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ASTRA – Autonomous Satellite Technology for Resilient Applications: A Technology Demonstrator

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ABSTRACT

ASTRA is an on-orbit technology demonstrator establishing a new paradigm for implementing on-board "thinking." ASTRA is a system-level autonomy capability (including digital twins, anomaly detection, diagnostics/prognostics, and mission management) enabled by an innovative technology, NPAS - NASA Platform for Autonomous Systems. NPAS is developed by NASA Stennis Space Center (SSC) Autonomous Systems Laboratory (ASL) with support from NASA Exploration Systems Development Mission Directorate (ESDMD) Advanced Exploration Systems and Mars Campaign Office. ASTRA leverages NPAS for on-board "thinking" autonomy. ASTRA also includes advanced hardware required for implementing autonomy. ASTRA Flight Software (FS) is running on commercial hardware that provides the computational and memory resources required for on-board autonomous behavior and operations. ASTRA's autonomy capability was successfully validated as a hosted payload operating on-board LizzieSat-1 (LS-1), a commercial satellite designed, built, and operated by Sidus Space. LS-1 successfully launched into a 97.4°, 510km orbit in March 2024. LS-1 satellite avionics include three on-board processors: an SP0 processor running LS-1 flight software implemented in Core Flight Software (cFS) and two NVIDIA General-Purpose Computing Graphics Processing Units (GPGPUs) running Linux. One GPGPU manages multiple Sidus payloads. The second GPGPU is dedicated to NASA SSC's ASTRA.

ASTRA's implementation is containerized and demonstrates a hierarchical distributed autonomy architecture. ASTRA FS includes two autonomous system managers that coordinate work to achieve mission objectives: a Vehicle System Manager (VSM) and an Electrical Power System (EPS) manager. In this way, ASTRA is a uniquely configured payload that can operate LS-1 when enabled. Furthermore, software updates enable ASTRA to evolve. For example, ASTRA Flight Software (FS) version 1.0 includes core capabilities required to validate communication, command, and control. Then, ASTRA FS version 2.0 is intended to monitor and manage the LS-1 onboard EPS, including load-shedding non-essential power under low power generation conditions. ASTRA FS operations are coordinated with LS-1 using NPAS' Software Bus Network (SBN) bridge (SBN bridge enables ASTRA FS integration with LS-1 cFS applications). SBN publish/subscribe capabilities enables transmission of telemetry from LS-1 systems (e.g. power) to ASTRA, as well enabling ASTRA commands to change satellite EPS onboard state.

Data flow from LS-1 to ASTRA includes ground operations performed at the ASTRA ASL Payload Operations Command Center (POCC). LS-1 data is downlinked at least 16 times/day into Sidus leased commercial ground stations which automatically relay LS-1 data (including ASTRA data) via Amazon Web Service (AWS) commercial lines into Sidus Space Merritt Island, Florida Mission Command Center (MCC). ASTRA, in addition to validating successful autonomous operations, served as a testbed for NASA SSC's ASL on-board the LS-1 satellite on-orbit. The ASTRA FS technology demonstrator on-orbit shows potential to enable development, test, and validate autonomous operations on-orbit (e.g. satellites, spacecraft) and autonomy capabilities required for future Moon-to-Mars missions.

INTRODUCTION

Autonomous operations are crucial for long-term deep space sustainability beyond Low Earth Orbit (LEO) due to the numerous operational challenges, specifically those associated with sparse, low-data rate space to ground communications. The capabilities that autonomous systems need to provide include: the ability to monitor systems, assess performance, perform tasks, increase overall efficiency, enable independent decision-making, understand, and address caution and warning issues as they arise, to fundamentally reduce reliance on Earth-based operations. This is particularly important for long duration satellite missions and deep-space exploration where human intervention is limited. However, the current state-of-the-art is constrained by technology challenges and capabilities, especially when implementing autonomous systems of systems. This is due to the system's need to perceive; process data, information, and knowledge (DIaK); and make decisions, in real time, as well as the need to handle unexpected events.

For satellites and deep space exploration, one critical capability is autonomous management, which focuses on enabling spacecraft to manage their own systems without persistent human intervention. This autonomy need also directly correlates to increased mission complexity; current satellite missions can involve complex tasks and extended duration, requiring sophisticated, real-time decision-making and resource optimization. To meet this challenge, the National Aeronautics and Space Administration (NASA) Stennis Space Center (SSC) leveraged the NASA Platform for Autonomous Systems (NPAS)[1] to execute a technology demonstration on orbit, as a premier payload rider on a commercial partner's small satellite, LizzieSat-1 (LS-1).[2,3] (LS-1 was built and is operated by Sidus Space; additionally, subsequent mentions of Sidus Space will be Sidus for the remainder of this paper).

BACKGROUND

To support the development of an innovative autonomous technology capability for enabling deep space human exploration, NASA SSC partnered with industry. For this purpose, NASA SSC Autonomous Systems Laboratory (ASL) submitted a proposal to NASA entitled Autonomous Satellite Technology for Resilient Applications (ASTRA).

Project Description

NASA selected 10 proposals under Project Polaris, a new initiative to engage the NASA early career workforce in efforts to meet the significant challenges associated with sending humans to the Moon and Mars. Project Polaris included small flight experiments or risk reduction projects to fulfill high-priority capabilities gaps. The projects were awarded through NASA Exploration Systems Development Mission Directorate (ESDMD) Mars Campaign Office (MCO). The ASTRA proposal, submitted by NASA SSC's ASL, was one of the selected proposals. For ASTRA, NASA SSC, as mentioned previously, is partnered with Sidus Space, an innovative provider of space-based technologies and platforms. ASTRA is a premier payload rider onboard the LS-1 small satellite, Sidus Space's satellite platform designed to provide technology demonstrations access to space. Sidus Space assumed responsibility for rocket launch to deploy satellite and all mission operations. As part of the partnership with Sidus, the NASA SSC team worked with Sidus to integrate the ASTRA hardware and software on LS-1.

ASTRA is a technology demonstrator that encompasses an integrated software and hardware system. ASTRA proposed demonstrating autonomous operations in a spaceflight environment, while providing flight heritage for the underlying NPAS. ASTRA is a payload rider that includes its own ARM/NVIDIA General-Purpose Computing Graphics Processing Unit (GPGPU) based avionics hardware – which provides the computational power and storage requirements necessary for implementing autonomous operations. This is the first use of this hardware for an autonomous operation demonstration on orbit. The software and hardware will close or mitigate multiple autonomy capability gaps, advancing Technology Readiness Level (TRL), integrating ASTRA Flight Software (FS) with Core Flight System (cFS) applications[4] implementing distributed autonomous operations (based on Gateway autonomy design[5]) and conducting mission management from ground. NPAS, the software platform that ASTRA FS is built upon, is being cultivated as a paradigm shift in the way NASA develops autonomous operations software that will enable cost effective, comprehensive, "Thinking", and evolutionary autonomy for future space and ground systems. "Thinking" autonomy which is comprehensive and establishes on-board knowledge and processes for applying the models to generate solutions by the system, contrast to "Brute-Force" autonomy, which tries to consider every possible circumstance that autonomy needs a solution, which is very system/process specific, painstakingly complex, difficult to track and evolve, and provides incomplete system coverage.

ASTRA's autonomous systems capabilities developed are immediately applicable to multiple Artemis elements. While Artemis crew missions may only last days; other Artemis systems (e.g., Gateway, Lunar Terrain Vehicle (LTV), Human Lander Systems (HLS), Habitation Modules) will remain uncrewed in lunar orbit and on the lunar surface for many months and will rely entirely on autonomous capabilities to maintain function. Keeping these systems viable is vital to the success of Artemis. Trust must be established for autonomous systems to run spacecraft and surface systems, as well as plan and conduct mission operations. ASTRA is paving the path for reducing the time to deploy high-priority capabilities to Artemis missions and reduces risk, program cost, safety issues, and schedule challenges through the successful demonstration of autonomous operations on-orbit.

The mission objectives for ASTRA's on-orbit technology demonstration includes flight software for autonomous Vehicle System Manager (VSM) for the satellite and an autonomous System Manager (SM) for the Electrical Power System (EPS). The SMs embody mission management, Integrated System Health Management (ISHM), and resource management. ASTRA utilizes a Gensym G2 Software[6] -Software Bus Network[7] (G2-SBN) bridge to cFS, developed by prior public-private partnerships with industry, to communicate and integrate with the LS-1 flight software (cFS) running in an SP0 processor with VxWorks OS.

Sidus Space

Sidus facilitates access to space by offering flexible, cost-effective solutions for various space mission needs, including, payload hosting, mission management, and space manufacturing. The Sidus LizzieSat™ platform provides a solution for hosting payloads and collecting data in LEO.

Sidus serves as a critical industry partner for ASTRA. Sidus has relevant prior experience and expertise to support this integration and infusion activity, and these skills were a critical component responsible for optimizing success of the ASTRA project. Sidus leveraged multiple launch agreements with SpaceX[8] to facilitate launch of LS-satellites into space.

For ASTRA, Sidus provided a rideshare opportunity on the LS-1 small satellite. Sidus had the responsibility for ASTRA payload integration/testing, securing rocket launch, orbit insertion, satellite deployment and satellite operations.

The LS-1 mission is managed by the Sidus LS-1 Program Manager, Senior Vice President of Mission Ops, Mission Operations Manager (MOM), and Mission Ops Team.

LizzieSat-1

LizzieSat™ provides a comprehensive and adaptable space solution, which seamlessly integrates custom payloads with access to LEO, that includes a robust infrastructure of communication, power, navigation, and computing subsystems. LizziesSat-1 (LS-1) was successfully launched and deployed to low earth Orbit, see Figure 1 (LS-1 on the left, seen prior to deployment) on SpaceX's Transport-10 rideshare mission on March 4, 2024.

Figure 1: LS-1

Additional details of LS-1 are provided below in Table 1, Table 2,

Table 3 and Table 4.

Table 1: Size Specifications

Size	
Class	microsatellite
Mass	100 kg
Shape	Octagonal prism
Volume	188 U

Table 2: Power Storage Specifications

Power Storage	
Battery Type	Lithium Ion
Energy Storage	1100 Wh
Operating voltage	24.0V-33.6V

Table 3: Solar Panel Specifications

Solar Panels	
Power	400 W
# of Deployable Panels	8
# of Mount Panels	1

Table 4: Downlink Specifications

Payload Data Downlink Methods		
Transmitter type	X-Band	S-Band
Data Rate	124 Mbps	2 Mbps

Sidus LizzieSat-1 Command & Data Handling

The main interfaces of the elements of LS-1 Command and Data Handling (CD&H) with respect to the LS-1 flight computer are serial (RS-422) and Ethernet. Please see Figure 2 for additional details.

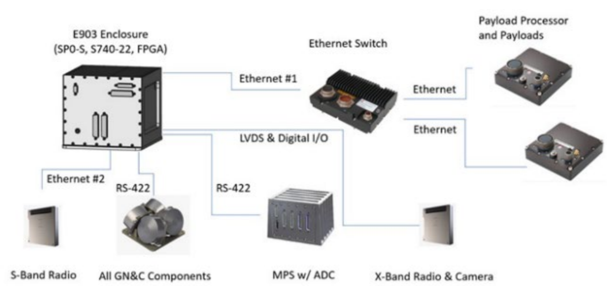

Figure 2: LS-1 Command and Data Handling

ASTRA CONCEPTS OF OPERATIONS

The following sections provide an overview of the hardware, software, data architecture, communication plan, facility and support systems, and ASTRA Payload Operations Command Center (POCC).

ASTRA Hardware Configuration

The ASTRA project utilizes both engineering and flight models of the AiTech version of the NVIDIA GPGPU with 32GB onboard memory. As a risk reduction measure, ASTRA and Sidus have agreed to utilize the same hardware with common physical interfaces; ASTRA payload is depicted in **Error! Reference source not found.**.

As a payload rider on LS-1, ASTRA is a hybrid test bed for demonstrating autonomous operations on-orbit with ground simulation and validation. ASTRA is demonstrating an innovative technology in a spaceflight environment, advancing TRL, and gaining flight heritage for a GPGPU/ARM processor and the NPAS autonomous systems development platform.

Figure 3: ASTRA GPGPU - Flight Unit

For the duration of the ASTRA project, the engineering unit GPGPU (model 1S-A1760) is retained at the Sidus Systems Integration Facility (SIF). The engineering GPGPU is integrated into the SIF in a configuration that provides the SSC software development team remote access via a VPN to the SIF for on-going development and integration testing. This unit will serve as the pre-flight test bed for the AFS version 1.0. Post-launch, the ASTRA engineering unit was intended for troubleshooting any anomalies observed during flight and to validate ASTRA software updates prior to upload to LS-1.

Unlike the engineering unit, the flight GPGPU (model 3S-A1760) with optional 1TB SSD is radiation characterized (at the vendor, AiTech) for tolerance in LEO. Integration of the ASTRA flight unit and harness fabrication was done by Sidus. This integration occurred prior to the modal/environmental tests of LS-1. Sidus was responsible for any additional payload integration, launch arrangements, and operation of the satellite-as-a-service.

Communication Plan

During ground and flight operations, the ASTRA POCC Lead is responsible for ensuring all procedures and guidelines are adhered to with coordination and direction from Sidus.

The ASTRA POCC Lead is also responsible for ensuring all individuals operating within the POCC are qualified, trained, and/or certified. The ASTRA POCC Lead and Sidus Mission Manager will work in conjunction with each other regarding ground preparations and on-orbit flight plans. Similarly, mission plans will be jointly developed and agreed upon in two week increments throughout the lifespan of the ASTRA mission.

All anomalies or discrepancies related to ASTRA are appropriately documented and reported to the ASTRA POCC Lead for dissemination if required and as needed.

Facility and Support Systems

ASTRA is managed by the SSC's Technology Innovation and Research Office (TIRO) which sponsors the ASL. Part of the ASL is the ASTRA POCC. The POCC connects to a dedicated payload server at Sidus Mission Operations Center (MOC). Prescribed telemetry streams(s) are transmitted from the Sidus MOC to the ASTRA POCC. The LS-1 data is transmitted (encrypted) to ground via the KSAT network to the Sidus MOC. All data collected from the Sidus MOC is pushed to the SSC Data Center for ground validation. Sidus Concepts of Operations for LS-1, include the following: telecommands sent from MCC to LS-1 via the S-Band Telecommand Up Link, then telemetry data is sent from LS-1 to the MCC via the S-bank Telemetry Downlink. See Figure 4, Network Group Architecture for additional Concepts of Operations details.

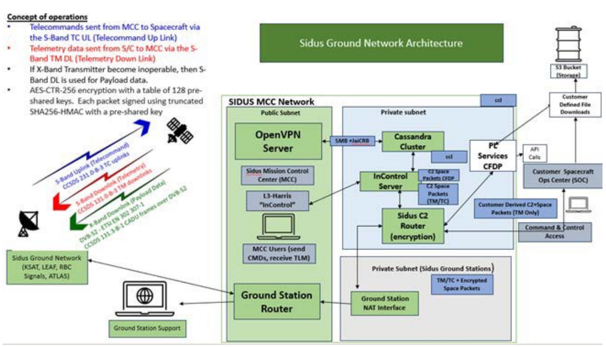

Figure 4: Sidus Ground Network Architecture

Sidus Mission Control Center (MCC)

Sidus provides mission operations for LS-1 and payload mission, ASTRA. The Sidus Mission Control Center (MCC) utilizes Amazon Web Services (AWS) cloud-based servers for data transfer and archival to enable payload data collection. LS-1 telemetry and payload data is post processed with proper time stamps into .csv files for archival and populated into human readable format onto MCC displays. All data collected at Sidus' MCC is pushed (encrypted) to the SSC ASL POCC via UDP connection. Telemetry data is streamed immediately to ASTRA POCC during each LS-1 communication pass.

ASTRA POCC

For ASTRA-Sidus Communication, LS-1 payload data comes down over the X-band from AWS cloud, to the Sidus MCC, and then to the ASTRA POCC. X-band payload downlink is 124 mbps. ASTRA absorbs a prescribed subset of the downlinked LS-1 data stream at the Sidus MOC. The ASTRA FS system health and status were verified via heartbeat signal integrated into LS-1 S-band telemetry stream and downloaded to the ASTRA POCC via a data path defined by the Sidus, as shown Figure 5.

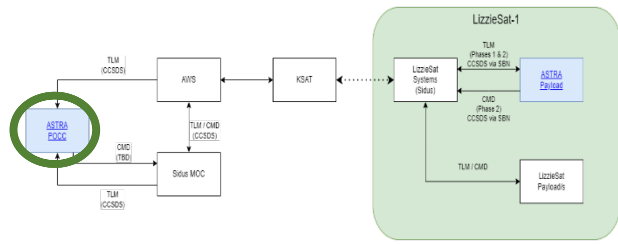

Figure 5: ASTRA POCC

Similarly, all ASTRA ground commands, and the software version update files were uplinked to the ASTRA flight unit from the Sidus MOC. In addition to the ASTRA FS heartbeat, the ASTRA POCC downloaded all LS-1 data related to ASTRA FS.

A combination of Open MCT[9] (Open-Source Mission Control software) data visualization framework and YAMCS[10], (Yet Another Mission Control Software) an open-source software framework, is being used for operational displays of telemetry in the ASTRA POCC.

During ASTRA AFF, downloaded LS-1 data is used help design the power monitoring algorithm. In future version, the data could be used to create off-nominal use-case scenarios, i.e., to inject anomalies into LS-1 data that is download. Those use-cases could be passed through a parallel ASTRA FS LS-1 implementation (on ground), further exercising autonomy capabilities. The result of this parallel activity with real-time LS-1 data, could potentially be used during LS-1's lifetime; should any of the use-case scenario anomalies that are being tested occur during flight. In that case, ASTRA FS would have the opportunity to perform validation activities for further LS-1 operations. The results of associated analysis will also be used to validate the robustness of ASTRA FS monitoring and autonomy capabilities.

METHODS

ASTRA Flight Software (FS) implements hierarchical distributed autonomy architecture that includes two autonomous system managers, ASTRA VSM and EPS-SM.

ASTRA Flight Software v1.0

ASTRA FS v1.0 includes one NPAS applications and implements the foundation of a tailored version of the distributed hierarchical Autonomous Systems Manager (ASM) architecture[11], and Gateway Autonomy and Flight Software Concept of Operations.[12] VSM serves as the top level of the distributed hierarchy of autonomous managers with purview over the entire satellite and satellite operations using information provided to the VSM by Sidus OBC and the satellite's current mission objectives. VSM provides the infrastructure to remotely update the VSM software and install new ASMs into the hierarchy in future versions. This architecture has been previously demonstrated in previous work conducted by SSC's ASL.[13,14]. The intent for future version of ASTRA is for the VSM to use information provided the lower-level SMs and the LS-1 Flight Computer to perform vehicle wide health assessments and to plan, schedule and execute autonomous control of the satellite.

Plans for ASTRA Flight Software v2.0

ASTRA FS v2.0 adds EPS-SM with a simplified digital twin of the electrical power system to ASTRA FS v1.0. In ASTRA FS v2.0, ASTRA EPS-SM will monitor the battery level throughout LS-1 orbits to predict a future battery SoC based on the current mission requirements. In addition, the EPS-SM will be responsible for monitoring the state and health of the LS-1 EPS components and report anomalous behavior, fault conditions, fault diagnostics, and recommendations to the satellite VSM. The satellite VSM will send operational timelines and holistic failure assessments back to the EPS-SM. Using the VSM provided mission context, the EPS-SM will continuously assess LS-1's ability to power the required systems and loads to meet the current mission objectives by forecasting the battery's SoC based on current loads and future power needs to insure SoC does not go below a mission-defined SoC lower-limit. To protect LS-1, this lower-limit will be guaranteed to be greater than the satellite's operational lower-limit of 27.9V. When the SoC is predicted to be lower than the threshold within the minimum required operation time for current mission configuration then EPS-SM will determine which of the lowest priority loads to shed and provide the recommendations to VSM to shed. VSM will command Sidus' OBC to power-off the recommended loads and record the action and reason as a downloadable report and/or telemetry.

ASTRA Software Configuration

ASTRA will demonstrate operation on the LS-1 spacecraft leveraging NPAS, and the G2-SBN bridge to cFS software. Details of the software design and interface follow.

Each NPAS application (ASTRA VSM and EPS-SM) is run within a Linux Ubuntu 18.04 LTS Docker container. When the GPGPU system boots up, the application containers launch, which in turn launch the applications and respective G2-SBN communication bridge. All inter-ASTRA communication and ASTRA-LS-1 communication is implemented via cFS SBN messages. Bidirectional interface definition for SBN messaging will go between the ASTRA VSM and the LS Flight Computer. Command and telemetry between the ASTRA POCC and ASTRA VSM will go through the LS-1 Flight Computer.

Prior to the Sidus spacecraft modal/environmental tests, ASTRA FS v1.0 was loaded and verified on to the flight GPGPU. Upon deployment of the LS-1 spacecraft, ASTRA operates in AFF mode. While in AFF mode, ASTRA FS v1.0 will have the capability to perform remote software updates/reloads from the NASA Stennis ASTRA POCC. During AFF mode, all ASTRA applications operate in a strict monitoring-only mode. All communication between ASTRA FS and LS Flight Computer will be telemetry messages. ASTRA will accept command messages from ASTRA POCC and LS Flight Computer.

The ASTRA FS v2.0 will also have the capability to evaluate the on-orbit performance of LS-1 software to flight related real and/or simulated faults. ASTRA FS will include the capability to operate the satellite while on orbit and will execute nominal tasks approved by both parties, NASA and Sidus.

Goals of ASTRA VSM and EPS-SM

Intended mission goals for ASTRA VSM and EPS-SM follow:

Goals of VSM include:

- Command Sidus On-Board Computer (OBC) to power on/off component/s based on EPS-SM's recommendations
- Record the action/command, the reason for the command, and when the command was sent.
- Create an audit record and provide the record to ground in the form of a telemetry message and/or a downloadable report.

Goals of EPS-SM include:

- Perform trending on battery state-of-charge (SoC).
- Periodically forecast the time until the battery SoC is reduced below a specified threshold based current usage and publish for VSM.
- Modify parameters to meet mission objectives
    - Customizable battery SoC limit
    - Forecasted time until the SoC threshold is exceeded.

- Have a customizable table of component priorities.
    - Customizable table of load priorities
    - Remotely update the load priority table
- VSM executes load shed to deactivate LS-1 non-essential components and reduce power draw when low voltage Fault Detection limit trips.

ASTRA MISSION OPERATIONS

The following sections provides an overview of Mission Planning, Exercises and Rehearsals, Data Acquisition and Handling, Mission Safety, Mission Flight Rules, Astra Payload Activation, and ASTRA Mission Objectives.

During on-orbit operations, ASTRA operates in what is defined as Automated Flight Following (AFF) mode. Operating in AFF will include monitoring the health and status of the satellite and power system, as authorized by the Sidus Mission Operations Director (MOD). Approval and concurrence from the Sidus MOD is needed to send messages to LS-1 payload processor to autonomously accomplish targeted mission opportunities associated with managing LS-1 power, as needed.

ASTRA minimum success criteria includes successful activation of the ASTRA payload within 60 days of ASTRA power on, ASTRA performing one remote update while on orbit within 6 months of successful activation, and ASTRA successfully transitioning to a new version of ASTRA FS while on orbit. Minimum success criteria objectives were completed within the planned time requirements.

Mission Planning

Mission Planning (MP), which involves generating an approved two-week mission plan for the ASTRA payload, is performed by NASA SSC, under the direction and guidance of, and in concurrence with Sidus. The following planning priorities, listed in Table 5, are maintained during the mission:

Table 5: Mission Priorities

Priority 1	Prevent spacecraft Loss of Vehicle and/or Loss of Mission (LOM)
Priority 2	Successfully complete ASTRA Primary Mission
Priority 3	Non-Time Critical Activities
Priority 4	Time Critical Activities (assumes ASTRA FS v2.0 is in control state – VC mode)

Exercises and Rehearsals

A period of exercises and rehearsals was undertaken to ensure mission readiness. These activities range from mission planning, replanning, and data acquisition. While the operational procedures do not vary widely from standard defined procedures, these activities do ensure the readiness of all parties involved. All output, and results, from the exercises and rehearsal were verified and documented.

Data Acquisition and Handling

For compliance to current NASA cybersecurity protocols, data transfer to/from Sidus to the ASTRA SSC Payload Operations Command Center (POCC) meets or exceeds the current agency Data in Transit and Data at Rest protocols. All data shared between SSC and Sidus is considered Controlled Unclassified Information (CUI) unless otherwise specified. Access is controlled using a Virtual Private Network (VPN) using user certificates. Once users are on the VPN they must have credentials to login to InControl™ (COTS - satellite Command and Control, L3Harris) or must have an authorized Secure Shell (SSH) key to gain access to systems or servers. All ASTRA mission data is archived locally at the SSC Data Center.

Mission Safety

Software Assurance has assessed ASTRA FS based on NPR 7150.2D[15] and NASA-STD-8739.86[16] and determined that ASTRA FS v1.0, is classified as Class C not safety-critical. The software's classification and safety-criticality will be reassessed for future versions of ASTRA FS.

Mission Flight Rules

Mission flight rules describes the ASTRA Payload Activation and Mission Objectives. The ASTRA Payload activation procedure consists of requirements, GO/NO-GO criteria, and the procedure the ASTRA Payload is following upon power on. Mission Objectives include both Primary Mission Objectives and planned Secondary Mission objectives.

ASTRA Payload Activation

ASTRA payload activation states the required conditions of the LS-1 before ASTRA payload activation, provides the criteria for GO/NO-GO once the activation requirements were met, and lists the steps taken by the ASTRA payload after receiving power from the LS-1.

ASTRA Payload Activation Requires

- LS-1 OBC must be active and broadcasting telemetry. Ethernet switch must be on and connected to OBC and ASTRA GPGPU.
- Assumes same physical environmental conditions/safety conditions as LS-1 Payload processor (GPGPU)

ASTRA Payload GO/NO-GO criteria:

- Telemetry downlink communication between LS-1 and LS-1 MCC available for at least half of a communication window after transmission of the ASTRA Payload power-on command
- ASTRA personnel available on console

ASTRA Payload Power ON Procedure:

- LS-1 provides power to ASTRA Payload
- ASTRA FS will automatically launch after powered
  - ASTRA FS subscribes to LS-1 telemetry
  - ASTRA FS will initiate publication of status message

ASTRA Mission Objectives

Primary ASTRA Mission Objectives list the conditions to be met by the ASTRA Payload for a successful mission. Secondary ASTRA Mission Objectives list all other targeted objectives; however, failure to accomplish these objectives does not constitute mission failure.

ASTRA Primary Mission Objectives

1. Successfully activate the ASTRA Payload within 60 days of ASTRA power ON
   - Successful activation is confirmed by ASTRA sending a telemetry message to the SSC ASTRA POCC
2. ASTRA performs 1 remote update while on orbit within 6 months of successful activation
   - ASTRA successfully transitions to a newer version of ASTRA FS while on-orbit

ASTRA Secondary Mission Objectives

1. ASTRA performs on-board data collection of a subset of LS-1 telemetry
   - ASTRA successfully demonstrates on-board data collection by logging the receipt of LS-1 telemetry messages to SBN data logs
2. Demonstrate successful flight heritage of ASTRA Application
   - ASTRA is operational and sending telemetry for a minimum of 30 consecutive days in a spaceflight environment.
3. Demonstrate ASTRA FS operating in AFF mode
   - AFF mode is successfully demonstrated when SSC reports ASTRA FS mission operation recommendations to Sidus MCC
   - ASTRA performs additional remote updates within the lifetime of LS-1 mission
   - ASTRA successfully transitions to a newer version of ASTRA FS while on orbit
4. Demonstrate ASTRA FS operating in Vehicle Commanding (VC) mode
   - Upon flight opportunity designated by the Sidus MOD
   - Permission is provided by Sidus MOD for ASTRA to initiate VC mode
   - ASTRA send messages to LS-1 payload processor to autonomously accomplish targeted mission opportunities.

RESULTS

The Sidus team successfully completed the Launch and Early Operations Phase (LEOP) after establishing two-way communications with the orbiting spacecraft. After LEOP, the Sidus MCC team transitioned to the commissioning phase, conducting thorough performance evaluations of all critical subsystems. The Sidus MCC team activated each critical spacecraft component individually and as part of the entire system to verify satisfactory performance after two months in LEO.

Following these critical evaluations, Sidus confirmed that LizzieSat-1 had met the rigorous commissioning criteria and was operating effectively as a fully functional satellite. With this milestone achieved, the Sidus MCC team focused on activating payloads onboard LS-1 and executing critical mission activities to meet or surpass payload mission success criteria.

Upon completion of LS-1[17] commissioning phase, Sidus proceeded to support activation of the ASTRA payload. The ASTRA activation sequence included ASTRA FS v1.0 upload and two-way communications testing to ensure the hardware and software were functioning as expected. Upon completion, the ASTRA payload was deemed successfully commissioned, and primary mission objectives had been satisfied.

Following commissioning, the ASTRA team was able to successfully baseline the next ASTRA requirements for ASTRA FS v2.0 and complete both verification and validation (V&V) testing on the ASTRA Engineering Unit. FS v2.0 included autonomous power management to enable LS-1 to meet its mission power needs. Figure 6 shows a partial digital twin that encompasses the Solar Array Interface Module. This is a live digital twin that is populated with sensor and signal data coming from the physical sensors and from commands using the SBN bridge. The ASTRA EP-SM subscribes to all sensor data and commands that it needs to manage the LS-1 power systems.

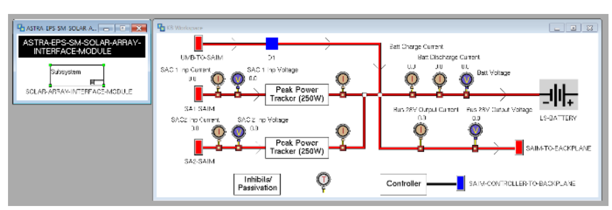

Figure 6: Partial Digital Twin of LS-1 Power System

The ASTRA Power Management Algorithm considers battery state-of-charge, availability of solar energy, opportunity to communicate to ground, and mission priorities to advise LS-1 when to shed loads to maintain an adequate margin of power[18]. Figure 7 shows the logic of the power management algorithm.

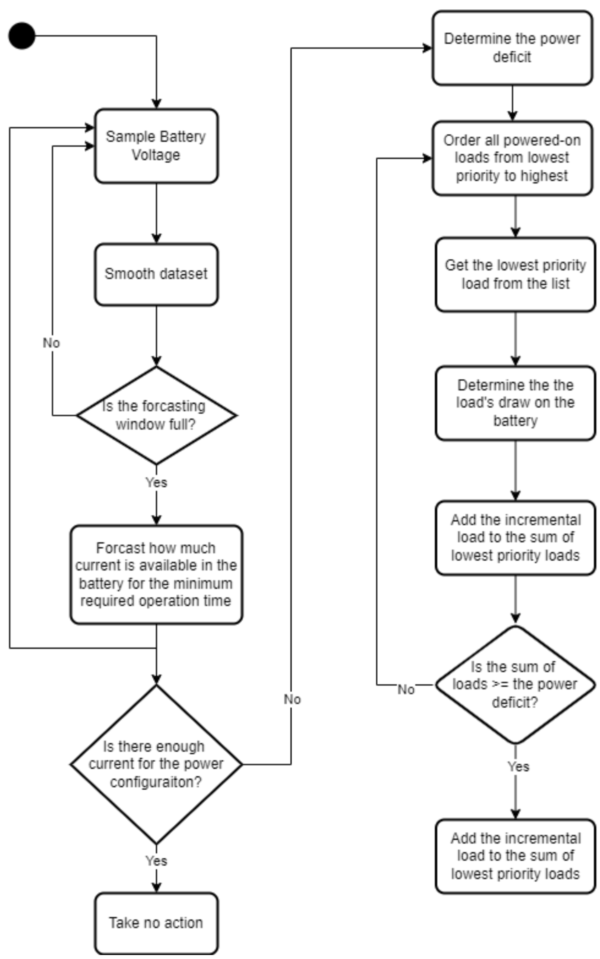

Figure 7: Power Management Algorithm

CONCLUSION

NASA SSC and Sidus Space established a partnership to demonstrate an on-board autonomy capability in a spaceflight environment. As a payload rider onboard the first Sidus LS-1 small satellite the ASTRA FS was successful in both completing activation and accomplishing primary mission objectives. As a payload rider on LS-1, ASTRA is providing a hybrid test bed for demonstrating autonomous operations on-orbit with ground simulation and validation. Using ASTRA autonomous operations technology in a spaceflight environment helps advance TRL and gain flight heritage for a GPGPU/ARM processor and the NPAS autonomous system development platform. Demonstration of autonomous operations on-orbit, on an advanced processor (NVIDIA), has cross-cutting relevance for autonomy contributions to advance technologies needed to increase trust in autonomous operations systems. In conclusion, autonomous operations are critical for enabling more capable, resilient, and cost-effective satellite missions, and has an increasingly important role in enhancing the efficiency and cost effectiveness of these systems.

SUMMARY

This paper provides a detailed description of a unique, and first implementation of on-board autonomy using NPAS, a platform developed at NASA SSC. ASTRA is a project that has enabled advancing the TRL of multiple technologies and their integration to achieve on-board autonomous behavior and operations in space. ASTRA's achievements include:

1. An avionics architecture for implementing autonomy capability while ensuring no new risks are added as the satellite can be operated by proven flight software when caution is required. This architecture includes a separate processor for autonomy and a ConOps to maximize autonomous operations while maintaining a desired risk posture.
2. Use of a next generation space-qualified processor capable of supporting autonomy computational and storage needs.
3. Use of an autonomy implementation and deployment platform developed by NASA, the NPAS that enables "Thinking" autonomous behavior that is sustainable and evolutionary, featuring a large code re-use and systematic/modular evolution.
4. Implementation of hierarchical distributed autonomy encompassing a VSM (that manages the satellite) and an EPS-SM (that manages the satellite power system) as network autonomous system managers communicating using the SBN protocol.
5. Use of SBN for integration of the NPAS autonomy implementation with the satellite flight software developed as a cFS application.
6. A ConOps was implemented for satellite autonomous operations supported by a ground stations and ground control rooms.
7. A load-shedding power system management strategy was developed to manage power while minimizing the risk of power depletion that would need involved recovery procedures driven from ground.

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