Architecture & Manufacture for 1/7U to 27U 60 ThinSat Constellations: Flight Results

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ABSTRACT

New architectural and affordable Advanced Manufacturing (AM) techniques were successfully demonstrated on eight 1U-6U CubeSat payloads, launched over the past 8 months, followed by the launch of a sixty ThinSat (1/7U) constellation on April 17, 2019. The modular AM CubeSat systems tested in orbit (TRL=9) include new robotic manufacturing of unibody and articulating foldout structures, robotic assembly and testing of Globalstar Simplex radios, new ThinSat form factor, and many other subsystems.

The Globalstar links for the eight commercial CubeSats were all 100% successful and demonstrated for the first time, excellent polar 24/7 global coverage with latency of only several seconds. The new NSL “Black Box” with GPS is flight proven for near real-time tracking, ID verification, diagnostics, satellite recovery, and as a powerful redundant link. The constellation of 60 educational ThinSats were successfully deployed from the three 3U launch tubes, with the novel spring-loaded articulating panels all appeared to have unfolded gracefully. Within the first 12 hours 52 of the 60 ThinSats turned on immediately to reported back the satellite and student payload status. With a relatively high tumbling rate, about 5% of the full packets were received; however, over 95% of the partial packets were received.

1.0 INTRODUCTION

All necessary FCC, NTIA, and Globalstar licenses were obtained for the 8 CubeSats and ThinSat Constellation. The modular Automated Manufacture (AM) CubeSat systems that were tested in orbit (TRL=9) included new robotic or 3D printed unibody structure, thin articulating foldouts, EyeStar Simplex radios, and 241 other subsystems (NSL/Globalstar comms, tracking Black Box comm, EPS power, solar arrays, processor, horizon IR image, and other sensors). Recent orbital data (see Figure 1) illustrates Globalstar performance for polar versus lower inclination orbits, latitude, longitude, altitude, attitude, latency, throughput, and other metrics.

Figure 1: New CubeSat data from January 2019 showing excellent coverage with NSL EyeStar Simplex Globalstar Link over the polar region (Globalstar Satellites at 51deg Inclination and 1400 km altitude).
Architecturally, the new AM system used on the constellation will work well for larger 1U-6U Strings and for larger 12U, 24U and 27U form factors with scaled foldouts for many formation flying geometries.

The AM process was based on requirements of mil-spec high reliability parts, screening, and automated assembly with inspection, burn-in, and environmental testing. A modular 27U proto-flight satellite was previously built with an ESPA mount for comparisons to the new Automated Manufacture. ¹

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). ²⁷

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, providing student teams the opportunity to design, develop, test, and monitor their own experimental payload which will be integrated into a pico-satellite and launched from the second stage of NG Antares Rocket. ⁹

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) as shown in Figure 2 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 is possible and 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 2: Educational ThinSat for 21 Satellite Flock

Figure 3: STRINGS: Educational Demonstration ThinSat Launch 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.

New Study of Ionosphere below 350 km

The Very Low Earth Orbit (VLEO) or Extremely Low Earth Orbit (ELEO) Region (90 to 350km) 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:

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.

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

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

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

**Radiation Shielding:** of Atmosphere in VLEO orbits greatly reduces Radiation Damage (Resilience).

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

**Figure 4: 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 4. 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.

**2.0 WHY THINSATS & SCALED ARCHITECTURE**

Some of the advantages for going with a ThinSat versus a PocketQube or other structure include the following considerations:

**Ease:** Automated Assembly using two exterior parallel PC Board composite & structural assembly, Shielding for radiation and EMI reduction (Pancake assembly), Globalstar/NSL EyeStar Product fits with 24/7 real-time monitoring for ordered database.

**Larger Solar Array:** Area and Fit with fixed volume.

**Aerodynamic:** for less drag when small edge is pointing into ram direction.  More drag if rotated 90 degrees.

**Significant Lower cost:** by a factor of 10 for constellations to manufacture compared to using many smaller PC boards with connectors. One Main PCB with few connectors.

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

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

**No internal launcher:** required for ThinSats since they stack in existing Canisterized Satellite Dispenser (CSD) and PPOD launch canisters.

**Improved Thermal:** heat dissipation and isothermal shorting.

**Great for pushing New Technologies** to smaller smart phone sizes.

**Can have much greater Radar cross section** especially with the foldouts.

**Ease of calibration, charging, Burn-in, and environmental Testing,** and

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

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.

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 available as shown in Figure 5. In a 27U launcher six large ThinSats can be released that are 30 x 30 x 5 cm in size.
3.0 CONSTELLATION MANUFACTURE

To significantly reduce small satellite constellation cost it is 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 for 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.

Strings are ideal architectures for data and power connection between individual ThinSats for coordinated experiments with different purposes such as 1) ThinSat with GPS, IMU, cameras, 2) Propulsion unit like a train and extra batteries (like coal car), 3) Space weather experiments (on plasma and particles), and 4) Space Weather experiment with B and E field deployables, etc. The string with the flex cable bus can also act as a boom for plasma experiments. (See figure 8) Other advantages include gravity gradient stabilization with longer strings and various flying angled and circular geometries.

ThinSat Foldouts for one 3U showing three 6-ThinSat strings and one 3-ThinSat string are seen in Figure 9. A one segment Boom Assembly for one of the student teams is shown in Figure 10 for a thermal filament.
4.0 NG-11 SIXTY THINSAT EDUCATIONAL DEMONSTRATION; ORBITAL RESULTS

The ThinSat orbital model was constructed for the purpose of simulating the ThinSat flight on April 17, 2019 for Satellite Lifetimes of 50 hrs and 65 hrs. The results of this simulation are to help with interpretation of particle detector data, solar cell data, IR data, and payload data recorded during the flight. Correlating these data points and the simulation, a ThinSat string can be identified and ID orbit fine-tuned. The model includes an altitude dependent drag force as well as an asymmetric gravitational force to account for the oblateness of the Earth.

The basic orbit Earth track is shown in Figure 11 for the 50-hour orbit based on the orbital elements given in the official ThinSat TLE. The simulation is written in Mathematica and uses the function NDSolve to numerically solve the differential equations of motion derived \(^{11,12}\). The initial conditions in spherical coordinates were derived from the TLE given from launch.

From the particle detector data, we know that the satellite lasted in orbit about 2-2.5 days, so in the modeling process the drag parameter, gamma was varied to make the satellite deorbit, or fall below 100 km, from orbit after about 48 hours. This all-encapsulating drag parameter in multiplied by \(\rho(r-R)\), the density of air at the given altitude above the Earth's surface.
There are a few glaring ways this model does not completely encapsulate nature. First, the model accounts for oblateness in the gravitational force term, but oblateness does not have an effect on the altitude dependent drag term. This creates a discrepancy of about 15-25 km in altitude between the latitudinal extremes and the equator, which, is most likely small, yet non-negligible. Secondly, higher order terms of the gravitational potential could be used in calculation, as well as incorporating the variable density of the earth. However, these would result in very small changes to the orbital path and it is likely a better use of time to focus on sources of larger error. Third, the full parameterization of the drag is not known, so the “best guess” is simply what makes the model seem right in the end.

For comparison, a simulation was also done using NASA’s General Mission Analysis Tool (GMAT) software. It was found that the results of the simulation resemble closely that of GMAT, which provides greater confidence in the relative accuracy of the model, even if there are some obvious problems still to be resolved.

This model was constructed for the purpose of simulating the ThinSat flight on April 17, 2019. The results of this simulation are to be compared to particle detector data recorded from the flight. We hope to find correlation between this data and the simulation, so that we have a reasonable approximation of the orbit of the ThinSat. The model includes an altitude dependent drag force as well as an asymmetric gravitational force to account for the oblateness of the Earth. Once all the

\[
\begin{align*}
    r & : -\frac{GM_E}{r^2} + \frac{3\alpha^2GM_E(-1 + 3\cos^2\theta)}{5r^4} - \gamma\rho(r-R)\ddot{r}\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = \ddot{r} - \dot{r}\ddot{\phi}\sin^2\theta - r\ddot{\theta}^2 \\
    \theta & : \frac{6\alpha^2GM_E\cos\theta\sin\theta}{5r^4} - \gamma\rho(r-R)r\dot{\theta}\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = \ddot{\theta} + 2\dot{r}\dot{\phi}\sin^2\theta\cos\theta \\
    \phi & : -\gamma\rho(r-R)r\dot{\phi}\sin\theta\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = \ddot{\phi}\sin\theta + 2\dot{r}\dot{\phi}\sin\theta + 2r\ddot{\phi}\cos\theta
\end{align*}
\]

Figure 12: Orbit period versus time

Figure 13: Orbit altitude versus time for 50 hr orbit (Red) and 65 hour orbit (Blue). The Weiss ThinSat lasted 66 hrs.
dust settled; the equations of motion are above (pg.6).

ThinSat Solar Cell Instant Measurements:

The relative solar intensity is a unitless value ranging from 0-100 which represents a normalized output of the satellite’s two solar cells (see figure 14). The solar voltages were summed and averaged in ten-minute intervals from the time of payload separation before normalizing.

To determine whether the satellite was believed to be in daylight at the time of each solar reading, the longitude of the day and night terminators at mission epoch were calculated using SatPC32 software, neglecting the effects of the satellite’s latitude and Earth’s orbit around the sun. These longitude values were then extrapolated through the mission’s approximately 50 hour mission lifetime by moving the longitude values westward at a rate of 1 rev/day.

Using the longitude predicted by the solution to our model of the orbit, the satellite was inferred to be in

![Figure 14: Terminator periodic variation with ThinSat solar cell data (zero points in eclipse).](image)

![Figure 15: Energetic particle measurements for 540 minutes from six ThinSats for comparison.](image)

![Figure 16: Energetic particle measurements from the Apollo and 618 team ThinSats as they passed near the auroral region. The time delay of 2 min and 44 sec helps to identify the strings and fine tune the orbit.](image)
light or darkness by its position relative to these terminators. In other words, the peaks and troughs of the square waveform represent predicted daylight and darkness cycles respectively of the satellites in their orbits.

**ThinSat Energetic Particle Measurements**

The high-energy particle detectors on each of the satellites reported a count value over the sampling interval which was used to calculate the number of counts per minute at several times throughout the mission lifetime. Using the solution to our model of the orbit, we were able to determine the approximate latitude and longitude at which each of the readings was taken (see Figure 15).

In Figure 15, the horizontal axis represents the time since mission epoch which was set at the time of payload separation (17 Apr 2019 20:55:10 UTC). The vertical axis scaled on the left-hand side represents the number of high-energy particles per minute through our detector for all points on the scatter plot. The waveforms superimposed on the scatter plot are the predicted latitude and longitude of the satellite which are scaled by the vertical axis on the right-hand side.

In Figure 16 the particle counts are shown from two ThinSats that crossed the auroral oval region with significant count rates but at different time. The crossing of a stable auroral precipitation region (the “horns” of the oval) can be seen best in the south near Australia where a inclination orbit of 51 degrees actually brings you well into the polar cap region. The unique auroral oval signatures allow for identification of all the ThinSat orbit positions and time delays between all the various autonomous ThinSats (It is a poor man’s GPS).

**ThinSat IR Horizon sensor image:**

An 8x8 pixel gridded IR sensor was flown on each ThinSat during the NG-11 mission. This sensor was able to remotely sense temperatures between 0 to +80 C, and functioned as an Earth Horizon Sensor, contributing to the attitude determination of the ThinSat.

The IR sensor image took some extra processing because of the floating of the Most Significant Bit (msb’s) and a sign bit missing in the data.

Once processed, the Grid IR sensor can be used to verify deployments, view the earth/sun horizon limb, and contribute to the onboard ADAC.

Figure 17 shows one example of a Grid IR image, after several layers of post-processing.

![Figure 17: Top panel shows the infrared (IR) 64 pixel raw data array after some adjustments for a lost sign bit. The lower panel shows an image enhancement of the top array image. Conspicuous in the images is the earth’s horizon limb of the earth.](image-url)
5.0 NG-11 60 THINSAT EDUCATIONAL DEMONSTRATION: DESIGN

With size and power as the driving constraints on the ThinSat design, a thinner and wider design evolved to maximize the surface for the designed enclosed volume. This allowed sets of ~2W Alta Devices solar arrays to be mounted on front and back. With an Al 7075 frame clamped between two PCBs, the electrical design was greatly simplified with no need for additional connectors and interfacing between boards. The inner volume was divided into two sections, separated by an aluminum wall: The Payload section and the NSL Bus section. Half of the inner volume of the satellite is available to be used by the payload, with the other half used completely by the NSL Bus electronics. This division continues to simplify the design by allowing a single point electrical interface, and a clean mechanical interface, with no mixing of systems.

The payload has multiple ports, providing an unobstructed access and viewing of space. Two circular ports are available along the thin, aluminum side, while three larger ports are available on the larger face. A diagnostic port is also available for direct testing of the payload while integrated into the ThinSat.

ThinSats are designed to be fully independent satellites, but if desired can be connected in sets, or Strings, of any number of units. For the NG-11 mission, Strings of 3 and 6 were used. These Strings were connected by articulating foldout arrays, or Foldouts. Sets of panels joined by spring loaded hinges provided a gentle deployment, with semi-rigidity once deployed to transfer rotational momentum.

**CSD Mechanical design**

The ThinSat Constellation launched on the NG-11 mission used three sets of 3U Planetary Systems Corporation (PSC) Canisterized Satellite Dispensers (CSD). Several design features were driven by this selection of dispenser. This includes the total length of the ThinSat stack, which drives the spacing between ThinSats, as well as the thickness of the individual units. This also includes the use of clamping rails and the inability to contact the +Z door of the dispenser. Another large feature is the ability to make use of four areas traditionally used for the rails (standoffs) of a CubeSat.

**PPOD Mechanical Design**

The ThinSat design has been adapted to meet the requirements of many different form factors, as well as different CubeSat dispensers. It is currently designed to meet the specifications of the most traditional launcher, the PPOD. In order to accommodate the shorter total length available to a 3U form, the number of ThinSats in a stack reduced from 21 to 18. However, this reduction in total ThinSats also allowed for more space for the thickness of each ThinSat, as well as the spacing between them.

Figure 18: CSD Canister launcher standard for the ThinSats. 21 ThinSats can fit in one 3U CSD launcher.
Figure 19: System layout of ThinSat, showing the PPOD designed version.

Figure 20: ThinSat and 3U Stack of 18 ThinSats designed for the PPOD launcher.

Figure 21: Block Diagram of ThinSat system. Note the extra options on the right, and the EyeStar-S3 transmitter used as a downlink (dotted section).
**ThinSat Constellation SYSTEM Block Diagram**

The Block Diagram for the existing 1/7U ThinSat which is 1.7 cm thick is shown in Figure 21. The EyeStar radio product (dashed box) is shown as one of the redundant, 24/7 links. Power is generated from 16 solar cells for low-rate beacon transmissions and higher rates if power is available. The Grid IR array is 8 by 8 pixels and is used as a Horizon sensor and/or a crude imager to verify deployments and/or view earth/sun. Other options for the basic ThinSat include a) a high sensitivity, low bandwidth imager (96 by 128 pixels) to snapshot internal or external mechanisms, b) encryption, c) additional mission specific sensors, d) various sizes, e) an integrated GPS receiver and antenna, f) extra battery power, and g) quality control testing levels. During normal operations, the ThinSat can transmit mission critical data at 8 bytes/sec using the Globalstar satellite network over the entire globe, with 24/7 coverage and a latency of seconds after the ThinSat is activated. A full ICD for students is referenced for all of the mechanical, electrical, and sensor details for the payload and the bus.

### 6.0 THIN-SAT FOLDOUT STRING DYNAMICS

Snapshots of video dynamics are shown in Figure 22. Note the sinusoidal, low energy, unfolding of the four strings within one CSD. As planned, all of the strings push away from each other, so they do not collide. Within a few minutes the strings settle down and become stable if no external disturbance torques are present.

![Figure 22: Dynamic deployment of a full stack of 21 ThinSats, in 4 strings over time. Note the wave formations, and the snakelike twisting of panel 3.](image)
High Vibration or Spin Rate

Current evidence points to a relatively high string vibration rate (at the resonant string frequency with angular variations of greater than 90 degrees) and/or a spin rate along the string axis (low inertia). In the ThinSat reference frame the solar panels and patch antenna were rotating back and forth about +/- 90 degrees at about 10 RPM which is a string resonant frequency. Some of the evidence of this rotation interpretation from the data include the following:

1. **Previous Experience**: Based on many NSL flights in various orbits and tumbling rates we see a strong correlation of tumble/spin rates with data throughputs. We had over 17 Simplex units in LEO orbit before the ThinSat constellation flight with spin rates between 0 to 12 RPM. For low spin rates we get over 90% throughput of data at Anytime and Anywhere in the world. All of our previous CubeSats had spin rates of less than 2 RPM, with the exception of one which spun up to 12 rpm for a short period.

2. **Ground Testing** of rotation rates: Our Chief Engineer ran some ground based rotational spin rates with a EyeStar Simplex and antenna on a variable speed motor drive that was connected to the Globalstar network. When viewing the earth he used an RF absorber to better simulate the satellite environment. Our Chief Engineer verified the strong dependence and throughput efficiency of rotation rate on a 36-byte message through Globalstar network as illustrated in Figure 25.

3. **Theoretically** we expect why throughput changes with spin rate since it takes about 12sec to stay locked to a Globalstar satellite for a 36 Byte (Figures 23-24)

4. All of the 12 ThinSat strings had data throughput of less than 5%, indicating an extremely low throughput and a common source problem with all of the Strings.

5. Nearly all of the ThinSat partial packets were received. Globalstar servers captured all the ThinSat 9 Byte partials of the 36 Byte messages that we sent. For the Weiss School ThinSat (TSLPB) they had 133 completed 36-byte full messages that where charged, and 3,280 partial packets received (either 9, 18, or 27 bytes). This indicates that our ThinSats were operating properly with full RF link power. The problem is that because of the high spin rate we were not able to point long enough to maintain RF contact with a connected satellite. Normally we get over 90% throughput with 36 Byte long messages.

6. Consulting engineers with their experience substantiated a very fast spin rate.
7. **Opposite solar voltages equal.** Both back to back solar array surfaces on the ThinSats observe the same solar illumination indicating that the surfaces are rotating < 4 RPM. At low spin rates we expect very different solar cell voltages (see Figure 26).

![Figure 26: Solar panels from opposite sides read same voltage indicating rapid rotation.](image)

8. **Increased Drag:** Because of the tumbling and spinning of the string the drag rate significantly increased by over a factor of 2 to 4. The reason for this is that the full 11 by 11 cm solar array panels were facing the Ram for half the time. Analysis and simulations show the best and worst case drag factors.

9. **Prompt Rotation:** The high rotation rate occurred within the first several minutes of ejection-based on flight solar cell data.

10. **Mechanism –** With dynamic simulation of the ThinSats and foldouts all the nitinol spring torques cancel with each other. Also, by conservation of angular momentum there should only be a very slow rotation rate since the moment of inertia is significantly increased during unfolding (assuming no opposing rotations). The main problem of the high rotation (assumed to be along the hinge axis or String axis) seems to have occurred because of a subtle resonance of the foldout spring hinges with a disturbance torque or low density air spin-up (still under investigation with a direct Monte Carlo technique using atmosphere disturbance torques). A spin could also be along the String axis. In addition, to the string vibration and rotation there is likely a small tumbling rotation from the CubeSat launcher. The foldout resonant frequency was on the order of 6 seconds which is consistent with a rotation period of 10 RPM.

11. The rotation / string vibration made it very difficult for the ground tracking radars (cross-section) to lock to the individual ThinSats to get specific TLEs.

**Damping:**

The purpose of the foldouts with associated torsion springs and dampers is to push the individual satellites and strings away from each other when first released. There were three foldout panels between each ThinSat and four hinges with damping. Each foldout panel was approximately 10 cm long giving a separation between ThinSats of 30 cm. The other purpose of the nitinol torsion springs with dampers was to maintain a stiff force along the hinge axis to keep the strings linear. The hinges also allowed a torque to be applied between all the ThinSats in the string that was perpendicular to the hinge pin. This way all the ThinSats in a string would have the same attitude relative to each other for sensor comparisons. The assumption was that the initial vibrations of unfolding would damp out in several minutes. This assumption may be incorrect if there is a disturbance force that can resonate with the natural frequency of the foldout hinge assembly as discussed later (remember that even a steel bridge, like the Tacoma bridge, can collapse from a small continuous disturbance force).

Figure 27 snapshot of the video shows the foldout shapes during maximum overshooting when first released for Undamped, Nominal, and Overdamped absorbing energy material.

![Figure 27: Video Snapshots from the Dynamics video of the maximum first overshoot of the unfolding process for three damping constants.](image)
Resonance String Vibrations

Dynamic 2-D analysis of the 3 ThinSat string and the 6 ThinSat string were made using measured material, spring, and damping constants. The natural frequency of the first Harmonic is 11 RPM and is shown in the Figure 28. Note that the two end ThinSats are pointing in opposite directions during this resonance and flipping back and forth every 6 seconds. This string vibration could explain the rotation spin anomalies if the amplitudes are similar to that shown in the figure. Rotation about the string axis could also explain the spin data. There are likely higher resonant harmonics for the 6-ThinSat string as well which is still being simulated.

Figure 28: Resonant oscillations as the foldouts unfold to steady state.
7.0 NODE THINSAT CONFIGURATION

The original plan for NG-11 constellations was the NODE ThinSat design because there would be many multipoint measurements and each student team would have their own autonomous satellite to track and understand. However, the initial NODE design was put on the shelf for the reason that it did not meet the FCC and JSpOC requirement of having a large 1U area for radar cross section. Also, there were some benefits with the strings for students to collaborate with their data together on various sensors for comparison and all having the same attitude reference point. The ThinSat launch design allows for releasing hybrids or combinations of Strings, Nodes, and/or 1U or 2U CubeSats.

Requirement Plan for NODE Flock:

- Optimize message for greater than 80% throughput, even if spinning at 10 RPM
- Concentrate each string mass and size to increase ballistic coefficient and radar cross section with corner reflector. Creates full 10cm by 10cm cross section in all orientations
- Keep symmetric design with torque cancelation
- Include 3x1T unfolding strings with one drag foldout
- Trains of ThinSats would have less ram surface area and higher ballistic coefficient
- Optional: Front ThinSat could be Mothership, while other two could each support two payloads
- Mothership has extra batteries and radio, other two ThinSats would only have payloads and solar cells
- Increases total possible payloads per Mothership.
- Use drag foldout for aerodynamic stabilization, damping, increased radar cross section in each dimension, collimator for sensor FOVs, and increased solar area
- Only one hinge between each ThinSat in Train increases stiffness
- Include a magnetic detumble circuit and control loop

Figure 29: Baseline NODE configuration showing the box solar array foldout and radar reflector on the right.

Figure 30: Snapshots of Baseline NODE configuration unfolding and showing the box solar array foldout and radar reflector on the right.
8.0 SPACE WEATHER CONSTELLATIONS (MULTIPOINT MEASUREMENTS)

Much space Weather research and relevant student education can be advanced with ThinSats and CubeSats in the weakly sampled Space Weather region below ISS altitude of 400 km. Space Weather Phase 1 Benchmarks from the National Science & Technology Council, June 2018 Agencies, Departments, Executive Offices follows:

Benchmark: Induce Geo-Electric Fields
Less noise: ThinSat can fly E and B field sensors in VLEO.

Benchmark: Ionizing Radiation
Less Background radiation! Direct precipitating energetic particle sensors in VLEO. Also monitor UV and X-ray ionization in Ionosphere.

Benchmark: Ionospheric Disturbances
Direct in situ F-region densities, Temperatures, and Dynamics

Benchmark Upper Atmospheric Expansion
Direct in situ measurements of drag, plasma trough, auroral compression, and composition

ThinSats could be launched between 325 to 425 km altitudes (e.g. from ISS), and will spiral in over several weeks to months interval, with an earth orbit period of about 90 minutes. By using many low costs and small ThinSats, this relatively unexplored region will likely reveal interesting atmospheric science. Some of the reasons for opening this new window into the earth’s environment are: 1) ThinSat orbit rides are very low cost and many are available, 2) to better understand the Sun-Earth climate connections, it is critical to make global measurements in the 100-250km region, 3) being an unexplored space region, many new discoveries are expected, 4) current atmospheric models could be validated or corrected with real data from this region, and 5) the recent availability of a global communication network like Globalstar, with near real time data access from the internet,

Figure 31: A unique purpose for ThinSats is to map and explore the ionosphere and atmosphere in the VLEO and ELEO region (350 to 90 km). While sounding rockets probe this region (vertical profile at one location) for tens of minutes, the ThinSats will make unique horizontal and global cuts and measurements for >40 orbits.

Figure 32: S81-1 SEEP Plasma and Energetic particle Space Weather nighttime measurements in the VLEO region (180-240km). The TE2 detector viewed the trapped flux and LE5 the precipitating flux.
permits data collection above the “black-out” region anywhere on the earth.

In the future, ThinSat or full CubeSat orbits could use high efficiency ion engines to add impulse to compensate for drag. Tether systems could help transform orbital energy into power at high altitudes when drag is low.

The extremely low altitude data set of the S81-1 SEEP satellite flown in 1982 (which required propulsion to maintain orbit) provides an example of the rich data available from this region of space. SEEP made some of the first space weather observations$^{10}$ with unprecedented signal to noise ratios, due in part to the low altitude platform. The SEEP top panel shows the red 630nm optical line with the Auroral and equatorial fountain emissions. The SEEP plasma probe data in the Center panel used the same electrometer design found on TSAT and ThinSats. It was also attached to the front-end cap edge and in the ram direction. Note the clarity of data in the south to north pass of Figure 32; auroral irregularities and strong ionization, plasma trough density depletions, increased ionization in the South Atlantic Magnetic Anomaly region, Traveling Ionospheric Disturbance (TID) in the F-region (above thunderstorms), the equatorial fountain effect with equatorial depletions (bubbles), the E-F region transition at lower altitudes, and E-region irregularities.

The lower panel in Figure 32 shows the energetic particles (E>45 keV) for precipitating (LE5) and quasi-trapped (TE2). Prominent are the auroral zone, SAMA, equatorial ion zone, mid-latitude zone, and the Lightning-induced Electron Precipitation (LEP) events.

9. CONSTELLATION GROUND SEGMENT

The NSL server web API provides the programming capability to send and receive all data streams over the Internet. That includes receiving Simplex telemetry packets, sending and receiving data files, sending SMS commands, and the option of receiving link metadata.

The Globalstar ground segment can service thousands of satellites with storage available to the client on a single time ordered database. The servers are redundant and fault tolerant. The Console provides supervisory management of the various satellites and constellations.

The NG-11 Constellation included a special data Dashboard for the student teams. It was created by Virginia Space, TSL, NSL, and volunteers to maximize student learning. Some of the features of the student Dashboard include:

**Students and Teachers can...**
- See test data from satellites before launch
- See real-time data in charts
- Pick among potentially hundreds of satellites to view
- Compare data across multiple satellites in the constellation
- See real-time constellation tracking
- Collaborate with others in the same launch in a discussion forum
- Configure custom parsing for their packet formats

**Administrators can...**
- Configure each mission
- Control who has access to the site
- See status of live devices, users logged in, and active teams
- Send email blast to all participants
- Upload resources for students

![ThinSat Communications Architecture](image)

**Figure 33: Flow Diagram and Data transfer from many ThinSat EyeStar radios to the Internet, Console and Dashboard for the constellation Ground Segment,**
10. CONCLUSIONS

Eight CubeSats were successfully launched into various polar and lower latitude orbits and all of the Simplex radio systems worked well. The mission enabling “Black Box” was validated with GPS for the first time, diagnostics received, and redundant link demonstrated to ensure mission success. The Advanced Manufacturing techniques employed in the mass production of ThinSats, foldouts, and radios will expedite the deployment of future constellations, low cost satellites with ground segments with fast turnaround and high yield mission assurance.

Some of the main successes of the NG-11 ThinSat program include:

- Flight approvals by Northrop Grumman (NG), FCC, Globalstar and NASA
- Final delivery of 63 ThinSats with rigorous testing
- NG second stage integration and CSD release performance
- Most of the 120 inhibit switches/light sensors activated
- 180 deployable foldout panels were deployed as expected and as validated by solar intensity
- We received unprecedented ThinSat link contacts with much data in first orbit for students and VIPs to observe
- Quality data received from MEDO, TSL, and Custom boards to debug and verify data interfaces
- Data link transmission protocols worked well
- Even with a very high spin rate (>10RPM), the NSL/Globalstar link still worked well, giving us thousands of 36 Byte packets (Total of 3,168 packets or 114,000 Bytes for mission) for basic mission success and debugging payloads. Nearly all of the partial packets were received.
- ThinSat data available for the entire mission till reentry
- The Space Data Dashboard performed well
- The first time-ordered constellation data base was effortlessly obtained
- Nearly all of the students have some data to debug their electronics and analyze sensor data.
- The Dynamics for STRINGS and NODES can now we controlled with damping and detumble design to increase lifetime, radar cross section, & throughput.
- NG-11ThinSat was a successful Pathfinder for establishing educational and research constellations.
- Many other breakthroughs

It is also a good teaching experience for why some small unforeseen problems occur when you are pushing the Research and Development envelope forward.

To our knowledge the April 17, 2019 ThinSat launch, and deployment was the largest educational constellation in the world and likely one of the largest commercial constellations flown by industry or government (NASA, DOD, NSF) with 52 of the 60 satellites making contact. The ThinSat and CubSsat Constellations are now poised to form serious research and educational applications.

The Dream would be to launch educational and research constellations every 6 months with the ThinSats having various drag coefficients that cause the satellites to spread out and reentry every several days.

11 REFERENCES


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12. ACKNOWLEDGEMENTS

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