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Thin CubeSats and Compact Sensors for Constellations in VLEO to Deep Space

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ABSTRACT

ThinSat form factors have many advantages for constellations and are launched directly from all standard 1U to 27U CubeSat canisters. Currently NSL is completing two 6U constellations for launch in 2023. The Space Weather NASA SBIR Phase II consists of 4 satellites, each with dimension 7.5x10x20cm. Novel and compressed Space Weather instruments are being developed by NSL partners. Each satellite can be divided into two ThinSat sections separated by a 20 cm foldout to serve as a 1) sensor boom, 2) quiet low noise Faraday sensor box, 3) passively cooled from -40 to + 40 C platform, and 4) cleaner sealed sensor environment depending on sensor requirements. The Space Force SBIR Phase II consists of four longer ThinSats with each dimension of 2.5x10x30cm. ThinSats can be connected together to form thicker satellites for larger subsystems and identified as 2T, 3T, 4T, and others. Significant ThinSat advantages include 1) Ease of robotic assembly at lower cost, 2) Larger surface area for solar cells and sensors compared to cubes, 3) Aerodynamic for low altitude ionospheric planetary measurements, 5) Ease for workflow and testing, and 6) Superior low-noise isolation.

ThinSats also include 24/7 sat-links using improved Iridium (TX & RX) and previous Globalstar (TX) communication constellations. Recent NSL launches in the past two years will illustrate ThinSat sensor data and orbital results. GEARRS-3, TROOP-1, 2 and 3 launches and NSL ExoSat payload with many miniaturized sensors onboard is scheduled for 2023 launch on NASA EM-1 Deep Space measurements.

INTRODUCTION

ThinSat form factors have many advantages for constellations and are launched directly from all standard 1U to 27U CubeSat canisters. Currently NSL is completing two 6U constellations for launch in early 2023. The Space Weather NASA SBIR Phase II consists of 4 satellites with each dimension 7.5x10x20cm. Novel and dense Space Weather instruments are being developed by NSL partners from Laboratory for Atmospheric and Space Physics, Space Environmental Technologies, and The Aerospace Corp. Each satellite can be divided into two ThinSat sections separated by a 20 cm foldout to serve as a 1) sensor boom, 2) quiet low noise Faraday sensor box, 3) passively cooled from -40 to +40 C platform, and 4) cleaner sealed sensor environment depending on sensor requirements. The Space Force SBIR Phase II consists of four longer ThinSats with each dimension of 2.5x10x30cm. ThinSats can be connected together to form thicker satellites for larger subsystems and identified as 2T, 3T, 4T, and others. A constellation of 60 educational ThinSats (each autonomous withs own radio link) were successfully deployed in 2019 by NSL from three 3U launch tubes. All appeared to unfold gracefully into their respective “strings” of multiple ThinSats. with the novel spring-loaded articulating panels. Significant ThinSat advantages include 1) Ease of robotic assembly with a larger flat PCB area, 2) Larger surface area for solar cells and sensors compared to cubes, 3) Aerodynamic for low altitude ionospheric planetary measurements, 4) Significant lower cost with AM mass production, 5) Ease for workflow and testing, 6) No internal special release mechanism, 7) Improved thermal surface/tape, 8) Pushing more dense new technologies like in cell phones, 9) Have larger radar cross sections, 10) Ease of calibration, and 11) Superior low-noise isolation. Powerful new and miniaturized instrumentation include:

large area and geomantic factor energetic particle spectrometers and Telescopes, dosemeters, low energy particle detectors, Langmuir probe plasma density with sweep, RF plasma probes, VLF receiver, boom mounted 3 axis fluxgate magnetometer, Photon IR, Visible, UV, X-ray sensors and imagers, miniaturized GPS, and many others. Attitude Determination and Control (ADACs) include 3-axis with star tracking, nadir pointing, spin stabilized, passive magnetic, aerodynamic, and gravity gradient above 400 km. ThinSats also include 24/7 satellite links using existing phone constellations, X-Band high-data rate links, and available deep space radio links with ADAC pointing, to ensure prompt performance and Mission Success. Recent NSL launches in the past two years will illustrate ThinSat sensor data and orbital results [1] [2] [3] [4]. NSL ExoSat payload recently completed with many miniaturized sensors onboard is scheduled for launch on EM1 for Deep Space measurements.

IRIDIUM NETWORK LINKS WITH 24/7 PROMPT DATA

After the initial NSL flight in 2014 that demonstrated Globalstar capacity and performance for the first time NSL has now flown over 175 Simplex radios in orbit for universities, NASA, DOD, and industry with 100% success. NSL is now phasing out all new Simplex units by 2023 while continuing to support all S3 radio downlink data for the endurance of their operations into the foreseeable future. Building off the legacy from Globalstar to Iridium constellations is mutual between all stakeholders. The new modified for space NSL-Iridium radios now add commanding to their downlink features. NSL has recently launched two successful Iridium TX/RX links into space in 2022 for demonstration and testing.

Iridium and Globalstar links offer max transfer rates of about 1 byte/sec or 80K Bytes per day. Using just 10% of bandwidth (8 Kbytes/day) many bus and payload systems can achieve full mission success using compressed data 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, GPS, attitude vectors, all payload sensor responses, integral fluxes, and much more. All this first day data is pricelist but only cost about $40 per day that includes Iridium's

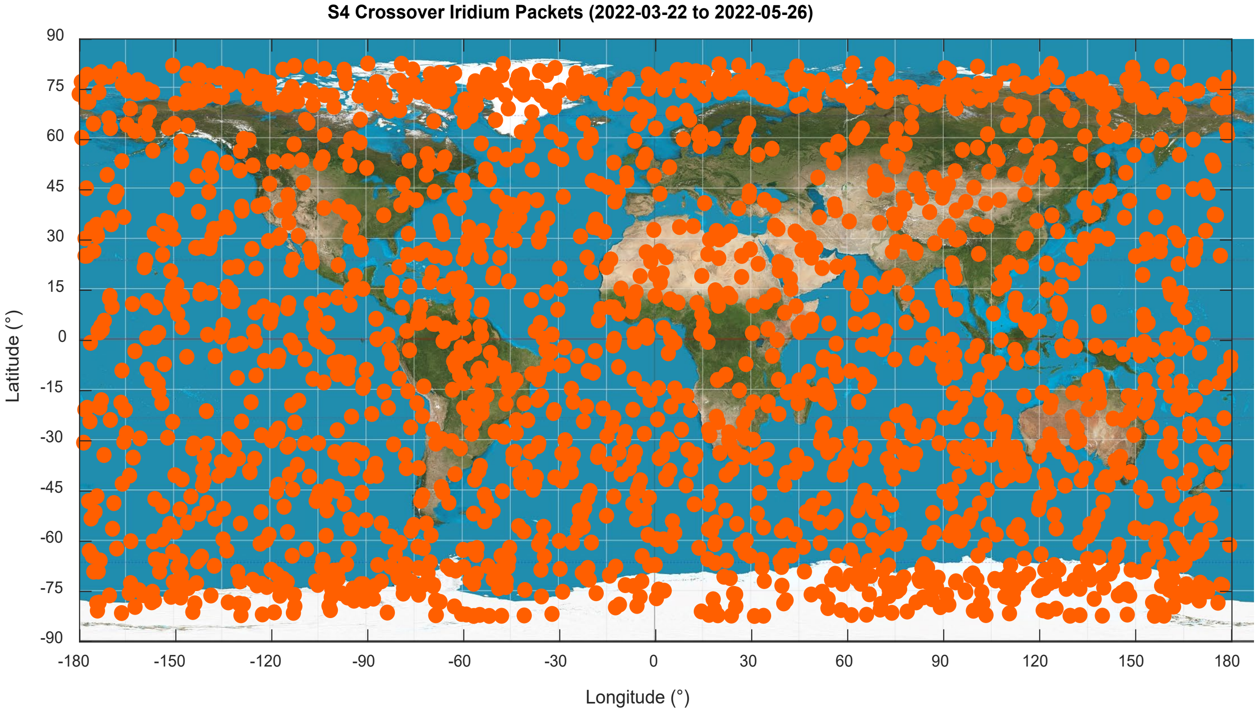

Figure 1 Global Iridium coverage data of transferred packets from the S4-Crosoover mission, using the Iridium TX firmware within the EyeStar-S4. Note the full global coverage, with increased connectivity over the polar regions.

constellation ground segment connected with data sent directly to the payload IP address.

Launching on May 15, 2022, the NSL-Iridium S4-Crossover was the primary payload onboard the Astra S4-Crossover (Spaceflight Astra-1) mission. Hard-mounted to the launch vehicle 2nd stage, the S4-Crossover collected relevant location and health & safety data on the booster for the duration of the orbit lifetime.

The primary payload of the S4-Crossover was the new EyeStar-S4, a simplex transceiver capable of transferring data to and from the Iridium constellation. Though the booster uncontrolled in a spin motion, the EyeStar-S4 maintained consistent connectivity throughout the mission duration. Global data coverage of transmitted packets over the globe are plotted in Figure 1.

Observed from the on-orbit data is the clear indication that the EyeStar-S4 was able to successfully establish connections with the Iridium network and transfer packets over the entire globe. With no discernable dropout zones, the coverage is especially noteworthy over the high latitude regions of the poles. Not only were packets downlinked to the ground via the Iridium network, but commands were also consistently uplinked through the mission. No difference was observed in the connectivity of the uplinks vs downlinks.

With only minor fluctuations in the flight data, the S4-Crossover showed that the EyeStar-S4 was able to achieve uniform global coverage through the Iridium network, with pole-to-pole connectivity and commanding capability.

Figure 2 shows the EyeStar-S4 Iridium packets versus time from the S4-Crossover mission. Small time scale was chosen to illustrate the timing between packets. Respective packet timing is 12, 10, 20, 35 s apart. Each packet was 18 Bytes.

Table 1 list some of the recent NSL missions that have flown the Globalstar S3 and iridium S-4 radios.

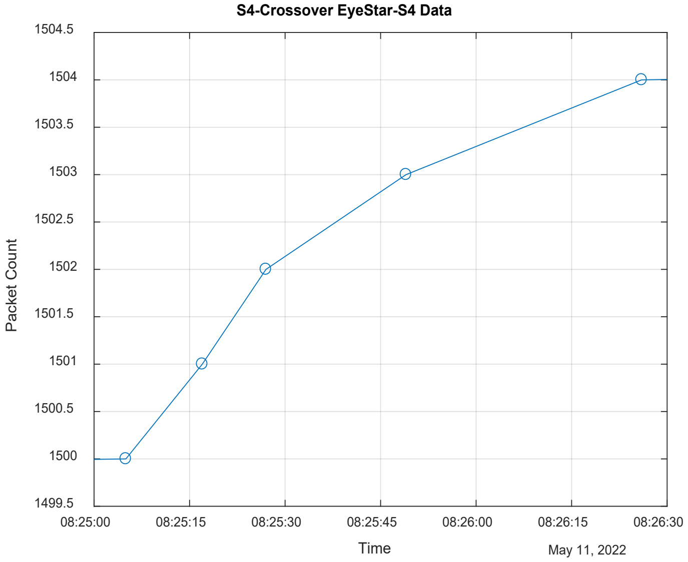

Figure 2 Each packet was 18 Bytes. EyeStar-S4 Iridium transferred packets from the S4-Crossover mission. Small time scale chosen to illustrate the timing between packets. Respective packet timing is 12, 10, 20, 35 s apart. The Crossover Satellite was spinning reducing overall thruput even though a packet is transferred within a second.

"CELL PHONE" TECHNOLOGY

Great advances and performance improvements are achieved in Small-Sats using miniaturization of sensors, electronics (using gate arrays, FPGAs, flex cables), integrated systems, robotic assembly, and new technologies.

A System Block Diagram is shown in Figure 3 of the existing ThinSats Bus for our NASA Space Weather Array for 24/7 Prompt Global Coverage Experiment. (SWAP-E) constellation for four satellites. The dashed-in boxes are the NSL EyeStar- Iridium radio product. The subsystems in larger ThinSats are smaller since overhead is relatively smaller. SWAP-E satellites have other options based on the preferred configuration.

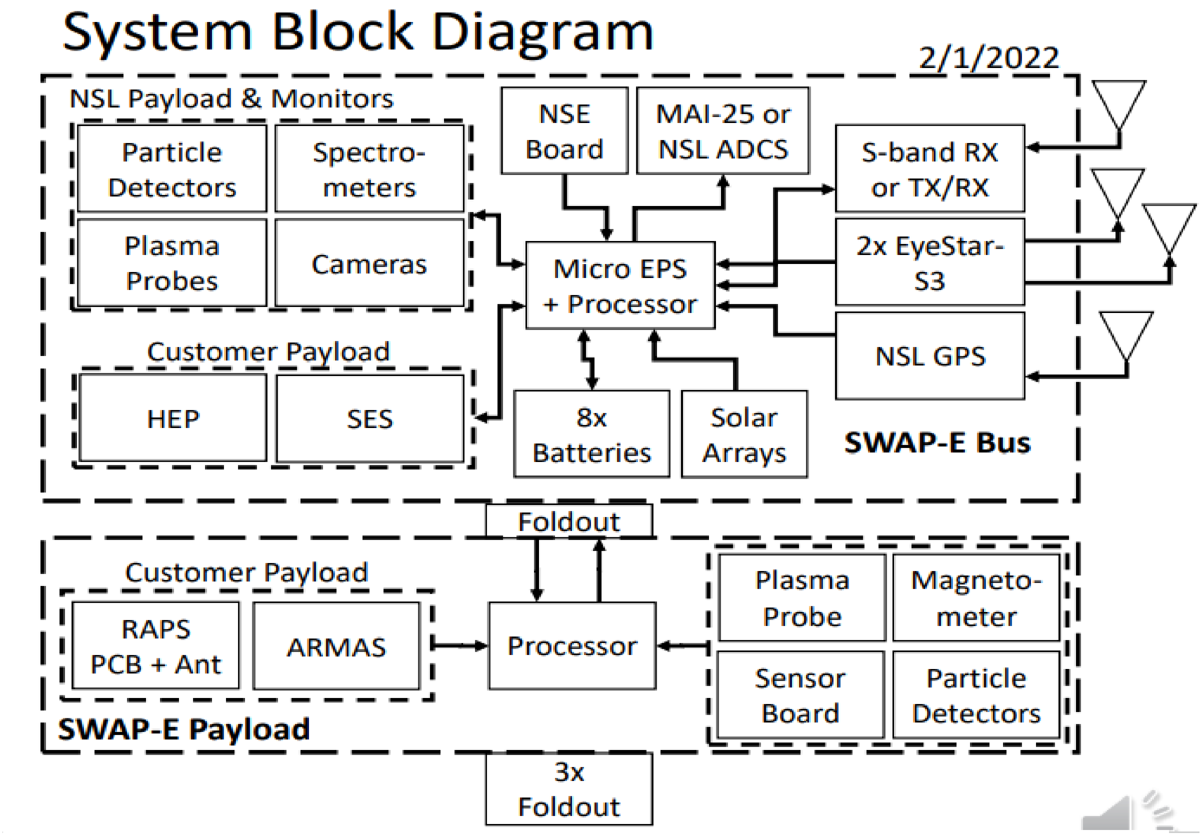

Figure 3 ThinSat System Block Diagram for ¼ of the SWAP-E constellation showing many of the compact and integrated systems.

Table 1 Results of 3 most recent NSL missions: GEARRS-3, S4-Crossover, and TROOP-3.

Spec	GEARRS-3	S4-Crossover	TROOP-3
Launch Date	1/13/2021 23:46:00 UTC	3/15/2022 16:31:00 UTC	5/25/2022 19:31:42 UTC
Rocket	VOX Launcher One	Astra Rocket 3	SpaceX Falcon-9
Orbit	SSO, 500x500, 90°	SSO, 550x498, 97.5°	SSO, 534x539, 97.5°
Tip off	~2.5 RPM	< 60 RPM	< 8 RPM
Current Tumble	~2.5 RPM	< 40 RPM	< 8 RPM
Radios	S3, BB-P (S3, GPS), GPS	S3, S4, GPS	S3, S4, GPS
Sensors	Mag, Plasma, PIN, Solar V, BUS+, Bat V/Q	Solar Temp, Bat V/Q, Mag	Bat V/Q, PIN
Uplink	NA	Yes	Yes
Downlink	Yes	Yes	Yes

WHY THINSAT STRINGS AND SCALED ARCHITECTURE: SIXTY 1/7 U THINSAT STEM

Since first presented [5] in 2014 ThinSats have also been called PCB-Sats, "Flat" Sats, Swarm-Sats, and Disc-Sats. Some of the advantages for going with a ThinSat constellation versus cubes include the following considerations:

1) Ease: Automated "pancake assembly" using two exterior parallel PC Board composite & structural assembly, shielding for radiation and EMI reduction, NSL-Iridium Product with antennas fits with 24/7 real-time monitoring for ordered database.

2) Larger Solar Array: Area and Fit with fixed volume compared to a CubeSat

3) Aerodynamic: for less drag when narrow ThinSat edge is pointing into ram direction. Controlled drag if rotated 90° to ram.

4) Significant Lower cost: by a factor of 5 for constellations to manufacture compared to using many smaller PC boards with connectors. One Main PCB with few connectors.

5) Easy Testing: and Debugging of ThinSat since it is comparable to a Flat-Sat. Easy workflow with multiple subsystems.

6) Advanced Manufacture: and Robotic mass assembly with modular ThinSat frames and 3D printing.

7) No internal launcher: required for ThinSats since they stack in existing CubeSat launch tubes and convenient for controlled release.

8) Improved Thermal: surface area ideal heat dissipation and isothermal shorting.

9) Great for pushing New Technologies to smaller cell phone sizes.

10) Can have much greater Radar cross section especially with the foldouts for tracking.

11) Ease of calibration, charging, Burn-in, and environmental Testing,

12) Isolation can separate noisy Bus and payload sections with a foldout: Isolation of sensitive low-power plasma, magnetic, and cooled experiments.

13) A concern with the ThinSats form factor is the volume constraint, but this can be mitigated with multiple T-sections in series or parallel or Scale to larger ThinSats.

14) Architecturally, ThinSat Modules can also be tied together directly or in groups (Strings) to provide improved data collection, workflow, redundancy, and solar/battery power. Standard CubeSat launchers range from 3U to 27U for availably as shown in Figure 6. In a 27U launcher six large ThinSats can be released that are 30 x 30 x 5 cm in size.

The ThinSats were developed in response to Prof. Twiggs' creation of the 5 cm on a side PocketQube to inspire STEM education, to drastically reduce student satellite cost, launch cost to space and cycle time to orbit (launch every 6 months). [5] [6] [7] [8] [9] [3] 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, have 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. [10]

All 60 autonomous satellites 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.

Figure 4 STRINGS: Educational Demonstration ThinSat Launch into a VLEO orbit on April 17, 2019 from Wallops Island, VA on NG-11 resupply ISS mission. Three 3U CSD launch containers each contained 21 ThinSats and 4 strings each for a total of 12 strings.

WHY VLEO IMPORTANT… NEW STUDY OF IONOSPHERE BELOW 350 KM

The Very Low Earth Orbit (VLEO) below 350 km or Extremely Low Earth Orbit (ELEO) Region (90 to 160 km) can now be explored with periodic launch of constellations of affordable small satellites. ThinSats are particularly suited for new research opportunities in this new region, DOD intelligence gathering, Space Weather multipoint measurements, and education. Some new areas for investigations include:

1) Science: Underexplored region of space that is very important for Atmosphere Climate coupling, Space Weather, Global Electric Circuit, E-F region, *in situ* Ionosphere, precipitating energetic particles, gravity waves, and much more! See science papers [11].

2) Technology and DOD: Aerodynamic control, Reentry Physics, tethers, Intelligence gathering, remote sensing, ion thrusters, radar calibration, attitude control, testing parts to TRL=9.

3) Little Space Debris Concern: Lifetime weeks to months, Ideal for constellations, Much less Radiation or damage from solar flares.

4) Aerodynamic ThinSats: for making unprecedented measurements with low-cost satellites for instant monitoring of waves, plasma, particles, EM spectrum, constituents, and remote sensing.

5) Radiation Shielding: of atmosphere in VLEO orbits greatly reduces Radiation Damage (Resilience).

6) Educational: space for many consecutive low-cost missions… a sandbox for rapid innovation.

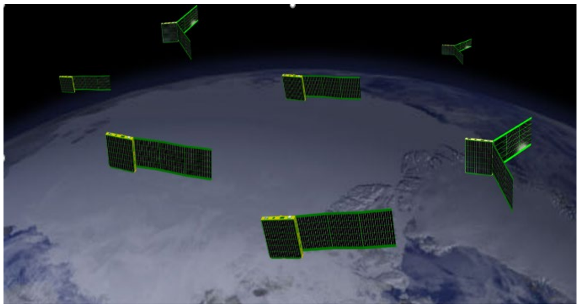

Figure 5 Autonomous NODE ThinSat Configuration: Multipoint & Instant Data to the Internet.

By adding a radar reflective box and solar array foldouts to each ThinSat the tracking and power available does not require the satellites to fly in strings. The independent NODE ThinSat configuration give more multipoint measurements with instant data available to the internet as illustrated in Figure 5. In addition, Constellations can be launched that are hybrids of both parallel and serial attachment of ThinSats providing more payload volume and increasing ballistic coefficient.

SCALING CONSTELLATION & MANUFACTURE

For improved performance, cost, and time the ThinSat concept can scale from 1/7 U to over 2 m (20U) with the Starlink "Thin" satellite example. See Figure 6, Figure 7, Figure 8, and Figure 9 for scale comparisons for 21 1/7U ThinSats in a 3U, 5 Satellites in 6U, 5 larger ThinSats in a 12U, 7 larger ThinSats in a 27U.

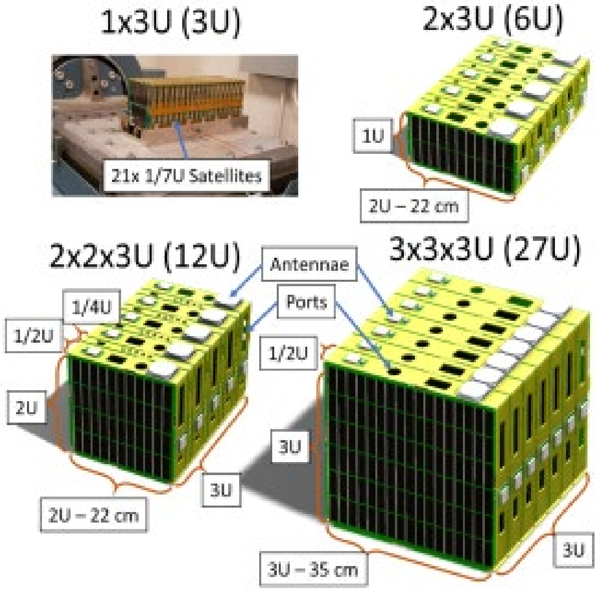

Figure 6 Larger 2.5 and 5 cm thick ThinSats permit improved volume for larger subsystems (e.g., ADACs and propulsion). Standard CubeSat launchers are available for use.

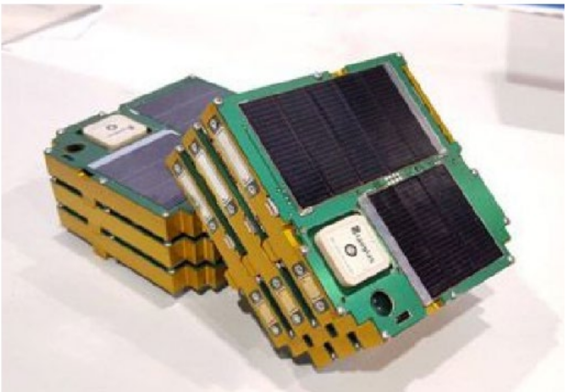

Figure 7 Completed sets of ThinSats in groups of three locked together with tabs and slots to fully constrain in X and Y directions.

Figure 8 3U stack of 21 ThinSats mounted to a Test Fixture secured to the vibration table for testing. All three 3U CSDs passed testing for the Northrop Grumman Antares rocket.

Figure 9 NSL launched sixty 1/7 U ThinSats in three 3U launcher tubes on April 17, 2019 and SpaceX launched 60 much larger (over 2 meters) Starlink "ThinSats" for the first time [13] [14] on May 23, 2019. Shows dramatic scaling of ThinSats for constellations and performance enhancements.

To significantly reduce small satellite constellation cost it is also advantageous to make use of mass production techniques that maintain high mission assurance while implementing new miniaturized mechanical and electronic technologies, 3-D printing, bulk CNC machining, automated pick-and-place electronic assembly, automated computer testing and inspection of each node, trace and function. In addition, a rigorous burn-in, day-in-the-life, environmental vibration, thermal-vacuum, and other tests as required. By building test fixtures 21 satellites were locked together for diagnostics during testing. Another innovation was an automatic diagnostic test connector for each subsystem with the ability to charge up to 84 ThinSat batteries in parallel.

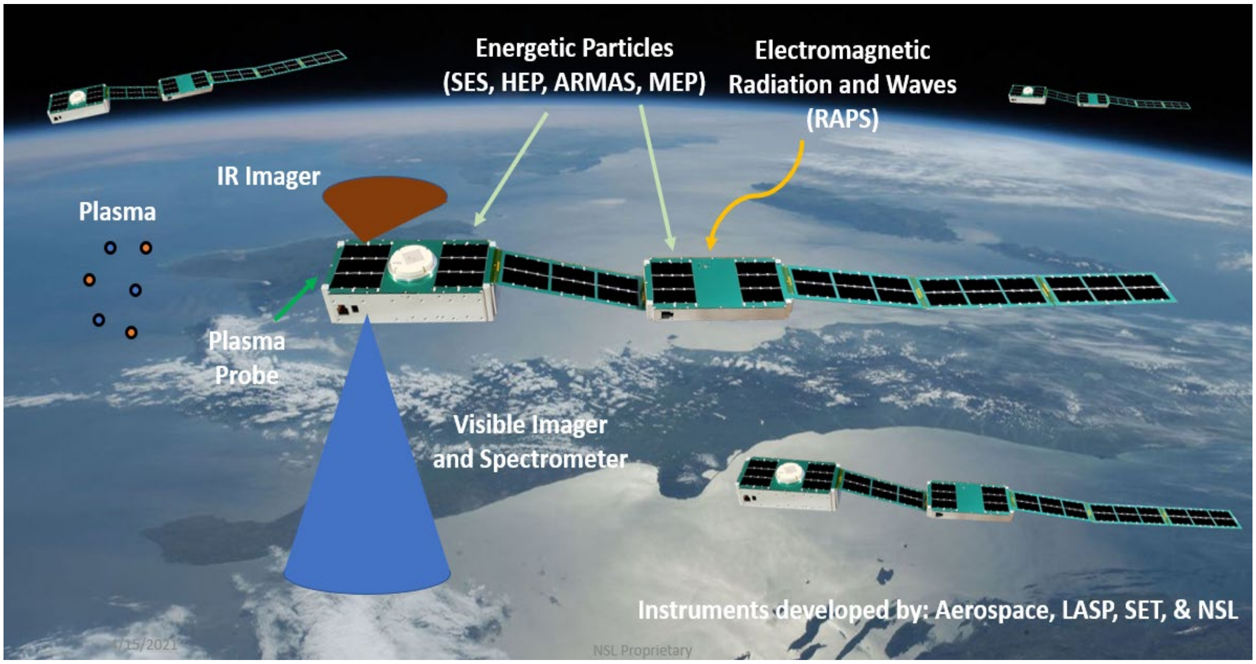

Figure 10 Illustration of String of multiple satellites and SWAP-E Phase II design for each of the four constellation ThinSats released from a standard 2U by 3U launcher that unfold into a 1.2 m string (shown as two ThinSats connected with four solar array panels. The Larger ThinSat (5 cm thick) contain the sensitive and passively cooled Space Weather 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.

Strings are ideal architectures as shown in Figure 10 for data and power connection between individual ThinSats and for coordinated experiments with different requirements such as 1) a ThinSat with GPS, IMU, cameras, 2) a propulsion unit with extra batteries (like train coal car), 3) Bus Comm systems, and 4) sensitive space weather experiments.

SWAP-E SBIR satellite Project

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 2023 as a SBIR Phase 2 grant.

- Merit: 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 10) 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 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.

- Feasibility: Currently most of the SWAP-E Bus subsystems and sensors been tested in orbit on two SpaceX rideshare flights in 2021-2022 and a 2022 Astra flight for SWAP-E risk reduction and radiation testing. NSL has flown 450 commercial subsystems in orbit with 100% success. The SWAP-E Prototype will be completed through TRL = 5- 7 for orbit demonstration in 2022

A key architectural innovation of SWAP-E is the division of a CubeSat into two unfolded ThinSats rigidly connected by four stiff solar array panels to form a rigid

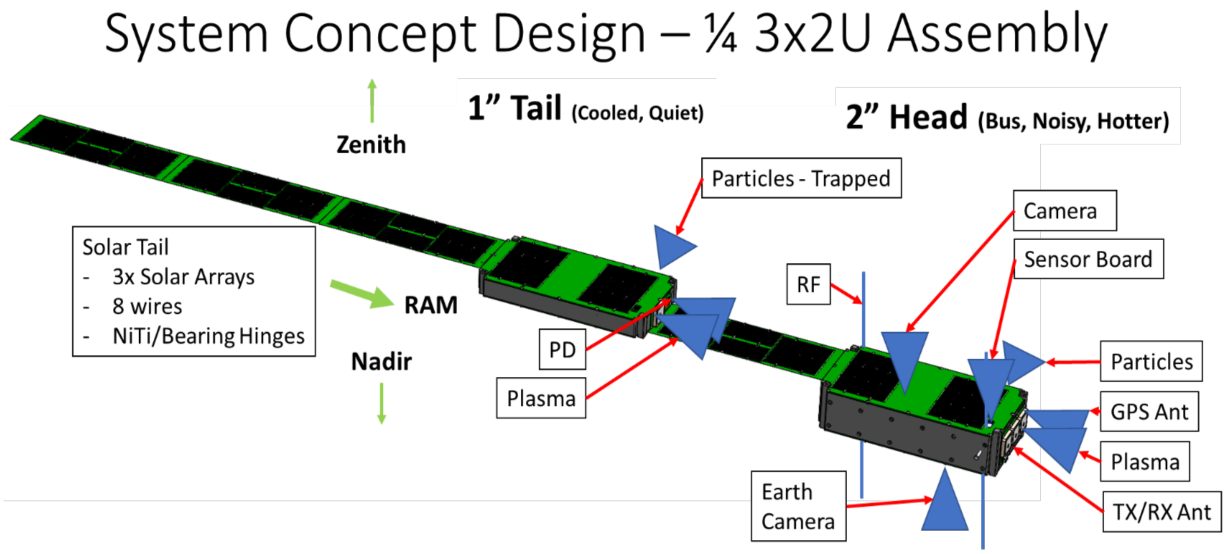

Figure 11 SWAP-E design for each of the four constellation CubeSats released from a standard 2U by 3U launcher unfold into a 1.2 m string as shown by two ThinSats and four Solar Array panels. The Larger ThinSat (5cm thick) contains the sensitive and passively cooled SW sensors while the ThinSat Bus (2.5 cm thick) contains all the relatively noisy spacecraft system functions of power, transmitters, flight processor, and solar arrays. The RF antenna and fields-of view are shown in CAD diagram. A shielded electrical flat flex cable with solar cells connects all of the foldouts and two ThinSats.

“String” as shown in Figure 11. Each ThinSat is an enclosed structure providing rigidity and minimizing electromagnetic interference for the payload. Conventional unit body satellites are usually much larger and more expensive since they include internal power and EMI isolators with subsystem shielding boxes, sensor booms, and intricate active sensor cooling. The benefit of the architectural String is that the Space Weather Payload Head section can be cooled to -10 to -30 C passively for improved resolution and low-energy thresholds (for Particle Solid State detectors, CCD Imagers, IR grid arrays and magnetometer sensors) and 2) all of the contaminating pickup noise, ground loops, and heating from the bus section is isolated. The unfolding of the String also provides aerodynamic stability and longer lifetime at low-LEO orbits, increased solar array area, ease for AM robotic assembly, inspection, and testing, good thermal heat dissipation with more surface area, and improved workflow with less integration cost. Additionally, the String drag can dramatically increase in the Ram direction using the ADAC pointing system (ThinSat orientation and foldouts can maximum drag for deorbit. If ADAC fails at some point, the string will naturally fly in an aerodynamic attitude at lower LEO orbits as observed on our TSAT experiment [5].

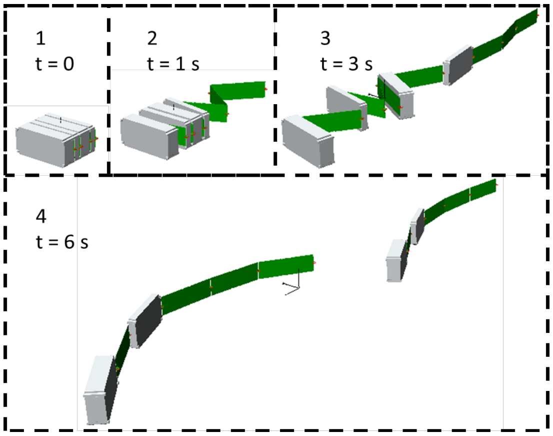

Figure 12 Deployment Simulation of 2x SWAP-E ThinSats. Note that the ThinSats are connected in sets of 2, deploying away from each other.

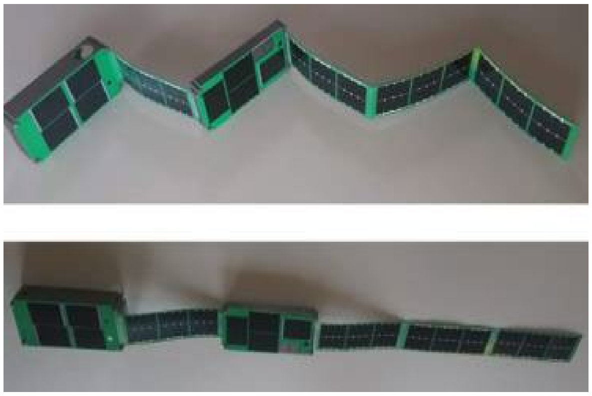

Figure 13 Natural unfolding of the SWAP-E string with spring loaded hinges.

Another feature of the String Architecture is that various configuration formation designs of ThinSats and solar arrays are possible in orbit: Gravity Gradient applications and V-shape to circle to cubic geometries. In addition, Strings can be used for "Trains" of CubeSats and ThinSats for coordinated experiments that need many ThinSat sensor cars (like a string of pearls). A thin flex electrical bus with shielding connects all the cars with optional data and power transfer. For the April 2019 pioneering VLEO flight, 60 CubeSats/ThinSats were used to demonstrate the unfolding of 170 solar array panels with 60 ThinSats into 12 strings in segments of 3 or 6 ThinSats [2], which is a foundational technology enabler for this SBIR proposal.

Figure 14 All 4 dual ThinSats compressed for loading into standard 2x3U launcher

The unfolding of the String is shown in Figure 13. A 3D printed model of the ThinSats and laminated solar array prints were used for this model. Each fold length is 20 cm for a string length of 1.2 m. The hinge is a special design using a flat nitinol spring wire, damping material, and a miniature hinge. The hinge is also used to push the four CubeSats apart after release from the launch tube (see SWAP-E stowed mechanical Figure 14 and dynamic simulation Figure 12. The design was validated with full vibration and thermal vacuum test and confirmed in orbit (2019) working as designed.

RAPSat SBIR Project

RAPSat is the Rapid Agile Production of ThinSats (RAPSat), which will deliver a 4 ThinSat slot constellation to improve the rapid demonstration of Space Force subsystems to the Warfighter. In this project, NSL will deliver 3 highly reliable, demonstration satellite bus platforms with near ubiquitous communications and terrestrial cloud-based delivery to Air Force Demonstration mission owners.

Merit: This SBIR Phase II addresses the strategic DOD Topic J201-CS01 problem of rapidly converting terrestrial innovations and new ideas into advanced space tested parts, subsystems, and constellation components for cutting edge operational and R&D space missions. The dual purpose Rapid-Agile-Production Satellite (RAPSat) uses advanced robotic manufacture production and many agile incremental delivery steps for testing new payload components.

The objective is to build and deliver Flight Prototype Platforms for demonstration, with LEO Flight Prototype delivery ThinSats ready for orbit using a standard 6U launcher (Figure 15), and to show advanced manufacturing was achieved. After successful Phase II completion, establish a Phase III contract to manufacture ThinSats for DOD to rapidly demonstrate subsystems and cadence every 6 months to assist Space Force warfighter efforts.

Figure 15 Existing NSL AF SBIR 6U RAPSat for launch in 2023 of 3 ThinSats.

RAPSat ThinSat Platforms for on orbit testing can have small impulse ion and chemical propulsion payloads. With RAPSat, radiation tolerance can be rapidly tested for COTS and tolerant parts in the real energetic particle spectrum environment (Also test self-healing algorithms, spot shielding, and safe recovery circuits tested). RAPSat Prototype ThinSats will focus with SMC and AFRL/RV on the new Space VPX GHz processors and solar cells for SEU and dose and test new lithium batteries for hibernation, performance, and bus integration. ThinSats scale from 1U to 27U CubeSat launchers.

Each of the four ThinSats released from a standard 2U by 3U launcher unfold into a 1.5 m long solar string tail. The ThinSat (2.5 cm thick) is passively cooled and contains the DOD experiments and the ThinSat Bus and monitors (IR and Particle sensors). As shown in Figure 15 two slices can be combined (called a 2T) if more ThinSat volume is required. ThinSats can be arranged in many form factors, but the required Space Force experiment sizes require the above configuration.

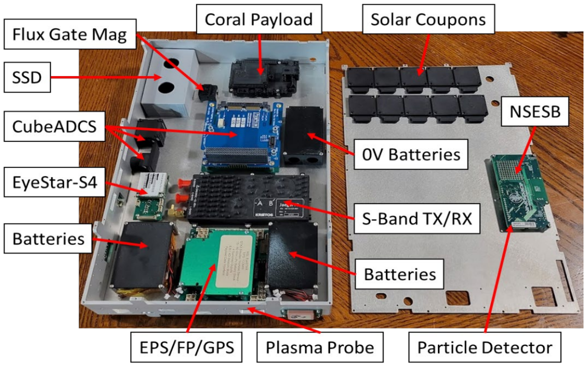

Figure 16 Picture of RAPSat-1B Flight Prototype unit with all bus subsystems integrated, & models of payloads and long lead items, with open top.

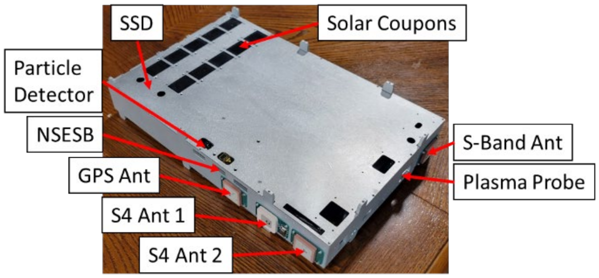

Figure 17 Closed top view of RAPSat-1B Flight Prototype unit showing antennas, sensor ports, and solar coupons.

The RAPSat is designed with long, wide, thin busses, emulating a Flat-Sat design, as seen in Figure 16 and Figure 17. This is mostly to accommodate payloads requiring this type of available volume, but does offer unique advantages over a standard CubeSat form factor. These include

1) Ease of integration and testing of subsystems.
2) Maximizing solar array surface area.
3) Allowing for stowing and unfolding of long (up to 1 m) solar arrays.
4) Provides large thermal radiation surfaces for internal component cooling.
5) Allows external view access to more bus systems and sensors than would normally be available.
6) Optimizes volume for PCB-like subsystems.

GEARRS-3 AND BLACK BOX

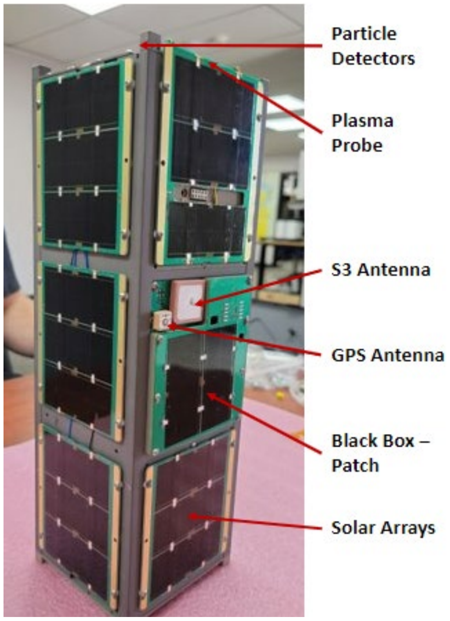

Figure 18 GEARRS-3 Satellite showing Black Box - Patch and 2 sides of solar arrays.

After the successful launch and deployment of the GEARRS-3 3U CubeSat (Figure 18), NSL observed the following results on orbit:

- Successful launch onboard Virgin Orbit's Launcher One on 1/13/2022
- Black Box – Patch validated with GPS; The Patch is an autonomous ThinSat like barnacle for CubeSat diagnostics (Figure 19).
- Mission Success due to Patch functionality and GPS operation
- EyeStar Communication Link nominal, with good throughput (72%)
- First packet received immediately after RF turn-on (1 min)
- First GPS Lat/Lon/Alt contact received 2.5 hrs after turn-on
- GPS data and Satellite ID sent promptly to 18th squadron (within 1 day)
- All Solar Array Panels working with excess power (~7.5 Volts)
- All Bus systems working (Batteries, Coulomb Counters, EPS, Comm, etc.)
- 3-axis Mag working, at low data rate
- GEARRS-3 Temperature Range nominal: -10°C to +20°C
- Good Sensor data collected, from Particle Detector, Plasma Probe, and Magnetometer
- Radiation testing for all subsystems

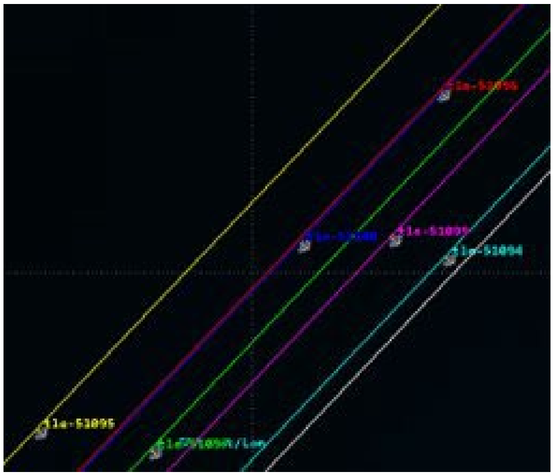

Figure 19 Space object orbit trajectories used to identify the GEARRS-3 ID. Onboard GPS data collected and downlinked from the Black Box - Patch provided location data to ID the satellite for AF

TROOP 1, 2, & 3 RAPID TRAIN TO SPACE

The Train Rapid On-Orbit Payload (TROOP) mission system is a platform for hosting payloads, allowing experimental systems to rapidly raise TRL levels in space environment while providing test and telemetry data. TROOPS are fixed to the released SHERPA ring and typically stay in orbit for 8+ years at 530 km.

TROOP enables rapid, repeatable testing of systems and subsystems enabling cost effective means of getting research into space. This makes TROOP perfect for sensor testing or any variety of commercial and government missions. TROOP provides all vital flight components of a FastBus CubeSat (EPS, EyeStar radio, battery, flight processor, etc.) allowing the payload provider to focus on the payload.

Some key highlights of TROOP are:

1) Launches every 6 months
2) Turnkey Solution: Mission includes Launch, Bus, Environmental Testing, FCC licensing, comms, and payload development
3) Variety of integration options

4) Ideal on-orbit test platform for payload and subsystems
5) Stackable payload volume options

To date, 3 TROOP missions have launched: TagSat-1 (TROOP-1), TagSat-2 (TROOP-2), and TROOP-3. TROOP-4 and 5 are currently manifested for launch within a year, and still accepting payloads.

TROOP-1

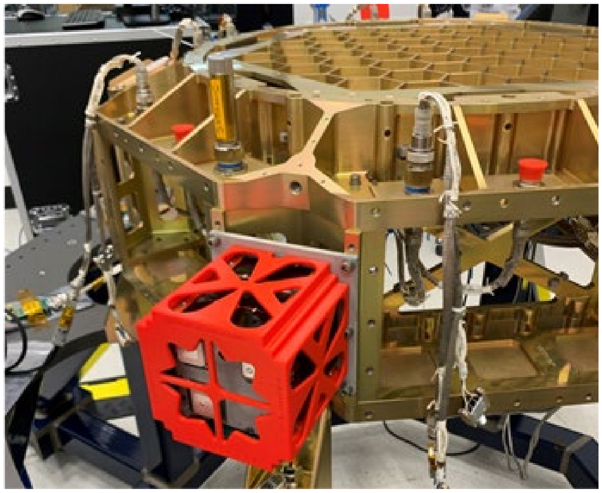

Figure 20 Picture of TagSat-1 (TROOP-1) mounted to the SHERPA deployment ring for

Launching on Jan 24, 2021, TROOP-1 (Figure 20) was the inaugural launch of the TROOP program. This tested, among other things, a novel miniaturized GPS which continues to operate and be characterized on orbit.

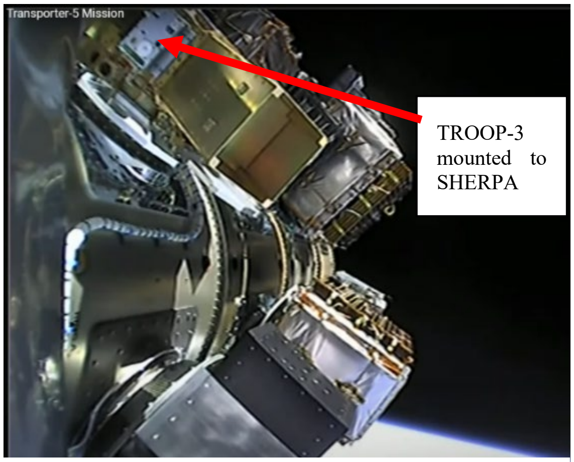

Figure 21 Still image taken from the SpaceX livestream showing TROOP-3 mounted to the SHERPA ring.

TROOP-2

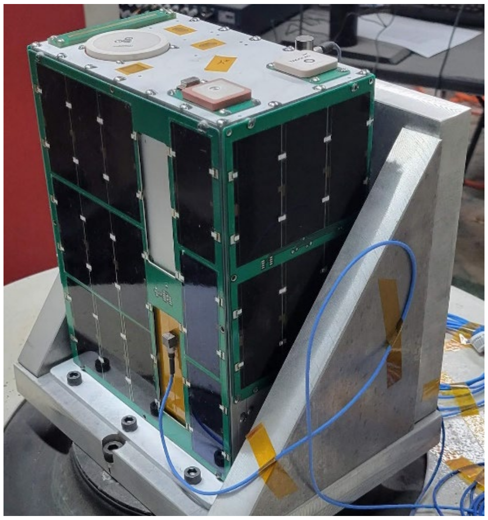

Figure 22 TagSat-2 (TROOP-2) Mounted to a vibe table for vibration testing ahead of delivery.

Launching on Jun 30, 2021, TROOP-2 (Figure 22) improved upon the original design, establishing the size and power standards to which all future TROOP missions will adhere to. With a full deck of payloads, this hosted a STEM sensor package, tested experimental batteries, characterized the radiation tolerance of a flight processor, and other experiments.

TROOP-3

The most recent launch, TROOP-3 (Figure 21), launched on May 25, 2022. Still in the early phase of the mission, this satellite has been performing nominally. As with all TROOPs, TROOP-3 hosts several payloads for on orbit testing, such as the new EyeStar-S4 transceiver, among other things.

VLEO ARROW-SAT

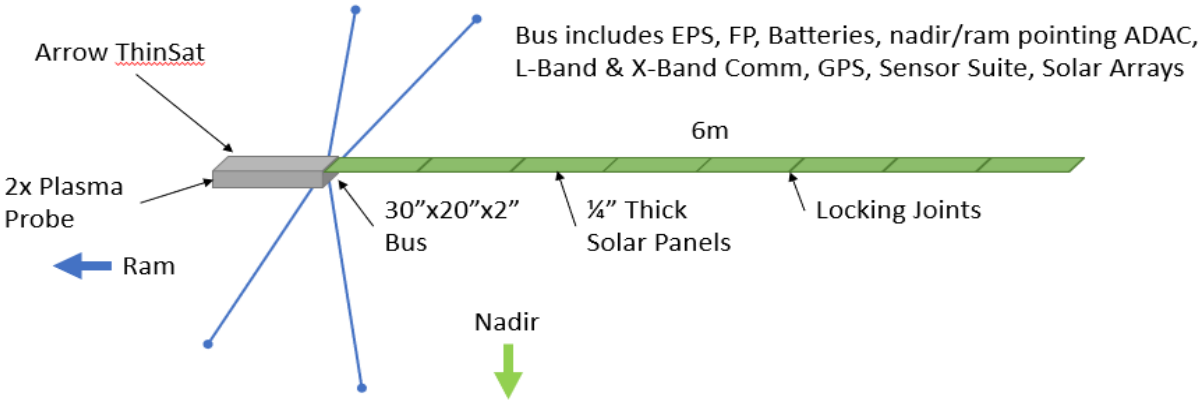

Figure 23 Aerodynamic ThinSat with low drag antennas for VLEO ionospheric studies

The Very Low Earth Orbit region is relatively underexplored due to excessive drag on big satellites. Topics rich for discovery include the critical Sun-Earth coupling region between space and earth's atmosphere: Space Weather, F and E region of Ionosphere, Scintillations, Orbit decay, thin gas Chemistry, Dynamics and waves, Traveling Ionospheric Disturbances (TIDs), VLF coupling, Precipitating electrons and ions, Low radiation belt contamination, Ionization and Absorption, South Atlantic Magnetic Anomaly ionization, electric and magnetic Transients, Plasm Physics, Atmospheric Model checking, Intelligence gathering, DOD technologies, and many others.

Special ThinSats (seen in Figure 23) have been designed for VLEO orbits that include low drag design and 24/7 Globalstar and Iridium Comms that work down to 110 km altitude [5]. The satellite acronym we ascribe to these products is called ARROW and stands for: **Aerodynamic** low drag with long antenna ThinSats, **Radio**, VLF to VHF Antenna & E- & B-field Booms, **Research** platform for 100 to 400 km, **Operational** Long Missions with ion propulsion, **Workstation** and general payload Platform

SENSOR MINIATURIZATION & EXOSAT

Sensors for ThinSats and Deep Space drive the community to more powerful and miniaturized instruments. As a final illustration we illustrate the design of the NSL ExoSat payload sensors on the Miles Team satellite (EM-1 NASA Deep Space CubeSat Challenge). The Explorer NASA EM-1 mission is scheduled for launch this year in a trajectory past the moon and into Deep Space.

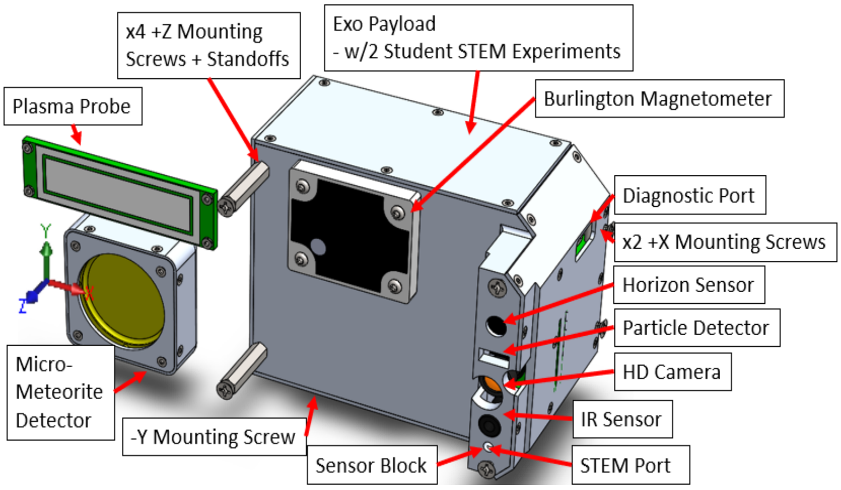

Figure 24 Illustration above showing the ExoSat payload mechanically removed from the Miles Space satellite and below the ExoSat Block Diagram.

NSL was involved in the diagnostics and STEM part of this project called ExoSat. It was about a ½ U ThinSat volume as shown in Figure 24. It contained a number of important instruments: Plasma probe, Micro-meteorite dust PVDF detector, 3Axis sensitive Magnetometer, Horizon sensor, energetic particle detector, low energy particle detector, HD camera, IR sensor, and a series of 2 STEM sensor boards (Figure 25). The STEM instruments were built by a team from Twiggs Space Lab (TSL) and \universities.

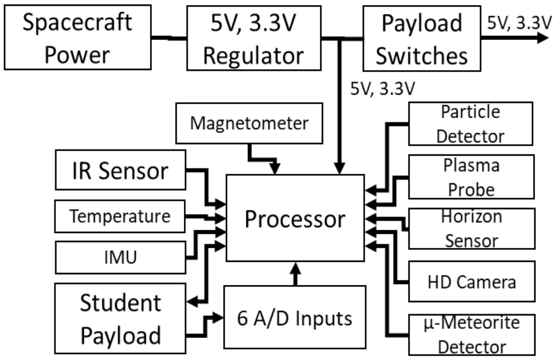

Figure 25 System Block Diagram for the ExoSat deep space payload.

COMM. SYSTEM SUMMARY

Small Sat transition from Globalstar to Iridium links continue to offer real time 24/7 coverage with the added benefit of a commanding uplink. With a max transfer rate of about 1 byte/sec (18 Bytes/packet) results in ~80 Kbytes per day. Using just 10% of this bandwidth (8 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 is pricelist but only cost about $40 per day for 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 supports high data rate (S, X, Ku bands) radios with Ground stations.

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Would also like to give special thanks to Iridium and Globalstar Engineers, Managers, and legal for their devotion and commitment to optimize their powerful constellations for Realtime Sat to Sat links. Mike Miller as our FCC legal engineer did a fantastic job of helping us stay on target.

Special thanks to the SWAP-E NASA managers and Partners at Aerospace, Laboratory for Atmosphere and Space Physics (LASP), and Space Environmental Testing (SET) lab. Special thanks to Mike Schuckel and the NSL team for developing so many successful satellites in a short period of time with 100% success.

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