Launch & Early Operations Phase (LEOP) Iridium EyeStar-S4 24-7 Link with Mosaic-X5 GPS and Launch Results

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ABSTRACT

Satellite Mission Success is best achieved during the Launch Early Operations Phase (LEOP) when a satellite first becomes alive as radio data (TT&C) appears on the ground station within seconds. Using the Iridium global network, no matter where a tumbling satellite is in orbit, TT&C data is available anywhere-anytime. Diagnostic data, GPS, spin rates, live ADCS, temperatures, voltages, electrical power systems, primary processor, deployments, and payload monitors like plasma density or integral particle fluxes can all be tracked during the turn-on process with the option of disabling or adjusting command parameters to the unexpected. Several EyeStar-S4 flight NSL/Iridium transceivers can be linked to each bus subsystem or payload for quick-look data using the S4 microcontroller for a direct link to the ground. Although each S4 data rate is low (up to 100 bytes/s in some cases) the selected compressed data from each parallel S4 link can provide a wealth of information and science data with the TM frame formatter. After the LEOP phase of a few days, the S4 link can be optimized for sending back prompt, quick look, diagnostic, and scientific data for mission duration.

Flight results are shown of the S4 Iridium link from the NSL S4-CROSSOVER Sat (Astra launch, March 8, 2022) and the NSL TROOP-3 Sat (SpaceX launch, May 25, 2022). Each was in ~525 km polar orbit and tumbling at 40 and 8 RPM, respectively. Both the satellites sent "first light" packets of data soon after first transmitter turn-on to the NSL console via Iridium. Both rad tolerant satellites were operating for close two years before being decommissioned in early 2024.

NSL delivered the TROOP-F2 satellite (6U) for a SpaceX launch in June 2024. The satellite includes 1) three NSL-Iridium S4 transceivers with different antennas and pointing, 2) several Space Weather NSL-SWAP-E Lite sensors (Low Energy particle detector, Medium Energy Particle spectrometers, a total integral dose particle detector and a Plasma Probe), 3) several NSL Bus systems (new Mosaic-X5 GPS, new ADCS, EPS, rad hard solar cells, 900 MHz link for Sat-Sat or Sat-Ground transceiver, processors) and 4) a primary rendezvous experiment payload. In addition, 5) NSL has added two more GPS antennas to test the differential GPS capability (high-position accuracy and attitude determination required for science, rendezvous, and lower cross section for orbital debris mitigation).

The 6U SWAP-E (Space Weather Array Prompt Experiment) four-satellite constellation and the 6U RAPSat three-satellite mission are scheduled for late 2024 launch (they have 22 Flight S4 transceivers). To date NSL has 100% success of all flight EyeStar- early S3's and current S4's in orbit and the time ordered database on the NSL secured console is ideal for analysis and constellations.

Automation is everywhere in the S4 Iridium link from robotic assembly to smart algorithms. The web console is accessible from desktop or mobile to check incoming packets, send uplink commands, or receive SMS notifications. A Web API allows programmatic access.

INTRODUCTION

Satellite Mission Success is best achieved during the Launch Early Operations Phase (LEOP) when a satellite first becomes alive as radio data (TT&C) appears on the ground station within seconds. Using the Iridium global network, no matter where a tumbling satellite is in orbit, TT&C data is available anywhere-anytime. Diagnostic data, GPS, spin rates, live ADCS, temperatures, voltages, electrical power systems, primary processor, deployments, and payload monitors like plasma density or integral particle fluxes can all be tracked during the turn-on process with the option of disabling or adjusting command parameters to the unexpected. Several EyeStar-S4 flight NSL/Iridium transceivers can be linked to each bus subsystem or payload for quick-look data using the S4 microcontroller for a direct link to the ground. Although each S4 data rate is low (up to 100 bytes/s in some cases) the selected compressed data from each parallel S4 link can provide a wealth of information and science data with the TM frame formatter. After the LEOP phase of a few days, the S4 link can be optimized for sending back prompt, quick look, diagnostic and scientific data for mission duration. A good summary of past experiments with Iridium space link is called, "Lessons Learned Using Iridium to Communicate with a CubeSat in Low Earth Orbit" [1].

LAUNCH AND EARLY OPERATIONS (LEOP)

Flight results are shown in Figure 2 and Figure 1 of the S4 Iridium links from the NSL S4-CROSSOVER Sat (Astra launch, March 8, 2022) and the NSL TROOP-3 Sat (SpaceX launch, May 25, 2022). Each was in ~525 km polar orbit and tumbling at 40 and 8 RPM, respectively. Both the satellites sent "first light" packets of data within a few seconds of cold start first transmitter turn-on to the NSL console via Iridium. Both rad tolerant satellites have been in flight for almost two years no and still working well.

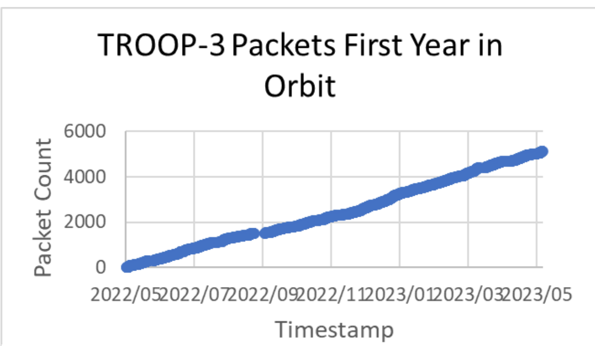

Figure 1 packet rate was nearly linear during the first year with about 14 packets per day to track critical data and health and safety.

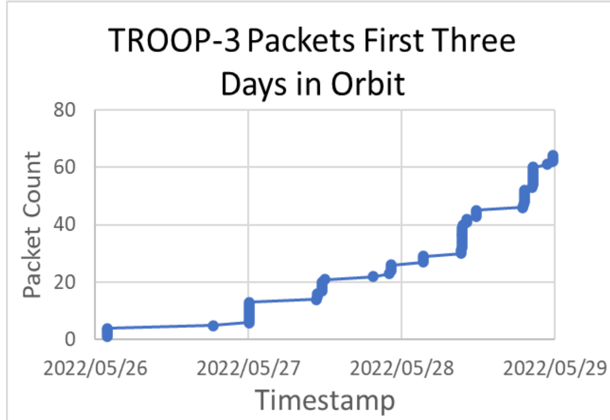

Figure 2 TROOP-3 cold start Turn-on command after being in orbit, each dot is a full packet of data received. Note data usually comes in burst as satellite is tumbling. Data rate designed to be low.

IRIDIUM LINK

The EyeStar S4 is 24/7 seamlessly connected to a secure internet within a few seconds or minutes to the client's server. The EyeStar is designed for constellations of satellites or for multiple EyeStar units per spacecraft. Some important features of the NSL EyeStar link via Iridium are listed below.

Over the past several years, NSL has gained substantial experience and expertise with delivering and operating the Iridium connected EyeStar-S4 (though we still have quite a bit to learn!). Since development started, over 118 EyeStar-S4 units have been delivered to partners. In the past year, over 10 EyeStar S4 units have been launched and operated in orbit. Results from some of the recent missions can be found below in Table 1, with on orbit data coverage shown in Figure 4.

With this experience and consistent development going hand in hand, this new link has been proven out with the following attributes.

Table 1 Results of 4 most recent NSL missions: S4-Crossover, and TROOP-3. Transporter 10, 11

Spec	S4-Crossover	TROOP-3	S4-A (T-10)	S4-LN	S4-F2 (T-11)
Launch Date UTC	3/15/2022 16:31:00	5/25/2022 19:31:42	3/4/2024 2330 UTC	3/4/2024 TBD UTC	7/2024 TBD at Launch Pad
Rocket	Astra Rocket 3	SpaceX Falcon-9	SpaceX Falcon-9	Nanoracks ISS	SpaceX Falcon-9
Orbit	SSO, 550x498, 97.5°	SSO, 534x539, 97.5°	SSO, 534x539, 97.5°	430 km orbit, 51.6° inclination	SSO, 534x539, 97.5°
Tip off	< 60 RPM	< 8 RPM	TBD	TBD	TBD
NSL Radios	S3, S4, GPS	S3, S4, GPS	5x S4s	S4	3x S4s, GPS
Sensors	Solar Temp, Bat, Mag	Bat V/Q, PIN	NA	NA	Particles, Plasma, Mag, ADACS,
Uplink	Yes	Yes	Yes	Yes	Yes
Downlink	Yes	Yes	Yes	Yes	Yes

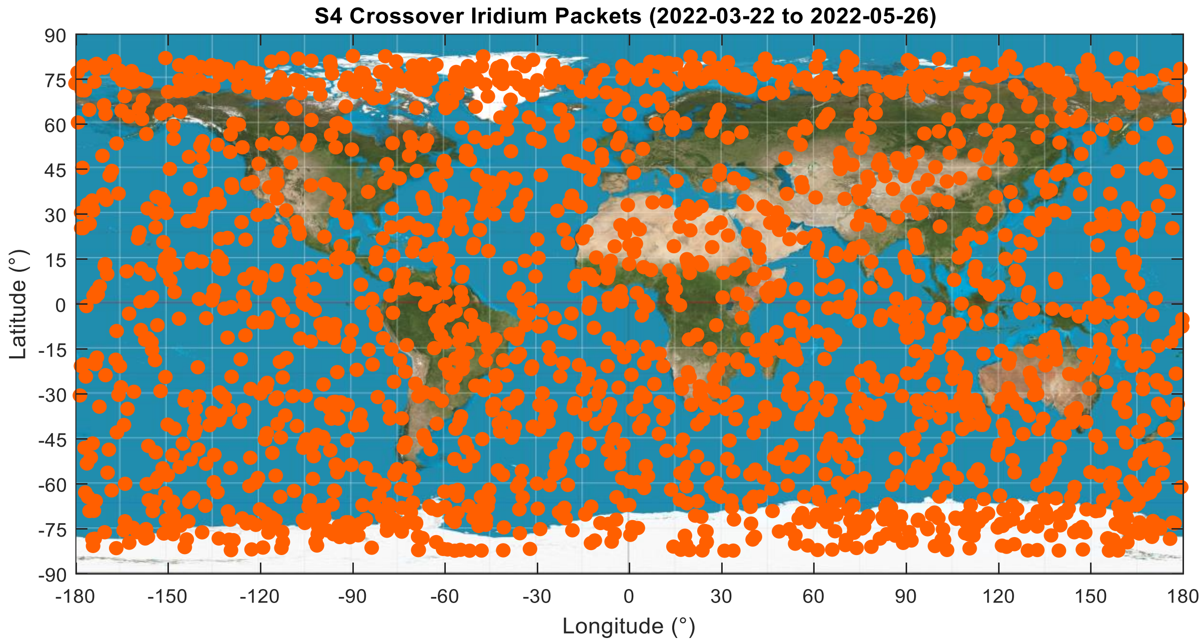

Figure 3 Global Iridium coverage data of transferred packets from the S4-Crossover mission. Using the Iridium TX firmware within the EyeStar-S4. Note the full global coverage, with increased connectivity over the polar regions.

Attributes:

- Coverage/Availability
  - Can operate anywhere below 650 km, down to low altitudes of 110 km for aerodynamic reentry and lower ionosphere.
  - Excellent polar coverage, no significant dropout zones inherent to geographical location in orbit, though some orbits can be more/less favorable.
- Data
  - Data Downlink and Uplink Available.
  - 10-202 byte packet every 15 seconds during favorable bursts, up to 1 Mbyte/day
  - Latency of 5 – 30 s from S/C to Console during a successful connection, L-band frequency use.
- Low SWaP-C
  - Standby Power = 18mA @ 7.0V.
  - Transmit Power, = 173mA @ 7.0V.
  - Size, LxWxH: 60.5 x 30.5 x 22.5 mm.
  - Mass: 29 g.
- Orbital Heritage
  - Tested at 600 km polar orbit over one year with S4-Crossover and TROOP-3.
  - Over 6 active radios in orbit receiving commands and downlinking data.
- Licensing/Certifications
  - FCC Compliant but need 6 months for license processing.
  - RE102, Vibe 14.1 Grms, Part 15.

Constraints:

- Orbit needs to be below 650 km for good Iridium connections.
- Data rate depends on orbit inclination (retrograde orbits have high Doppler shift), altitude, timing, stability, and accurate pointing.

Figure 4 Spaceflight NSL S4 Transceiver for the Iridium network and ground segment (TRL=9).

Option 1) Fast and accurate GPS, Mosaic-X5 direct to EyeStar S4

The GPS is critical for accurate flight navigation and pointing for generation of TLEs that also involves multi-constellations, and rendezvous. Above all the GPS must be robust to jamming and noise, lock rapidly to GPS satellites, work reliably, and consume low power. The Mosaic-X5 has an update rate of 100 Hz, differential GPS, L1, L2, L5, US, and power draw of 75mA at 3.3V. NSL will also be testing Rad hardness in orbit both standalone and with added spot shielding.

Option 2) GEO-Fencing with GPS module:

Many RF interference problems can be eliminated with Geo-fencing using the EyeStar Radio capability. A particular concern is transmitting near Radio Astronomy antennas (FCC concern as well), over international regimes with no permission/license, or interference with internal payloads. With Store and Forward (S&F) capability data can be captured anywhere at any time or at a higher rate over regions of interest (ROI) and then immediately transmitted through the network with time markers when outside the ROI. With accurate GPS and TLE orbit determination the EyeStar radio can respond using a command Time table when to shut off or go into burst mode.

Option 3) EyeStar-S4 integrated features to reduce interference:

The lower power of the S4, and fewer transmissions on orbit, are favorable for the FCC regulators and astronomers' noise reduction. The Iridium modem only transmits when the Signal-to-Noise (S/N) ratio is good, so no wasteful EMI transmissions, and very unlikely that any are directed towards the earth.

With Uplink commanding and autonomous operation, the S4 has the ability to change preset beacon rates and send raw commands to payload even under low-power, low-stability conditions. Payloads can power cycle subsystems, change pointing modes, uplink new orbit knowledge, enter fault recovery modes specific to the instrument, and perform operations to more consistently align with FCC requirements and minimize interfering transmissions.

SOFTWARE

NSL has continued development on its web-based Console, connecting desktops and smartphones to live data, basic telemetry, graphing, and TT&C monitoring. The Console can automatically send SMS messages to notify about first contact packets, error conditions on the spacecraft, or the availability of certain packet types. The Console allows direct access to send uplink messages to the EyeStar S4 Iridium queue, ensuring minimal latency from error detection to taking correctional action via uplink commanding. Dedicated uplink packet types are integrated to manage the S4's automated beacon rates, to ensure control even if the primary spacecraft computer is unable to interface to the radio. With the launch of TROOP-F2 in July, NSL will be testing additional functionality around mission management, automated orbit determination, and characterization of the S4. Finally, an API allows users to expand beyond the provided Console functionality.

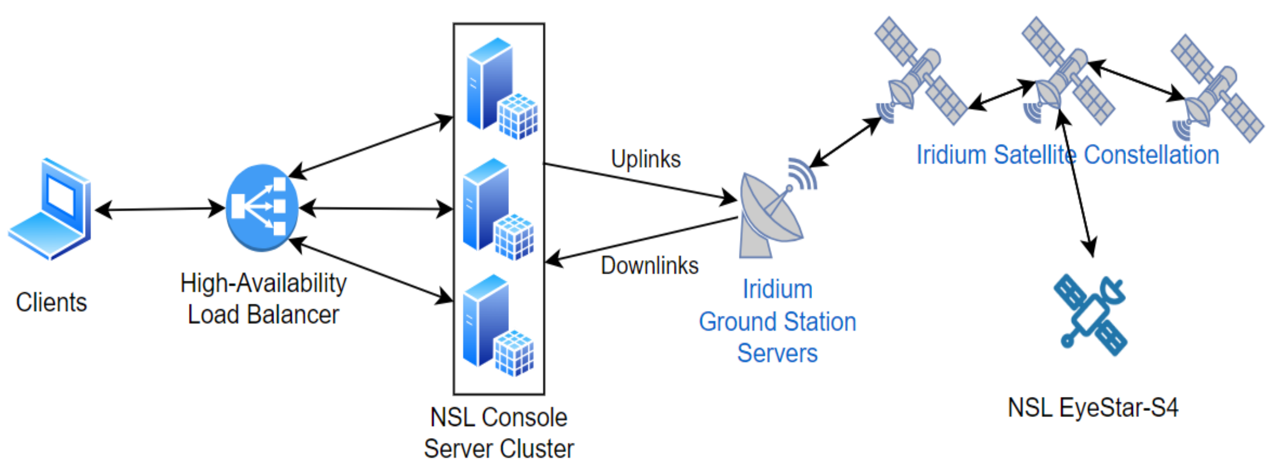

Figure 5 EyeStar-S4 Data Communications Pathway: Iridium-NSL Space and Ground Segments

CONSTELLATIONS

CubeSats were inspired by Prof. Twiggs' creation of 10cm on a side module basic dimension. ThinSats were developed in response to the need for lower-cost satellites and constellations with miniaturized sensors for high performance (ease of assembly, maximize solar array surface area for power, aerodynamic for lower drag or for deorbit, ease of testing, robotic assembly, improved thermal, high radar cross-section, and new paradigms of string interconnections) [2] [3]. Prof. Twiggs' creation of the 5 cm on a side PocketQube and implementation of the ThinSat concept were used to inspire STEM education, to drastically reduce student satellite cost, launch cost to space and cycle time to orbit (launch every 6 months). [4]–[5] The Virginia Commercial Space Flight Authority (Virginia Space), Twiggs Space Lab, LLC (TSL), Orbital ATK (Now Northrup Grumman Innovation Systems or NG), NearSpace Launch, Inc. (NSL), and NASA Wallops Flight Facility, collaboratively developed the ThinSat Educational Program with NSL, providing student teams the opportunity to design, develop, test, and monitor their own experimental payload which was integrated into a pico-satellite and launched from the second stage of NG Antares Rocket. [4]

All 60 autonomous ThinSats in the constellation were launched April 17, 2019 on an NG-11 Antares rocket for cargo resupply to the ISS. The 60-satellite constellation was mass produced using smart AM technology and using a strong rectangular frame with tab and socket on each sidewall to constrain and lock motion in two dimensions, while gently releasing in the third dimension. The 1/7U ThinSats were connected using a novel 30 cm long by 5 cm wide by 0.5 mm thick composite foldout using 5 nitinol hinges and a flex cable mechanical damper for power and communication bus.

The two parallel composite PCB plates (10x10x0.1 cm) with associated unibody frames with tabs are used to build the constellation with automation. The composite multilayered plates permit high density electronic part placements, thermal heat sink, EMI shield, radiation shielding, shear plane, and solar array thermal connection with a fused common bus electrical flex cable.

The spring-loaded foldout can also be used as a boom for experiments. It can support torques for stiffness and attitude control, unlike a tether, and can also connect to sensors. The ThinSats were daisy chained in strings with the foldouts so that six satellites have a length of 3 m. A 3U string with 21 ThinSats would have a length of about 8.5 m and improve formation coordination and gravity gradient stabilization. The foldouts were also used as an option to significantly increase solar cell area and power, maintain ground plane with plasma, and used with position control for increasing drag up to tenfold.

For improved performance, cost, and time the ThinSat concept can scale (see Figure 6) from 1/7 U to over 2 m (20U) and continuing scaling to the large Starlink "Thin" satellite example [6] [7].

In summary, ThinSats provide 1) Low-cost Robotic Assembly, 2) Large Solar Array and Thermal Radiation Area, 3) Decoupling noisy bus from high gain sensors, 4) Gravity gradient, aerodynamic, 3-Axis, other ADAC, 5) Easy testing, fewer Connectors, faster Workflow, 6) High Performance Advance Manufacturing, 7) Deorbit drag with 90 deg. rotation. 8) Multi satellite Strings option for cross calibrations, 9) Scaled technology for 1/7U to Star-link size constellation, and 10) String option for cross calibrations in early orbits.

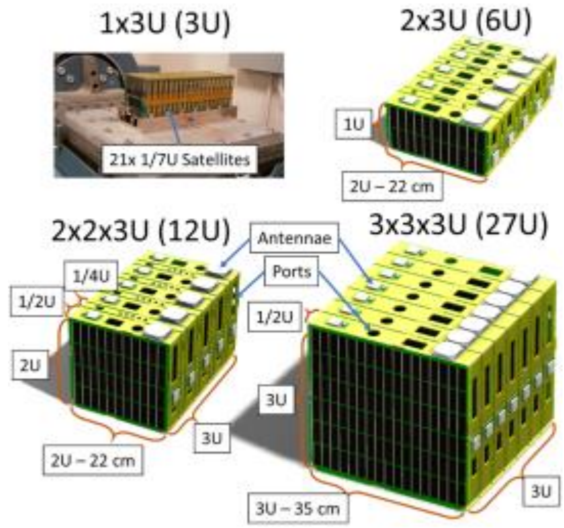

Figure 6 Larger 2.5 and 5 cm thick ThinSats permit improved volume for larger subsystems (e.g., ADACs and propulsion). Standard CubeSat launchers are available for use.

SWAP-E SBIR Satellite Project Example

SWAP-E is a Space Weather ThinSat constellation Array Experiment with Prompt data for forecasting and decision making and is currently being completed for flight in early 2025 as a SBIR Phase 2 grant. The 6U SWAP-E (Space Weather Array Prompt Experiment) four-satellite constellation is packed into a 6U canister.

SWAP-E addresses NASA R2O/O2R Strategic Action Plan for S5.06 SBIR area: Space Weather Instrumentation. A Space Weather (SW) array of 4 dual CubeSats (seen in Figure and Figure) released from a standard 6U deployer are linked through the Iridium constellation to provide near real-time ionospheric forecasting for 1000's of satellites. Each CubeSat provides low-latency connections via space-space links in a redundant, time-ordered, and common database (O2R) for prompt 24/7 data with a delay of seconds. In addition, an S-band transmitter is available high data rate links when needed.

The SBIR effort demonstrates a new satellite ThinSat platform to improve sensors in space with compact innovative instrumentation designed to validate SW models: energetic particle suite, plasma probes, sensors, and GPS. Each CubeSat string includes foldouts that

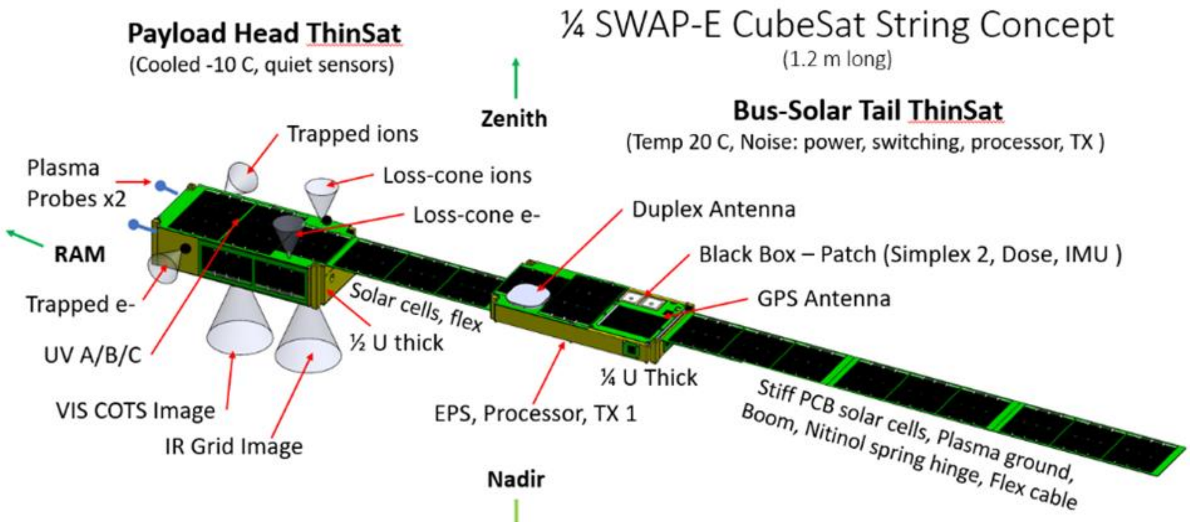

Figure 7 SWAP-E constellation layout for each of the four constellation CubeSats released from a standard 2U by 3U launcher unfold into a 1.2 m string as shown by two ThinSats and four Solar Array panels. The Larger ThinSat (5cm thick) contains the sensitive and passively cooled SW sensors while the ThinSat Bus (2.5 cm thick) contains all the relatively noisy spacecraft system functions of power, transmitters, flight processor, and solar arrays. A shielded electrical flat flex cable connects all of the foldouts and two ThinSats.

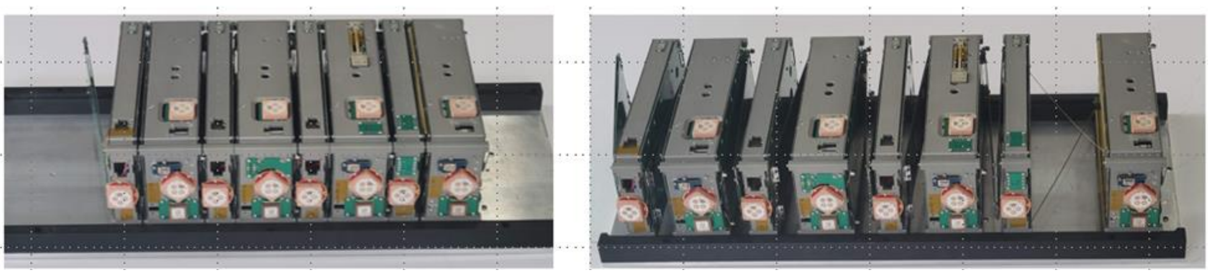

Figure 8 Final Flight SWAP-E four Satellite constellation in 6U Launch configuration (Left side) and illustrates how the four satellite strings unfold as they leave the 6U canister. Note the VLF two wire antennas fold out naturally with the last string unfolding. Also note all of the 12 EyeStar patch antennas.

separate the relatively noisy ThinSat Bus section from the quiet and cooled ThinSat Payload section to improve sensor performance. The SWAP-E 6U array of 4 CubeSats gives pole-to-pole orbit data every 12 minutes in the underexplored Space Weather VLEO region 100 to 400 km. Prompt and multipoint SW sensors improve rapid forecasting and understanding new energy transfer with the goal to deliver end user action.

The 6U SWAP-E four-satellite constellation and the 6U RAPSat three-satellite mission are scheduled for early 2024 launch (together they have 22 Flight S4 transceivers). To date NSL has 100% success of all flight EyeStar units (early S3's and current S4's in orbit). Lessons learned is that success is based on significant ground testing of end-end S4 data system and day in life testing to make sure all timing and specifications are met.

TROOP-F2 / SWAP-E Lite Ready for Launch

NSL delivered the TROOP-F2 satellite (6U) for a SpaceX launch in June 2024. The satellite includes 1) three NSL-Iridium S4 transceivers with different antennas and pointing, 2) several Space Weather NSL-SWAP-E Lite sensors (Low Energy particle detector, Medium Energy Particle spectrometers, a total integral dose particle detector and a Plasma Probe), 3) several NSL Bus systems (new Mosaic-X5 GPS, new ADCS, EPS, rad hard solar cells, 900 MHz link for Sat-Sat or Sat-Ground transceiver, processors) and 4) a primary rendezvous experiment payload. In addition, 5) NSL has added two more GPS antennas to test the differential GPS capability (high-position accuracy and attitude

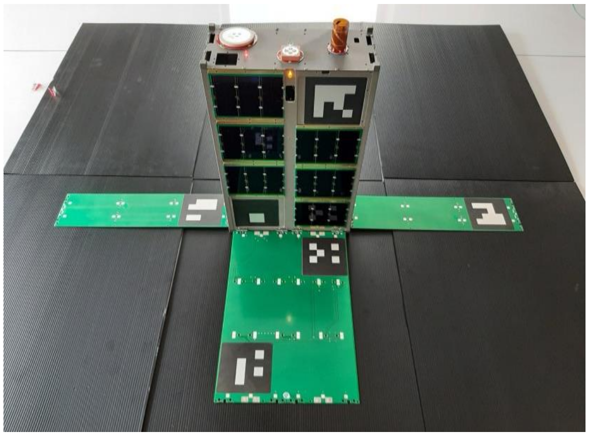

Figure 9 SWAP-E Lite presentation slide for risk reduction of SWAP-E bus and payloads.

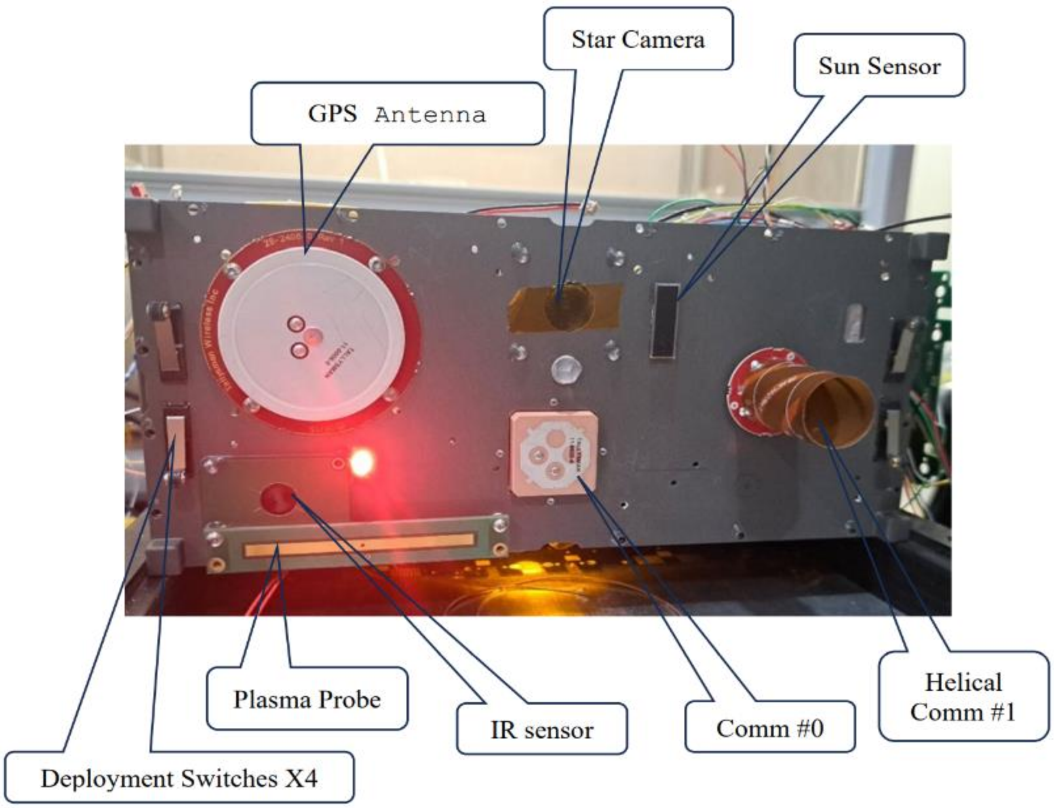

Figure 10 End panel of TROOP-F2 / SWAP-E Lite showing the array of antennas and sensors.

determination required for science, rendezvous, and lower cross section for orbital debris mitigation).

In addition to the primary mission of TROOP-F2, the satellite also contains the SWAP-E Lite package, which reduces risk for the SWAP-E mission by testing some of the bus and payload systems of SWAP-E. Some of these systems include

- New NSL ADCS with Horizon and Sun Pointing.
- New NSL RadStar particle detector suite.
- New NSL GPS with higher precision and faster cold start acquisition times.
- NSL Plasma Probe.
- NSL 3 axis fluxgate magnetometer.
- NSL Solar arrays.

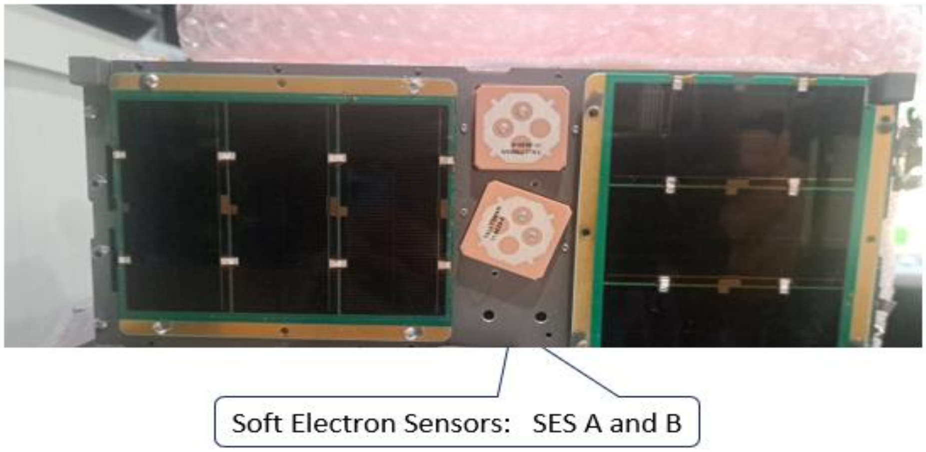

Figure 11 +Z Endplate of TROOP-F2 / SWAP-E Lite showing the solar panels and S4 antennas.

- Multiple S4 radio and antenna configurations to maximize connectivity on orbit.
- Direct comparison of different S4 antennas on orbit.
- ARMAS particle detector payload.
- SES particle detector payload.
- New S4 firmware and analysis techniques for improving and characterizing on orbit performance.

Some of these systems can be seen in Figure 9, Figure 10, and Figure 11.

CONCLUSIONS

Small Sat transition from Globalstar to Iridium links continue to offer near real time 24/7 coverage with the added benefit of a commanding uplink. With a max transfer rate of up to 100 byte/sec (202 Bytes/packet), and an average of 13 bytes/s (during favorable conditions) results in up to 1 Mbyte per day. Using just 1% of this bandwidth (10 Kbytes/day) many bus and payload systems can achieve full mission success using compressed data, log counting, and burst mode data at times of interest. Latency of the link is on the order of seconds to a few minutes making the satellite fully visible for attitude control, summary data with forecasting, resolving early problems, and responding with real time commanding.

Typical critical data in a continuous 1 byte/s data stream could include most health and safety, voltages, currents, mag, GPS, attitude vectors, all payload sensor responses, integral fluxes, and much more. All this first day data makes use of the Iridium constellation ground segment connected with data sent directly to the payload IP address for instant mission success milestones. In addition, ThinSats also support high data rates (S, X, Ku bands) radios with Ground stations. The new F2 6U CubeSat is ready for launch in one month and will be testing hardware improvements and algorithms.

ACKNOWLEDGMENT

We would also like to give special thanks to Iridium Engineers, Managers, and Legal for their devotion and commitment to optimize their powerful constellations for real-time Sat-to-Sat links. Mike Miller, as our FCC legal engineer, did a fantastic job helping us with navigating the FCC requirements.

We would like to thank Space Force for RAP-Sat SBIR, NASA Space Weather SBIR, Spaceflight Inc for several satellite launch integrations and rides, Space-X rideshares, Astra Rocket 3 successful integration and flight, VOX Launcher One, and NSL for internal project funding.

Special thanks to Mike Schuckel and the NSL team for developing so many successful satellites in a short period of time with 100% success. Thanks to many students, faculty, and staff at Taylor University who worked many volunteer hours to make ThinSats for student STEM learning. Several Taylor faculty were also involved consulting on NSL software data programs and orbital analysis. Thanks to the NSL team for funding this Data Analysis Research and drafting this SSC paper.

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