payload activity planning (the Planner), and to drive a status dashboard. The file share is for internal image distribution and facilitates creation of data products.

The ops team meets weekly to figure out a high-level plan for desired payload operations. Daily, an operator generates a schedule by setting a few parameters in a web app. These daily parameters, along with the weekly parameters, are read by the Planner. When the Planner generates command files, those are uploaded along with the latest state estimate (in the format of two-line element sets, or TLEs) to BCT. Upload processing also keeps track of expected payload ops times so that activities can be associated with later-received payload telemetry.

Software architecture

A more detailed look at our software architecture for the Payload Ops Center is shown in Figures 5 and 6.

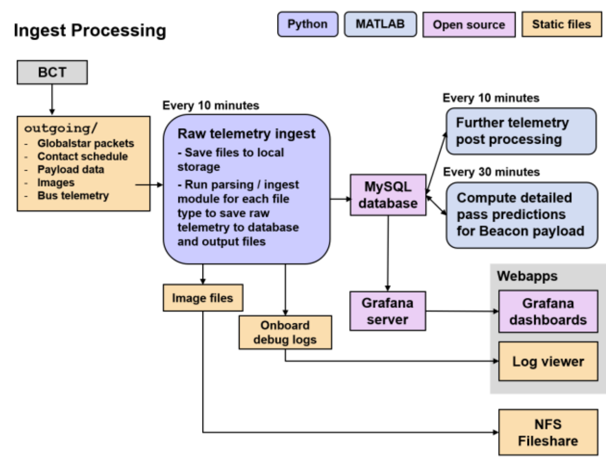


Figure 5: Software architecture for ingest of raw telemetry and further post processing.

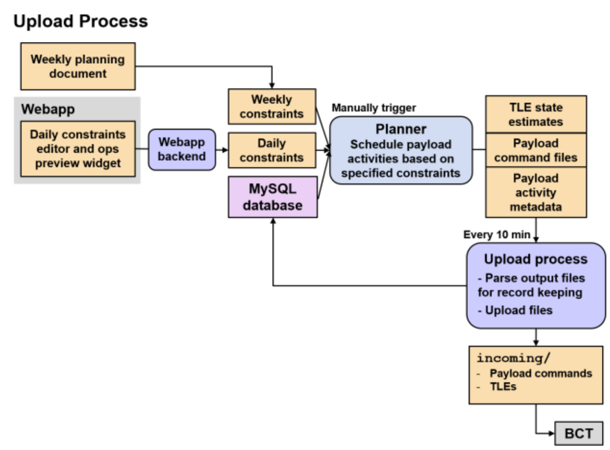


Figure 6: Software architecture for upload of command and TLE files.

We believe that overall, our software architecture design and specific technology choices struck a balance between being stable and maintainable by our small team while enabling the development and refinement of new capabilities as the mission evolved.

A relational database (rather than a schema-less database) was chosen since it is simple to query and it is straightforward to document schemas. Where possible, we generate table schemas from telemetry packet specifications. MySQL was chosen due to its ease of administration, particularly with setting up data replication. Python is used by the ingest and upload processing as well as the image processing pipeline, while payload planning and telemetry processing for the Grafana display is done in MATLAB; both language choices were motivated by developer familiarity. We have found that mediating interop between the two languages through the database and static file generation was straightforward and served our needs while allowing for asynchronous continuous development of mission capabilities. In addition, segregating the raw telemetry download and upload code from the continuously-developed MATLAB scheduling and post-processing code meant that we had stability in the outward-facing aspects of our pipeline and flexibility in the internal pipeline.

We use two browser-based applications in our daily operations procedures. Due to limited web developer time, we chose to leverage the Grafana dashboard software package as our main telemetry display. This proved to be a large time savings as non-website-developers were able to create their own plots and tables from the database for monitoring both the software processing system and the payload telemetry. A snippet of a dashboard is shown in Figure 7. Setting daily ops parameters is done through a custom form website built with Preact, and also contains other useful utilities for ops. The web backend is a combination of FastAPI as our web framework with Gunicorn as our WSGI HTTP server. Nginx is used as a reverse proxy for both the Grafana server and ops app in order to handle encryption and client authentication for ops users. Static files generated for commanding are all stored within a Git version control repository, which is easily viewable through an internal GitHub instance.

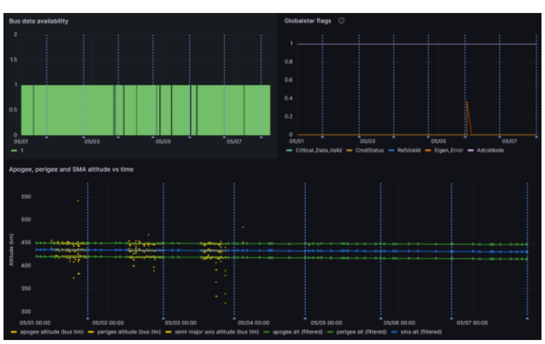


Figure 7: Some Grafana panels showing bus data availability in our database, Globalstar flags, and orbit info display.

For redundancy, we maintain two systems that are capable of running our daily ops process and telemetry processing. In addition, we have captured all of our software dependencies and setup using the Ansible configuration system so that if we need to stand up a new system, we are able to do so quickly. We also maintain two read-only replicas of our MySQL database with weekly point-in-time backups off of one of the replicas.

AMS STATE ESTIMATION AND PREDICTION

As a maneuverable satellite flying in the high drag VLEO environment, maintaining and communicating the current and projected orbital state is critically important for the AMS mission. Figure 8 shows an overview of how the estimated orbital state flows through the ground software. When new telemetry is received, automated processing fits an orbit to the telemetry measurements while considering any past or future planned maneuvers and sends this new orbital state estimate to mission operations ensuring that the next primary radio contact is successful.

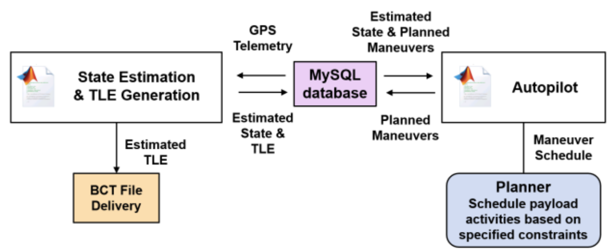


Figure 8: Maintaining AMS orbital state estimates

The telemetry consists of time-stamped ECI position and velocity estimates from the onboard GPS and filtered by the flight GNC system. This data is received by routine contacts as well as through the more frequent Globalstar data downlink. The state estimation routine automatically pulls telemetry measurements from the past 24 hours from the database and fits an orbit using a linear batch filter with a high-fidelity numerical propagator (30x30 gravity model, w/ Sun/Moon/Planets, and the MSIS00 atmosphere density model). This fit orbit is then used as a reference trajectory to fit a new TLE. The TLE is sent to Blue Canyon for scheduling future radio contacts and is also stored in the database. Additionally, the state estimate is propagated into the future while considering any planned maneuvers stored in the database. Predictive TLEs are fit at specific times into the future (e.g. +1hr, +1day…). This is done to capture the effect of maneuvers into the TLE for planning purposes. These predictive TLEs are useful for scheduling radio contacts up to a week in the advance as well as scheduling payload operations.

Figure 9 shows the difference between the most recent Space-Track TLE (red), our TLE (blue) and the high-fidelity propagated state based on our fit (purple) when compared against downlinked GPS telemetry for a seven-day period of active thruster operations. The dots indicate individual 3D position difference between the GPS telemetry and propagating the various orbit fits while the solid lines show the 24hr moving average. Here we see that the Space-Track TLE was routinely off by 1-10 km due to the active thruster operations, while our custom fit TLEs were generally within 500 m and the propagated cartesian state with knowledge of planned maneuvers was generally good to within 100 m.

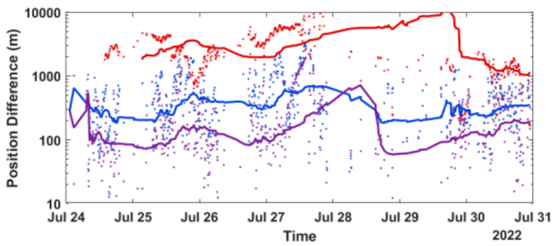


Figure 9: Comparison of the most recent Space-Track TLE (red), our TLE (blue) and the high-fidelity propagated state based on our fit (purple) when compared against downlinked GPS telemetry.

The effective drag area for AMS was also estimated as part of the orbit fitting process. The estimated effective drag area ($C_D A$ in the drag equation $F_D = 0.5\rho C_D A V^2$, ρ is the atmospheric density and V is the orbital velocity) is shown in Figure 10 during a 4-month period of aerobraking operations. During the month of January 2023, we gradually introduced aerobraking maneuvers up to ~50% of the orbit. This was increased to ~80% of the obit by March 2023. The dashed lines indicate the predicted effective drag area for no aerobraking (low drag orientation), 80% and 100% aerobraking duty cycle. This prediction was made using analytic equations of drag induced on a flat plate model of the AMS vehicle assuming diffuse reflections in free molecular flow[6]. Using this model, there is an 8.2x increase in the effective drag in the max drag orientation when compared to the low drag orientation with knife edge solar panels. Interestingly, in the low drag orientation, the solar panels contribute almost 50% of the effective drag due to skin drag effects despite only having ~9% of the total cross-sectional area in the ram direction. For reference, the effective drag area would be ~0.058 m^2 neglecting skin drag effects. This shows the importance of modeling skin drag in order to estimate drag forces and lifetime at low altitude.

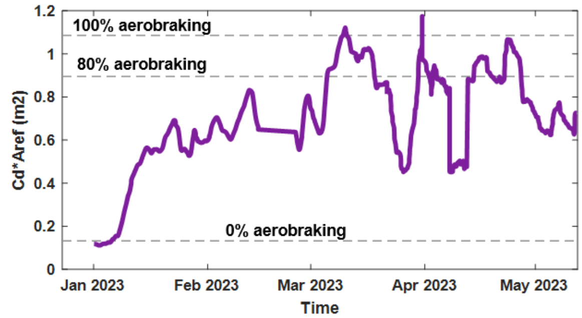


Figure 10: Estimated effective drag area (Cd*Aref) during aerobraking operations which commenced during the first week of January 2023.

PAYLOAD OPERATIONS / DECONFLICTION

Automated planning and deconfliction of payload activities is central to AMS's operation. Desired payload activities are planned and prioritized at a high level each week. Weekly planning parameters include the target orbit for the Autopilot algorithm, operating modes for the Beacon, Camera operation parameters such as the maximum number of targets and images to acquire daily, and relative planning priorities between payloads. A set of daily planning parameters can be adjusted if necessary. These include relative priorities between Camera targets and access constraints for each target. These parameters serve as inputs to the payload task scheduling software, known as the Planner.

The Planner propagates AMS's estimated state over the planning period and references this orbit against the desired payload activities. For the Camera and Beacon, the Planner must adjust the satellite's attitude to align the payload with the terrestrial target over the course of the operation. Access to specific sites is restricted by local illumination and relative bus elevation at the desired time of acquisition. Outside of typical daily Camera targets, an additional scheduling routine was developed to optimize the collection of photos for disaster management after natural hazard incidents. Throughout the mission, Camera operations have evolved to imaging non-terrestrial targets without changes to the Planner's user interface structure.

Thrust segments for orbital changes and maintenance are planned with ground-based Autopilot algorithms which target a desired orbit with a maximum duty cycle constrained by bus power generation. Figure 11 shows an example 12-hour maneuver schedule from Aug 20 2022 plotted as a function of altitude and power generation fraction. The maneuver segments are highlighted in red and comprise a maximum 40% duty cycle per orbit and burns are centered around apogee to reduce perigee. An instance of these algorithms exists onboard the satellite and is used for validation of onboard autonomous maneuver planning. Throughout the mission, these algorithms have evolved to handle aerobraking segments for orbital lowering and phasing operations.

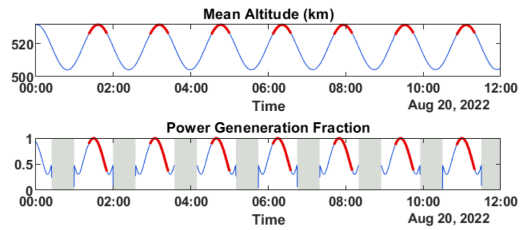


Figure 11: AMS maneuver segment times (marked with red) showing a 40% maximum duty cycle and burns centered around apogee to reduce perigee. Burns were scheduled during sun-lit periods to minimize stress on the bus power system.

Payload activities are often naturally deconflicted by the various constraints on each payload's operations. When conflicts arise, deconfliction is performed sequentially throughout the planning process. A static priority determines the order in which payload activities are planned. Each activity therefore restricts the available operating times for each subsequent payload. This process ensures each payload has independent operating times on at least a daily cadence. A visualization of AMS's multi-payload operation is shown in Figure 12.

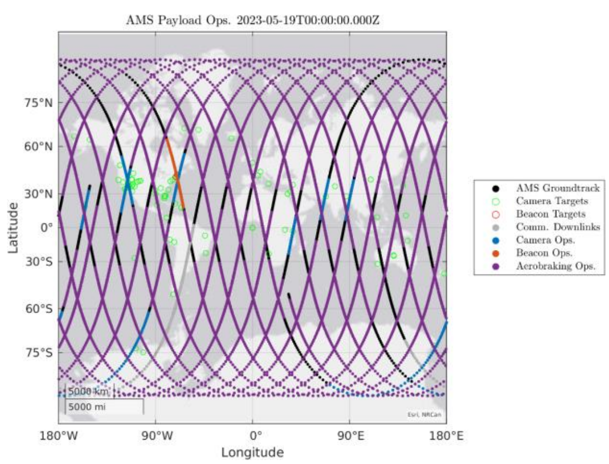


Figure 12: Visualization of daily AMS multi-payload operation.

This process generates high-level time-stamped commands for the bus and payloads for the course of a day. The Planner converts these commands into bus software syntax and generates a Payload Activity List (PAL) for upload to the satellite. These files include bus commands such as attitude adjustments, torque rod operation, and telemetry data rates; and low-level payload commands governing the operation of the Camera, Beacon, and Thruster. These files are automatically transferred to BCT and uplinked to the satellite on the next available ground station pass.

As of this writing, the Planner has scheduled and commanded over 1700 Camera operations, over 2400 Thruster segments, over 4300 aerobraking segments, and 35 Beacon operations.

POST-DISASTER IMAGING

A prospective application for maneuverable small satellites is rapid reconnaissance during disasters. Overhead imagery can provide useful information to emergency managers on the extent of natural hazards and affected areas, the status of transportation networks, and the level of damage sustained to homes and infrastructure. This section describes a tasking optimization model used to task AMS for disaster response and the image processing pipeline. AMS was used to collect images after several tropical storms in 2022.

Payload tasking for post-disaster imagery collection

A tasking optimization model, shown in Figure 13, generates PALs to collect images over areas of interest during disasters. The model uses TLEs, payload characteristics, and target priority data to create a tasking plan that maximizes the collection of high priority targets. The tasking planner then generates a command list, which is then uploaded to BCT to be sent to the spacecraft.

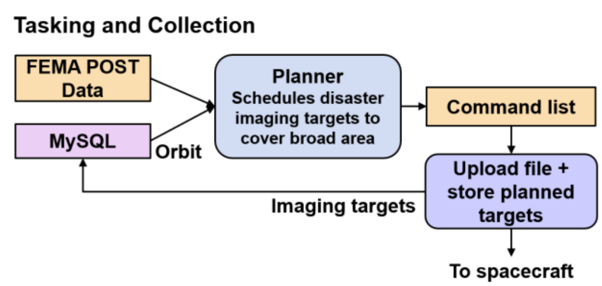


Figure 13: Disaster imagery collection scheduling

During natural disasters, targets and points of interest change frequently, especially in the days preceding predictable incidents (e.g. tropical storms) and in the 24-48 hours following an incident. The Priority Optimization Support Tool (POST) was developed by the US Federal Emergency Management Agency to inform remote sensing tasking during disasters. It uses hazard models, the Social Vulnerability Index, and foundational geospatial infrastructure data to generate a

1km x 1km grid indicating areas likely to sustain damage and require emergency services.

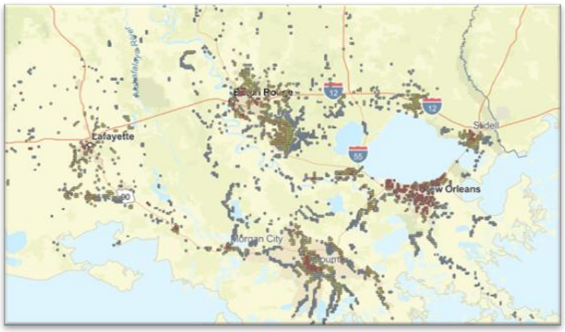
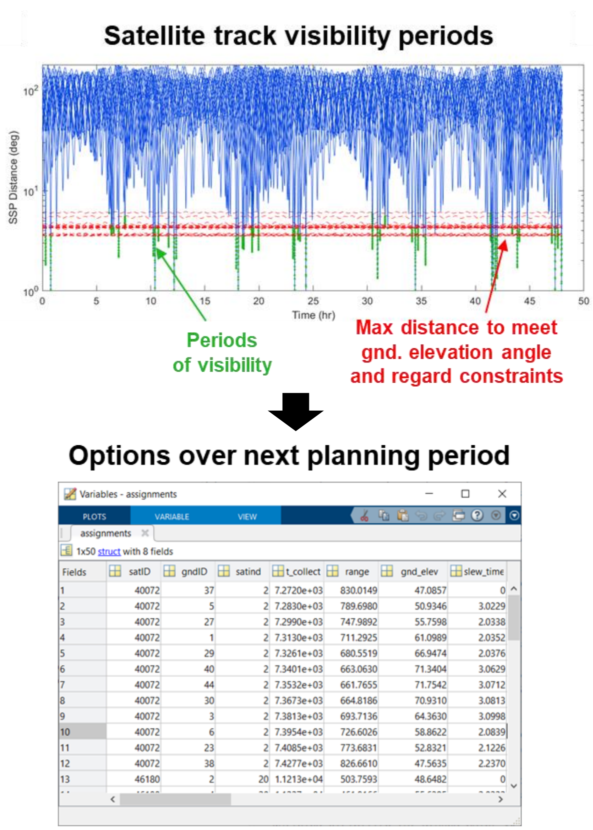


Figure 14: Priority Optimization Support Tool output from Hurricane Ida (2021, FEMA). Each grid square indicates priority based on the likelihood of disaster impacts to people and infrastructure.

To identify windows of opportunity for collection, the AMS orbit is propagated over an operational planning period. Bus slew capability and settle time, minimum and maximum acceptable elevation angle, and camera field of view are used to generate a list of collection opportunities for each target.



Fields	satID	gndID	satind	t_collect	range	gnd_elev	slew_time
1	40072	37	2	7.2720e+03	830.0149	47.0857	0
2	40072	5	2	7.2830e+03	789.6980	50.9346	3.0229
3	40072	27	2	7.2990e+03	747.9892	55.7598	2.0338
4	40072	1	2	7.3130e+03	711.2925	61.0989	2.0352
5	40072	29	2	7.3261e+03	680.5519	66.9474	2.0376
6	40072	40	2	7.3401e+03	663.0630	71.3404	3.0629
7	40072	44	2	7.3532e+03	661.7655	71.7542	3.0712
8	40072	30	2	7.3673e+03	664.8186	70.9310	3.0813
9	40072	3	2	7.3813e+03	693.7136	64.3630	3.0998
10	40072	6	2	7.3954e+03	726.6026	58.8622	2.0839
11	40072	23	2	7.4085e+03	773.6831	52.8321	2.1226
12	40072	38	2	7.4277e+03	826.6610	47.5635	2.2370
13	46180	2	20	1.1213e+04	503.7593	48.6482	0

Figure 15: Generating and prioritizing candidate imaging collects based on visibility, satellite constraints and prioritized POST outputs.

The optimizer uses a dimensionless utility index to schedule collections that capture as many grid points as possible given the constraints. Utility generated for any given collect is a function of the sum of the utilities for grid points that would be covered with the collect and the individual utility for each grid point is the product of the priority and the area that each grid point represents. In simulations, utility increases over time as targets are collected. The optimizer generates a collection schedule where the estimated image footprints maximize utility. This model integrates with the Planner to generate PALs that maximize overall utility. In simulations using a POST dataset produced for Hurricane Ida in 2021, AMS would achieve 80% utility within 2 days 50% of the time, within 3 days 80% of the time, and within 4 days 100% of the time.

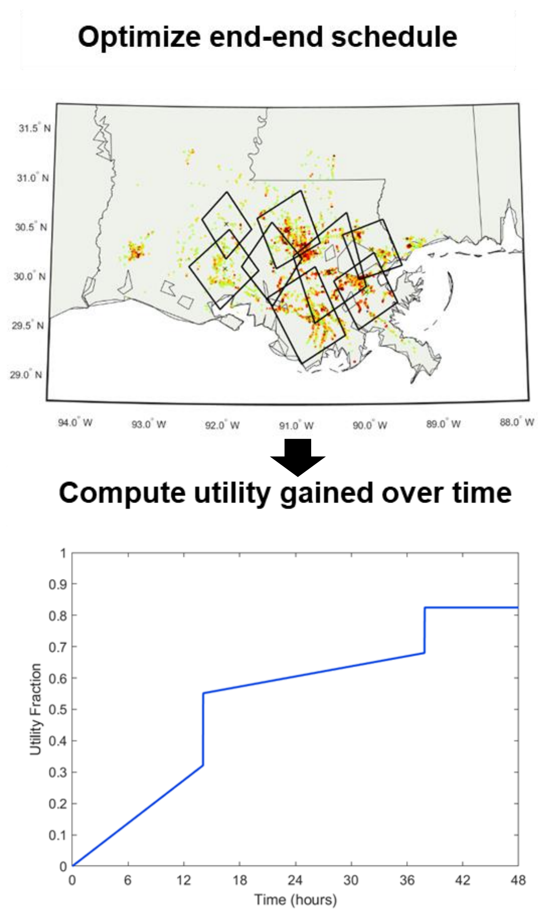


Figure 16: Example scheduler outputs showing image footprints overlaid on Hurricane Ida POST data (left) and the cumulative utility generated over 48 hours (right)

Image processing pipeline

The image processing pipeline is detailed in Figure 17.

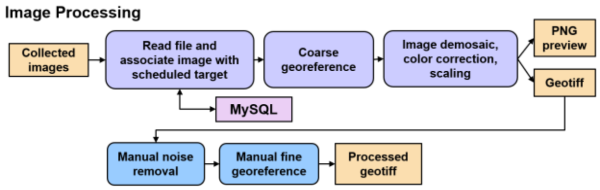


Figure 17. Image processing pipeline

Incoming raw images are processed into image products and cross-referenced with planned targets to associate the image file with the appropriate camera target. A change detection algorithm and image publication workflow was developed for using camera images to detect disaster damage. In demonstrations, image and change detection products were published as web-hosted tile services and feature services using Esri ArcGIS Online.

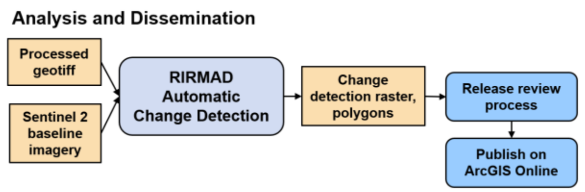


Figure 18. Data dissemination pipeline

Steady state workflow demonstration

The tasking and analysis process was first tested in late August and September, 2022, the full timeline is shown in Figure 19. To improve the likelihood of cloud-free images, the POST data from Hurricane Ida was geographically translated to Las Vegas, one of the least cloudy cities in the United States. After overcoming challenges with incorrect metadata assignment and a bus reset, the first successful collection was scheduled on September 4th, 2022 and executed on September 5th. Images were downloaded to the AMS mission ops center the same day. Processing and analysis were completed by September 9th, at which point the data product was submitted for public release. Sentinel 2 imagery was used as a baseline to compare changes seen in the AMS images. The time from tasking to analytic product was 5 days. An interactive public-facing webapp was published about a week later to display the pre-incident imagery, post-incident imagery, and the change detection polygon layer.

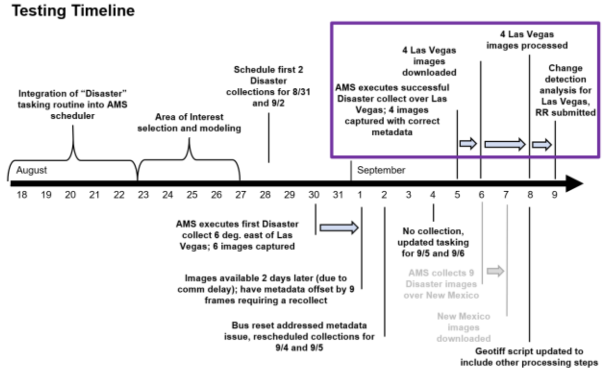


Figure 19. Testing timeline

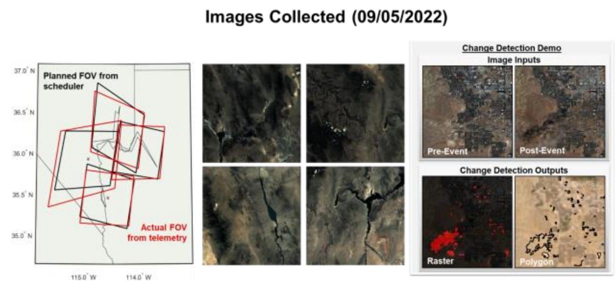


Figure 20. Testing images collected over Las Vegas

Hurricane and post-hurricane imaging

AMS was tasked to collect images during and after three major hurricanes in 2022 that affected the United States and Puerto Rico – we will discuss Hurricane Fiona and Hurricane Ian. Hurricane Fiona made landfall in Puerto Rico on September 18th, 2022, only two weeks after the Las Vegas demonstration. A POST dataset, available the day before landfall, was used for tasking, as shown in Figure 21. The first collection took place on September 21st, which was the same day other optical imagery providers were able to capture cloud-free images. Processed AMS images were available the next day, though they were too cloudy to be analyzed for change.

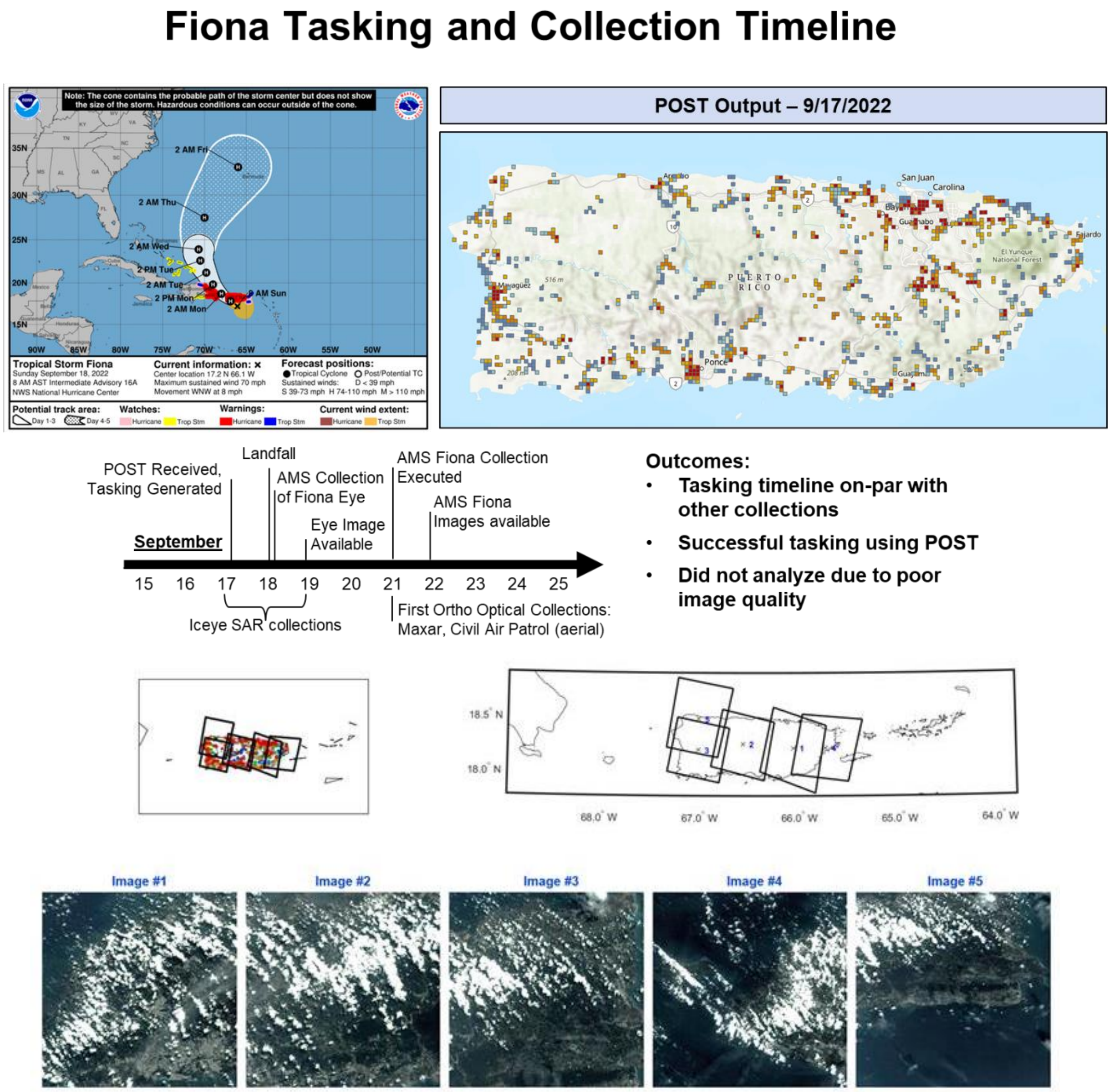
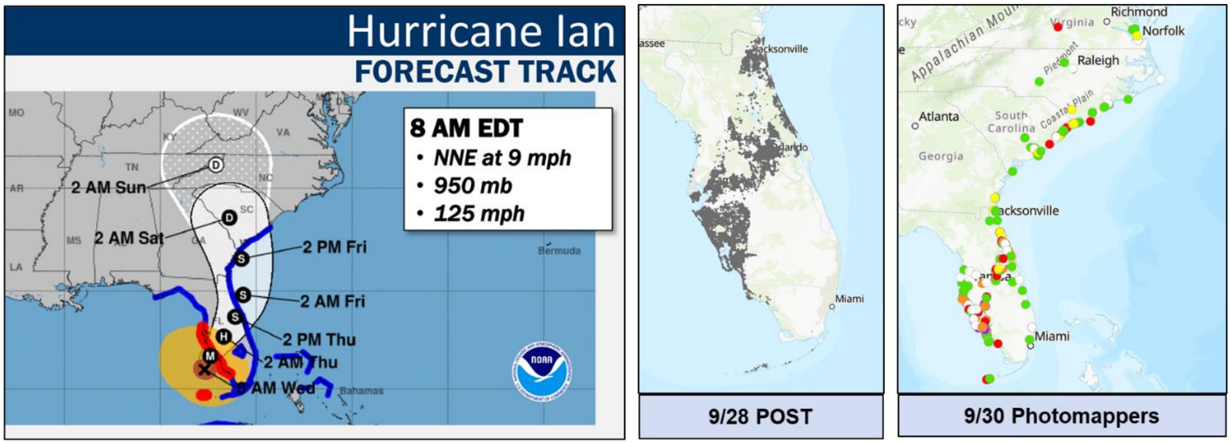


Figure 21. Fiona tasking and collection

Subsequently, Hurricane Ian made landfall in Florida on September 28th, shown in Figure 22. A POST data layer generated that day showed potential impacts across the state. Since the storm was slow-moving, no ground imagery collection attempts were made until October 1st. No new POST data was available for planning, so un-prioritized point targets were created from the GISCorps PhotoMappers data. PhotoMappers is a volunteer project that identifies photos of disaster damage posted to social media and other internet sources and determines the locations shown in those photos. No useful images were collected during the incident period due to a bus malfunction, however several photos were collected in the days afterwards; one is shown in Figure 23.



9/27 – Collection around the Tampa Area
9/28 – Eye Collection, pulled in POST, Landfall late in the day
9/29 – Stormy
9/30 – No POST update, used Photomappers points for tasking
10/1 – attempted collection

Figure 22. Hurricane Ian tasking

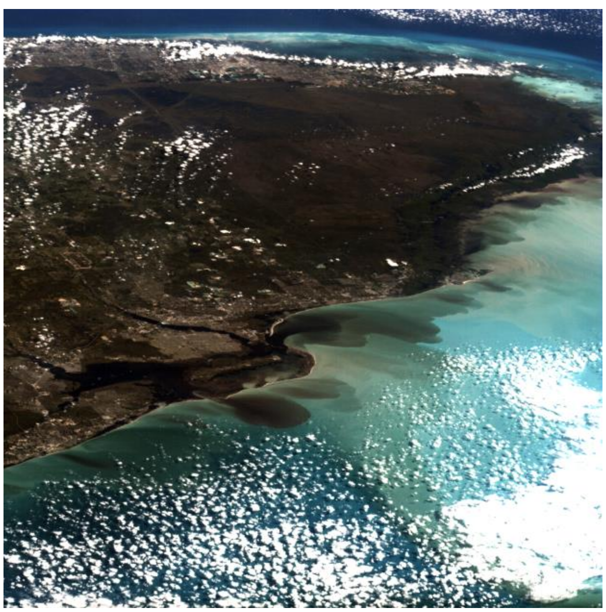


Figure 23. Sept. 30th, 2022 picture taken over incident area showing sediment after the hurricane.

In summary, AMS provided a useful platform for prototyping quick-turnaround satellite-based tasking and image collection for disaster situations. Future work includes improving the tasking model to simulate constellations with multiple satellites and prioritizing concurrent incidents.

CONCLUSION

The Agile MicroSat has been in operation for nearly a year at the time of this writing. Throughout the mission, the payload ops team has successfully operated multiple payloads through the use of custom scheduling software and a robust data pipeline; and we have been able to complete multiple post-launch collaborations such as the DisasterSat project. AMS has served as a highly successful experimental platform thus far, and will hopefully continue to operate at full tilt until it reenters the atmosphere (forecast to occur sometime after October 2023).

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