TSAT Globalstar ELaNa-5 Extremely Low-Earth Orbit (ELEO) Satellite

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ABSTRACT

This paper reports some of the initial results from the Taylor University, Technology, and TEST satellite (TSAT), especially results related to the new Globalstar communication network connection coverage, spacecraft temperature, magnetic field variations, reentry heating data, and new plasma science data measurements at extremely low altitudes down to 120km. TSAT is a two unit CubeSat (2.9kg), launched April 18, 2014 on a SpaceX rocket to the ISS (CRS-3 service). TSAT was released into a 325 km circular, 51.6° inclination orbit. This environment enabled unique extremely low-earth orbit (ELEO) data, but consequently only had a lifetime of 40 days. The primary objectives for TSAT were: 1) validating and characterizing the commercial Globalstar link capacity and coverage, 2) making new low-altitude ELEO measurements, 3) making plasma density measurements using a Langmuir Probe, and 4) educating a future workforce in STEM fields (Taylor University engineering program Capstone and other classes). A pioneering feature of TSAT is the near real time and continuous Globalstar link coverage, so that measurements could be made in the uncharted ionosphere region 120 to 300 km. This new region that TSAT explored is called the Extremely Low Earth Orbit (ELEO) region. At present, the near earth space region between 40 and 300 km is vastly underexplored since only sounding rocket flights (about 20 min) take measurements in this region, at only a few locations. Reasons for exploring this vast region of the earth's upper atmosphere with small satellites include: 1) an advanced understanding of climate; specifically Sun-Earth connection using real-time in situ data for global ionosphere models, and 2) new discovery potential for atmospheric, ionospheric, and magnetospheric underpinnings and dynamics. LEO satellites entering into the ELEO region spiral into the atmosphere within a few weeks and are not designed for ELEO measurements because of cost and scale factor. A new class of satellites can be proposed to study this under-represented region of the space weather field; niche small satellites to explore the ELEO region. This paradigm has been demonstrated by TSAT. Monte Carlo simulations have been used to calculate the force and torques on TSAT, as well as on more aerodynamic satellites, so that they can survive to make measurements further down into the atmosphere for extended periods of time.   Additional enablers of ELEO CubeSats include: 1) ISS resupply missions routinely have secondary slots in the ELEO region, 2) limited probability of space debris collisions in this region, and 3) the suitability of this region for ion engine thrusters to counteract drag, extending satellite operations beyond previously achievable mission lifetimes. The relatively low cost of these ELEO CubeSats, coupled with relatively long mission duration in the ELEO region, produces a large amount of useful data per unit cost.

INTRODUCTION

This paper reports on the preliminary results of TSAT. Early first results were reported at the April CubeSat workshop (1). The TSAT satellite was designed to better understand the E and F region global ionosphere below 325 km and down into the heating region below 120km. This uncharted new region of investigation is called the Extremely Low Earth Orbit (or ELEO) region, and is relevant to the understanding of space weather, atmospheric models, climate, global electric circuit, remote sensing, and intelligence gathering. In order to accomplish this goal, a ruggedized radio system enhances ELEO science missions; it is able to transmit satellite data in nearly real time to the internet for any location on earth. Future campaigns, such as QB50, are also dedicated to exploring this region with multipoint measurements using 50 orbiting CubeSats (2).

Problems leading to small satellite failure include the complexity of the communication system; a sub-system that involves low power transceivers (and low mass and size), spacecraft protruding antennas, and high gain tracking ground stations with infrequent and short line-of-sight overpasses. In addition, there are many difficulties associated with international radio community coordination, preventing downward spurious contamination for radio astronomy antennas, personnel time required for operating ground stations, deploying antennas, using Two Line Elements (TLE) to find satellites and point ground antennas, time-synchronization of data sent through multiple ground stations and organizations worldwide, and flight communication and ground station software systems. In addition, commanding a tumbling satellite during launch and early operations can be difficult, especially when transceiver power is low and short overpasses are spaced several hours apart. Furthermore, for constellations of CubeSats (i.e. the QB50 program) there is the significant complexity of de-conflicting operational resources such as numerous ground stations.

The TSAT spacecraft presents a new paradigm using the existing Globalstar network of phone satellites to initiate satellite-to-satellite cross-links. Risks included transmission uncertainties (e.g. Doppler, link margins, and interference), international radio community coordination and FCC license processing, legal Globalstar approvals, flight qualified processor

radio/antenna systems, and time synchronization of received data sets.

One of the first difficulties was learning how to navigate the requirements for coordinating with the international radio community for using a COTS satellite terminal in space. This required coordination of radio usage licensing through the applicable national regulatory body for Taylor University and NSL -- in this case the FCC, which is also responsible for international coordination. We want to report an entirely positive experience with the FCC. The FCC IB (International Bureau) was very cooperative and supportive and handled all the international issues. Another challenge is getting time-synchronized datasets. If a mission uses multiple ground stations and/or multiple data communication methods, it is essential that the data from all stations be time-synchronized. TSAT data synchronization was handled by the Globalstar network, and greatly simplified data correlation with satellite positioning. Using a communication model similar to the one employed on TSAT promises high reward potential as the opportunity for mission success greatly increases because of nearly global coverage of spacecraft telemetry with low latency, and no associated ground infrastructure beyond a data server.

The TSAT physical structure and sensor suite were primarily developed by nine senior Capstone students with majors in Engineering Physics, Computer Engineering, Physics, Environmental Engineering, and Mathematics (3,4,5,6). The final assembly and testing of the Electrical Power System (EPS), Flight Processor, and Globalstar communication processor was completed by NearSpace Launch Inc.
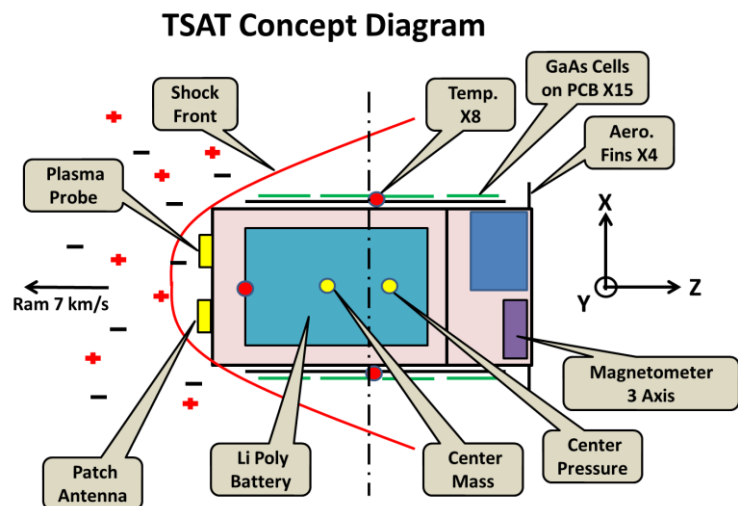

Figure 1: TSAT concept diagram

TSAT SYSTEM

A conceptual diagram of TSAT is shown in Figure 1. The 2U spacecraft has dimensions of 10 X 10 X 20 cm and was successfully launched alongside the 1U PhoneSat spacecraft by the Cal Poly P-Pod launcher as part of the ELaNa 5 program (see Figure 2) on the SpaceX CRS-3 ISS resupply mission.
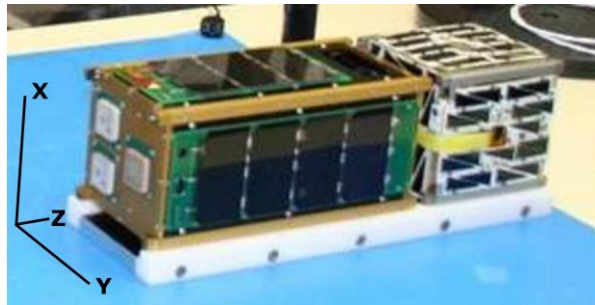

Figure 2: TSAT (2U) and PhoneSAT (1U) in P-Pod launcher during final integration at Cal Poly

The satellite was aerodynamically stabilized in the ram direction by moving the CG 2 cm forward of the centerline. Small fins on the back (+Z side) created additional drag to move the center-of-pressure behind the centerline and resulted in a restoring torque. Test Particle Monte Carlo (TPMC) simulations with individual atoms were used to calculate restoring torques, forces, and drag coefficients. Above 160 km, the TSAT was in a free molecular flow region, then entered into a transition region (120-160km), and finally into a hypersonic continuum flow below 120 km. A shock wave (red line, Figure 1) was produced by the 7 km/s orbital velocity. Three orthogonal sheets of mu-metal were used for damping spin in the earth's magnetic field at higher altitudes. The magnetometer, sun, and temperature signals are still being analyzed to better understand TSAT orientation during the different phases of the flight.

Each of the four 10 X 20 cm walls included a PCB board for mounting the GaAs solar arrays (green, Figure 1) and a temperature sensor (red dots, Figure 1). The 3-axis magnetometer was located on the +Z side end cap and within the EMI shield wall. The Plasma probe was biased at 4.1 Volt when not sweeping to collect electron charge (- & + plasma) over 5 orders of magnitude with a log amplifier. The plasma probe and simplex patch antenna were mounted to the –Z endplate and faced the ram flow direction as shown.

The TSAT frame structure was designed and fabricated on a CNC by students (7). The student sensor suite was also included in the design. Not all of the sensors qualified for the TSAT flight, but are scheduled for the next UNP flight. The design of the student suite is discussed in four student ASEE papers (3,4,5,6).

TSAT turn-on steps include 1) pull before flight switch active, 2) deployment switch active, 3) solar array illumination active, and 4) 1hr. countdown timer. This is essentially a 2-fault tolerant inhibit system, with a final solar panel illumination requirement to activate full data broadcast mode.

GLOBALSTAR COVERAGE

Globalstar constellation and simplex radio

The Globalstar communications network was originally designed as a classical duplex voice/data system. There are about 32 LEO satellites plus spares in the Globalstar constellation at 1414 km altitude (114 min period). The satellites are in prograde circular orbits at 52° inclination on 8 orbital planes spaced equally in right ascension. The ground footprint diameter is about 5790 km and there are 16 beams per satellite.

Globalstar was originally used for voice and duplex data communications. In 2003, Globalstar introduced a simplex communications system which uses transmit-only devices. Simplex messages, sent in bursts of 9-byte packets, can range in size from 9 to 144 bytes (1 to 16 packets). Simplex transmitters can send data immediately because they use a simple encoded broadcast transmission which has no link setup delay. This unique combination of low power, spread-spectrum connectionless links that are carried simultaneously over every satellite-gateway pathway available to the transmitter, along with randomized packet arrival times resulting from unpredictable multipath reflections of the transmitted signal, all contribute to a very high probability of packet receipt success. Although devices can further increase the packet success rate by sending multiple copies of each packet, this would increase the time between packets. Therefore, TSAT was designed to send only a single copy of each packet, in order to collect a more complete map of the space environment.

Data from TSAT was received by one or more Globalstar satellites and immediately sent to a gateway ground station (bent pipe concept and no onboard storage). The Globalstar space segment is lower cost and lower power than an interconnected satellite constellation, and more fault tolerant with a parallel architecture, and is supported by about 14 gateway ground stations around the world. All check-summed non-erroneous data received by any of the gateways is time-stamped and sent to the subscriber immediately (after removing duplicates).

TSAT implemented only the STX-2 simplex modem for initial testing, because it was low in power and size, with a simple TTL digital interface (no handshaking and less EMI). The user (TSAT) to Globalstar uplink used a single transmit frequency of 1.61625 GHz (RTU Channel C) to minimize the chance of radio astronomy interference, thus enabling the space-space link FCC license. There was no Code Division Multiple Access (CDMA) modulation on the simplex unit. The supply voltage is 3.3 V, mass 17 g and temperature range from -30 to 60°C. The transmit ERP is 200mW and the DC power draw while transmitting is less than 2W. The Standby mode power required is a mere 6 µA and Wait mode is 10 µA.

TSAT Simplex data rate

A small microcontroller Microchip 18F2620 acts as the communication processor controlling the STX-2 modem, and can send messages of 9, 18, and 36 bytes. Smaller messages (fewer packets) are expected to transmit through the communication chain with more success. For TSAT, the power/budget tradespace was the most limiting, resulting in a compromise selection of a mission data rate of an 18 byte message burst every 5 sec (3.6 Bps or max rate of 311 KBytes/day). To further reduce power, TSAT duty cycled the rate to transmitting burst messages for 3 min followed by 15 min in standby. This results in a maximum effective transmission rate of about 51 KBytes/day. Table 1 illustrates the selected data rates based on the simplex transmitter capabilities, and the design compromises selected in order to balance power needs for the

duration of the mission.

The TSAT packet rates using the Globalstar link for the 40 day mission is shown in Figure 3. Notable is that the first data packet was received 11 seconds after the anticipated modem power-up, based on the SpaceX mission clock. The location of TSAT at this time was over the southern Pacific Ocean. The data packet made

Table 1: Selected TSAT data rates

	Selected	Duty Cycled
Bytes/msg	18.0	18.0
Pkt/sec	.2	.2
Bytes/sec	3.6	3.6
Sec trans/day	86400	14400
B/day	311040	51840
KB/day	**304**	**51**
MB/day	**0.30**	**0.05**

its way back via the Globalstar gateways and through the internet for access anywhere. This new paradigm of the satellite "phoning home" eliminates the issues with most ground stations and the arduous process of fox hunting for a spacecraft in a cloud of recently deployed
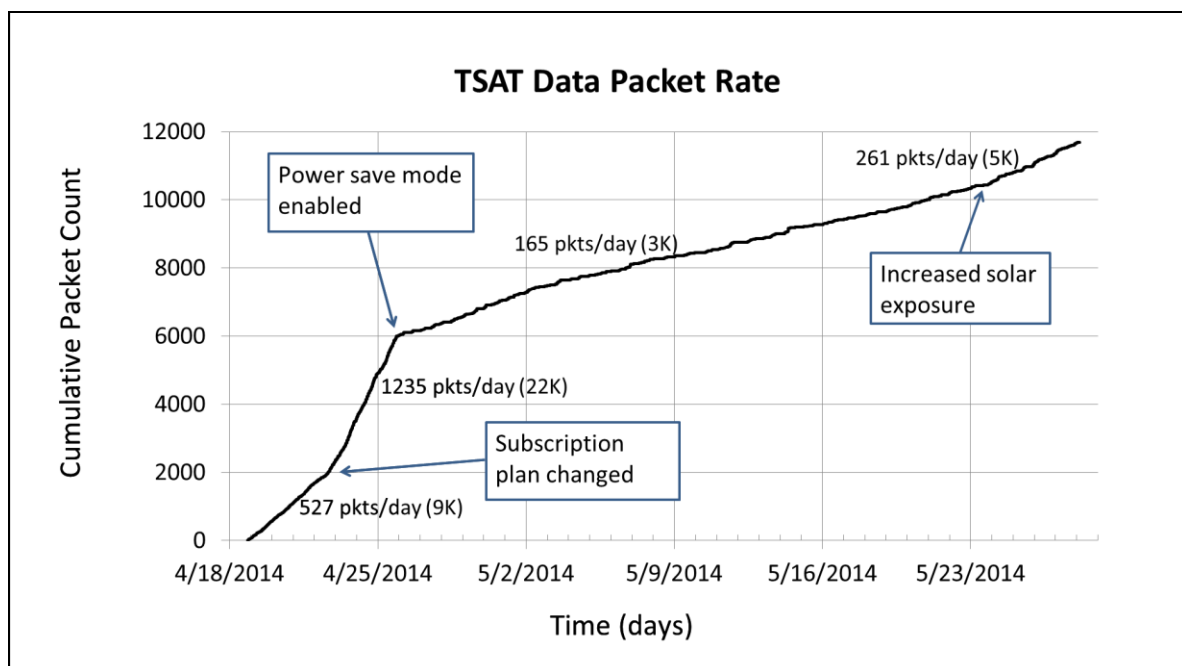

Figure 3: TSAT data packet rate

vehicles. The network supports a ready to use common sever data base, relying on parsed XML packets. Most if not all of the communication uncertainties listed for classical ground-station based communications in the introduction are solved with this new Globalstar capability.

In Figure 3, the first inflection point occurred when it was discovered the TSAT subscription was initially configured as a standard terrestrial SCADA transmitter, which transmits each message three times. The second and third copies are time-delayed from the previous message by a randomized 5-10 minute interval. As a result, any messages with a given MSG_ID that are received within a 40 minute period are considered copies of the same message. Since MSG_ID is a rolling counter from 0-15, and since TSAT was sending messages much more frequently than 30 minutes, the MSG_ID was cycling through all 16 IDs much faster than 40 minutes, so this error in the subscription profile is what prevented many messages from being sent to the TSAT subscriber. Although it was a minor inconvenience, no data was lost. Future subscribers

Table 2: Globalstar gateways, TSAT packets received

Gateway	Packets Received
Australia 1	4150
Venezuela	2293
Peru	2289
France	2155
Brazil	1867
Korea	1853
Australia 2	1396
Turkey	1333
Singapore	906
Russia	835
Western Canada	834
Nigeria	654
Eastern Canada	589
TOTAL	**21154**

should configure their subscriptions to have all unique messages sent to the server. Table 2 shows the packets actually received by Globalstar at each of the gateways (ground stations) for the duration of the mission. The total of packets received at the gateways was 21154,

almost twice the 11696 packets received by NSL and Taylor University. Assuming most of these additional packets were not forwarded due to the previously described subscription error (as opposed to checksum errors), data transmission rates will actually be higher than indicated, probably approaching the expected 51KB/day. Analysis of the additional data is still in process.

When the subscription plan changed, data throughput more than doubled (first inflection point, Figure 3). This higher rate continued for a few days until the spacecraft entered a low power mode to conserve battery capacity, helping to balance the power budget (second inflection point, Figure 3). In this mode, the solar arrays charged the batteries and ran the electronics. The data rate was greatly reduced (almost an order of magnitude), but TSAT continued to operate, providing engineering and science data. Near the end of the mission (third inflection point, Figure 3), the data rate fortuitously increased (about 60%) enabling greater coverage in the lower ELEO and reentry region. This increase in data rate was associated with the increase in power received due to improved solar illumination of the TSAT orbit.

The success of any communication system depends, in part, on managing the traffic so that no system components are overloaded, and to minimize the possibility of "collisions" which could corrupt data. Typical duplex systems employ 2-way traffic management protocols to dynamically control data flow. Simplex systems, however, do not have 2-way communications, and therefore require traffic management controls to be built into the transmitter.

The two most important system characteristics for simplex message timing are (1) randomization and (2) message load.

Randomization: TSAT messaging automatically satisfies the requirements for randomization because its ELEO orbit ensures that messages will be sent successively to each gateway in its path, in a pattern which changes with each TSAT orbit. TSAT messages are handled by a particular gateway for only a short portion of each orbit, and the message timing will be shifted with each sequence of burst messaging.

Message Load: Globalstar Product Approval enforces strict message timing guidelines for simplex products. The guidelines allow for a maximum of 4% duty cycle (in any given hour) for nominal usage (maximum in the EU is 1%), and up to 8% for alarm conditions (alarm-level messaging is allowed for a maximum of 48hrs in any given terrestrial region). TSAT was different from

all previous Globalstar simplex transmitters because of its ELEO orbit and its guaranteed limited lifetime.

As shown in Figure 3, a bottoms-up determination of TSAT mission data transfer requirements showed that the TSAT data transmission plan that was implemented was well within Globalstar's guidelines. The maximum message transmission rate was at the beginning of the TSAT mission, during which TSAT had fully charged batteries and was transmitting 36 dual packet messages in 18 minutes (3 minute transmission burst followed by 15 minutes idle). Due to TSAT's constantly changing position, there were only 36 dual packet messages (72 total packets) ever sent to any particular gateway in any given hour, which is a duty cycle of 2.9%. If this same message timing plan had been used by a terrestrial transmitter, the duty cycle would have been 11.5%; it is because TSAT is orbiting, which allows it transmit at a higher data rate without negatively impacting any simplex communications, and while still complying with Globalstar requirements. After the first 10 days in orbit, TSAT automatically reduced its messaging to 7 msgs/hour, or a duty cycle of 0.3% (7 packets * 1.44 sec/packet)/(3600 secs/hr).

Globalstar data capacity

Globalstar has sufficient current network and system capacity, as TSAT's conservative communications regimen did not even begin to register as a significant data source on the Globalstar network. CubeSat communications performance apparently won't be impacted by any system capacity issues for either simplex or duplex communications. Even if there were hundreds of CubeSats in orbit, all simultaneously using the Globalstar network, the communications load would be just a tiny fraction of the traffic that Globalstar currently handles. There are no capacity issues at any individual gateways, nor are there any capacity issues in any portion of the satellite constellation or any other portion of the Globalstar system. The Globalstar system appears to have capacity to handle many CubeSats transmitting thousands of packets per day. The potential of this capacity will be explored quantitatively in a future paper.

TSAT Globalstar coverage maps

The locations of all of the 11696 raw data packets received near real-time are shown in Figure 4. The STX-2 transmissions are global, but there are two lower yield regions as expected in the south Africa and the
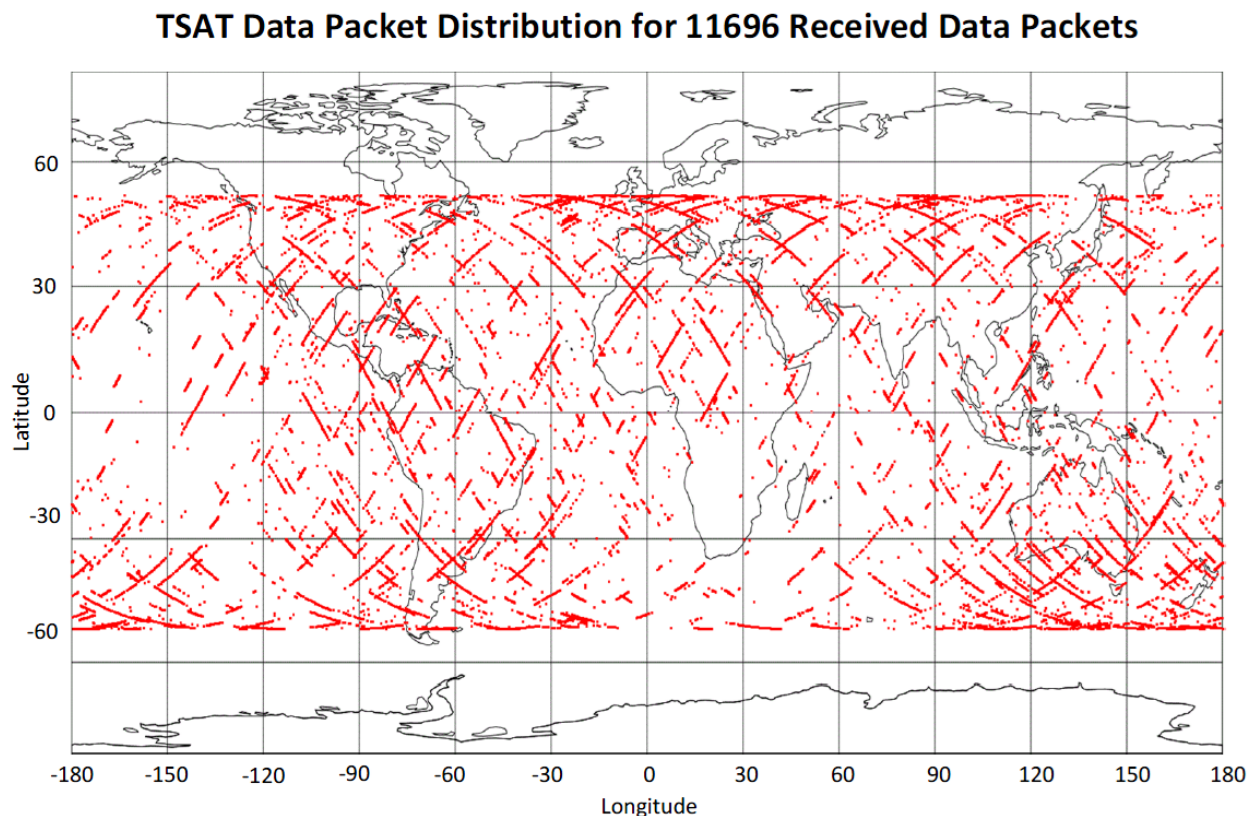

Figure 4: Global distribution of received data packets

pacific ocean areas. Yields are lower due to no ground station gateways being located in these regions. On TSAT, there was only one antenna and it was pointed in the ram direction, so potential connection to additional Globalstar satellites (and through them to additional ground stations) was somewhat limited. However, with a few more patch antennas pointing in orthogonal directions, the yield in these regions could be improved. A bin plot of the number of packets in each 30 degree latitude by 30 degree longitude region is shown in

packets received in the area of Australia and the southeastern pacific region. These disparate numbers of received packets appear to be well correlated with the distribution of ground stations (Figure 7).

Figure 6 illustrates the distribution of received packets via a non-normalized contour plot. Regions of high and low packet receipt are again clearly illustrated, and contours project a realistic picture of potential packet receipt coverage for a CubeSat equipped with a single
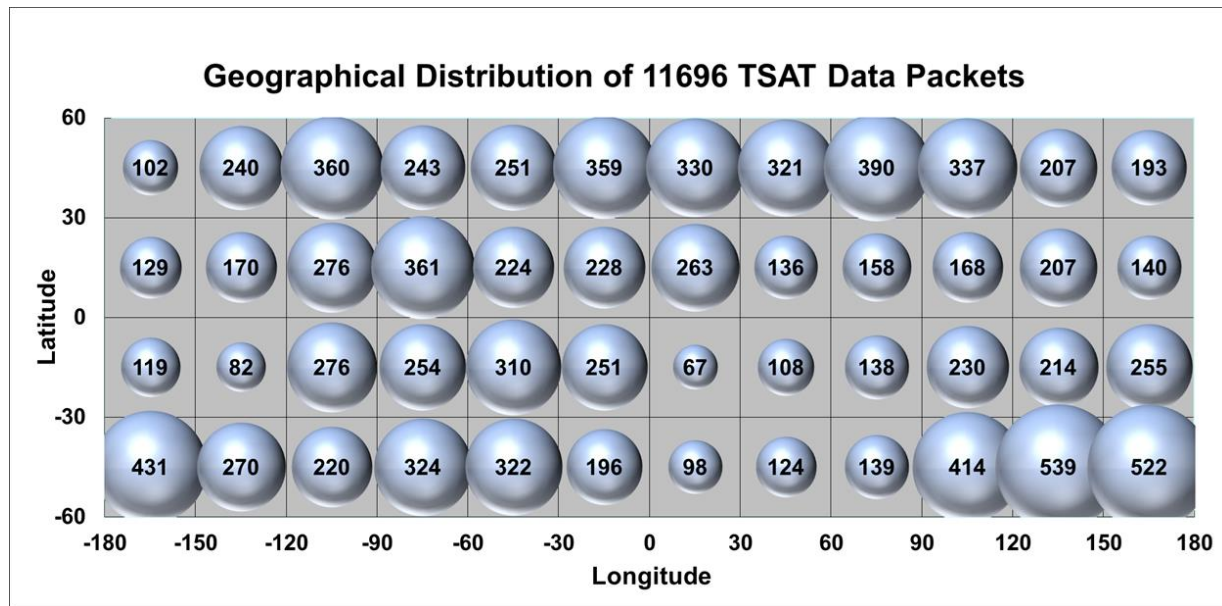
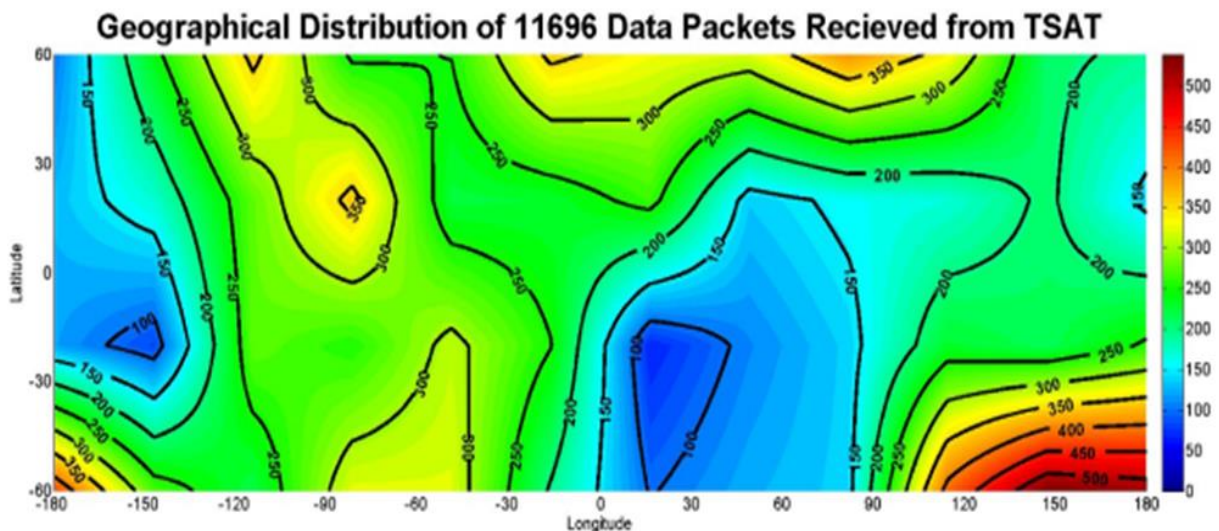**Figure 5: Bin plot of packet counts per gross region**

Figure 6: Global contour plot of data packets received from TSAT

Figure 5. The sparse regions of packet receipt in the pacific and the southern part of Africa are clearly illustrated. Also obvious are the large numbers of

ram-facing simplex transmitter, as was the case on TSAT. Figure 7 illustrates the coverage projected by Globalstar with the actual coverage experienced on the

TSAT mission. The data has been normalized by adjusting the northern and southern latitude bins using a simulated mission of 40 days with equally spaced 10 minute sample points projected using the earliest TLE applied to the SGP4 orbital model. This normalization tends to remove the bias for the orbital transit times in the northern and southern latitudes. A visual comparison of the projected and actual coverage in Figure 7 demonstrates that TSAT experienced better-than-expected coverage. In spite of meeting coverage expectations, Globalstar engineers drew the following conclusions about TSAT transmission limitations:

1) The TSAT antenna was not positioned optimally. Instead of being pointed toward space, the antenna is ram-facing. This design choice was made to diminish the likelihood of downward-looking transmission and potential radio astronomy interference. Another factor was limitations related to cost and power to control the roll of the satellite, so as to always maintain a side mounted antenna with its midpoint oriented along the X-axis. It is estimated the current orientation may only be 50% of optimal. An "upward looking" (toward space and the Globalstar constellation) orientation would guarantee better performance.

2) Multi-packet messages are not sent to customers unless packets are received successfully. Since the dual packet TSAT messages are well-structured, the NSL data processing system can extract significant data from partial messages, i.e. dual packet messages where either one or the other packet is missing. Future flight hardware will be programmed to send all data as single packet rather than double packet messages.

By special arrangement, in consideration of the irreplaceable scientific data from the mission, Taylor was able to contract with Globalstar to provide all the partial 2 packet messages. Preliminary analysis of the additional data packets, roughly equal to another 10,000+ packets not forwarded by Globalstar, will result in significantly higher final data rates for the mission, probably approaching the 51KB/day level projected for the duty cycle transmission mode (Table 1).
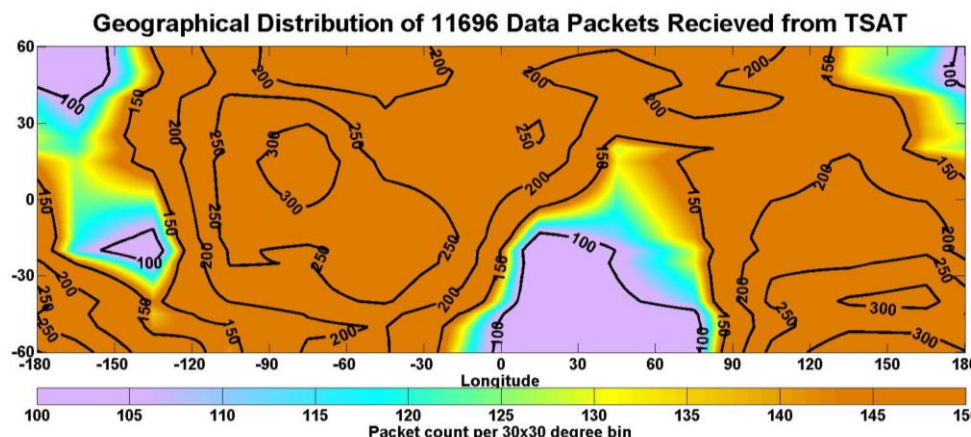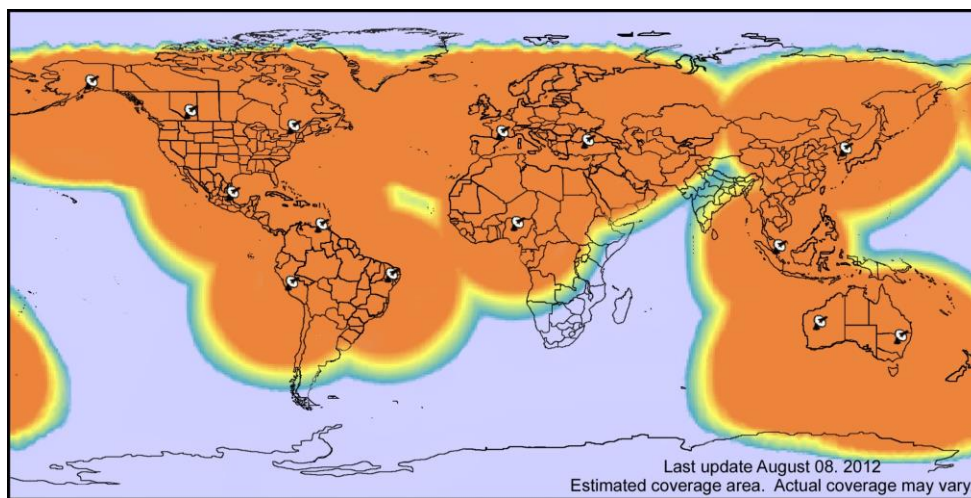

Figure 7: Comparison of Globalstar projected coverage and normalized TSAT results

EYESTAR SIMPLEX/DUPLEX VAR

The conference theme this year is "Commerce of Small Satellites". Much groundwork has been developed by NSL and Globalstar with TSAT, and the current focus is to keep actively testing and enhancing these communication products and services. NSL is committed to making these communication services and products readily available. The duplex unit and server ground segment are currently in beta testing.

NSL is a Globalstar Inc value added reseller (VAR) for spaceflight and HARP. In order to help mitigate and solve integration problems and to streamline FCC approval, NearSpace Launch Inc. (NSL) has secured both Globalstar and FCC approval for controlled use of the Globalstar network of satellites for a satellite-to-Globalstar-satellite link.

As mentioned earlier, developing a reliable communication link for a small satellite can be a daunting experience due to power constraints, varying data rates and data storage, infrequent ground station coverage, expensive ground station tracking and operation requirements, difficulty of maintaining links during tumbling spacecraft con-ops, antenna gain and link margin issues, timely command and control, and many other factors. A further complication can be the need for a commercial, secure link that does not meet the amateur radio constraints and ITAR restrictions. The process for getting an FCC license can be time consuming and challenging.

The new NSL-Globalstar satellite paradigm is to collect near real-time satellite data from nearly anywhere in the world, with nearly continuous data download and uplink command capability.

EyeStar Radio Specification

The EyeStar-3 board includes a beacon and simplex/duplex satellite radio set. It is based on research with previous command radios for the High Altitude Research Platform (HARP) balloons, and the new Globalstar STX-3 modem. The name "EyeStar" comes from the previous HARP Hawkeye communications board design, and the potential to fly many EyeStar units in constellations (analogous to multiple visual receptors in a simple eye). The "star" in EyeStar represents the connection with Globalstar and future satellite constellations. NSL has also developed a similar Globalstar-based board (EyePod) for High Altitude Balloons. NSL now has over 300 successful launches in the past decade with over 99% recovery. (8, 9)

The EyeStar modem product (see Figure 8) also includes certification, GPS and flight processor interface, patch antennas, ten beacon analog and digital inputs, and data plan options. The simplex EyeStar radio can fit in a "PocketQub" 5x5x15 cm, and transmits 200mW ERP. Data from the Globalstar network is immediately routed through the web and stored on a secured server for client access.

The EyeStar specifications are given in Table 3, and an ICD is available. Radio astronomy concerns were diminished by limiting the Globalstar simplex units to operate at 1616.25 MHz, with a bandwidth of +/- 1.25 MHz. No RF interference was reported for the TSAT mission.

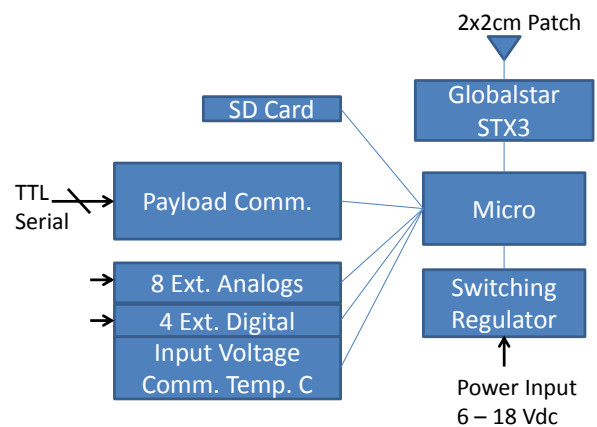**Figure 8: EyeStar radio for Globalstar link (STX-2)**

Figure 9: EyeStar block diagram

In Figures 9 & 10, diagrams illustrate the data flows from the EyeStar microcontroller via a patch antenna into the Globalstar network of more than 32 plus satellites, and from the satellites through numerous gateways to the NSL server. The data from multiple space platforms are then parsed into separate tables with time, GPS, and spacecraft data for a specific customer, to be downloaded or pushed to customer

servers. A number of encryption and security measures will be available.

Table 3: EyeStar Globalstar modem for spaceflight

Description	Conditions	Min	Typical	Max	Unit
Power					
Input Voltage		6	7.1	18	V
Standby Current		7	10	14	mA
TX. Current		350	400	450	mA
RF characteristics					
Frequency range			1616.25		Mhz
TX output		+16	+18	+20	dBm
		40	63	100	mW
TX + Patch			200		mW
Bandwidth			2.5		Mhz
Modulation			BPSK		
User Communication port					
Protocol			Serial N81		TTL
Bus voltage		4.8	5	5.2	V
Data rate			38.4		Kbits
Packet Size			38		Byte
TX Rate / Packet			1		Sec.
Beacon Mode					
Beacon Data Packet		0.5		60	Minute
User Data Packet		0.5		60	Minute
Analog inputs					
Eight	10bit	0		5	VDC
Source impedance			2.5K		ohm
Digital inputs					
Four	TTL	0		5	VDC
Antenna characteristics					
Polarization	LHCP				
Efficiency			80		%
Gain			5		dBic
Bandwidth (3dB)	Both axes		100		Degree
VSWR			1.3:1		
Physical					
Length			80		cm
Diemeter			20		cm
Heigth			6		cm
Weight		200	225	250	g

With NSL as a VAR and single point-of-contact (POC) with Globalstar, securing design services, FCC licenses, and data services is streamlined. NSL is currently validating the LEO satellite-to-satellite simplex and duplex communication links, and ground segments for commercial small sat community use (TSAT and GEARR-Sat). The VAR agreement with Globalstar also covers the use of the EyePod for high altitude balloon missions.

One of the powerful capabilities of the EyeStar data system is that it uses only one Globalstar data stream. This creates the opportunity to have a Common Time Ordered Data Base (see right side box in Figure 10) with common GPS data and EyeStar sensor data.

Elements of this database could be open-sourced, so that students and researches can compare their data to other common sensors flown at different times and locations. For example, constellation flight orbit data comparisons could be made with other missions.

Other NSL Satellite Products

NSL engineering services also include rapid CubeSat structure and bus development times -- as low as three months from contract start to completion and final delivery for environmental testing. The Air Force Research Labs GEARR-Sat was developed by NSL in less than three months, and is scheduled for flight this June, for later release from the ISS. GEARR-Sat includes three Globalstar data links, solar arrays, GPS, battery packs, magnetic stabilization, flight processor boards, power management boards, a Langmuir plasma probe, and other sensors.

Other NSL services include joint research project collaborations in an investigator capacity, or for hire. In many cases, customers are interested in custom designs based on NSL solid-body CubeSat frames and structures, mechanisms, communication links, flight and power electronics options, and payload
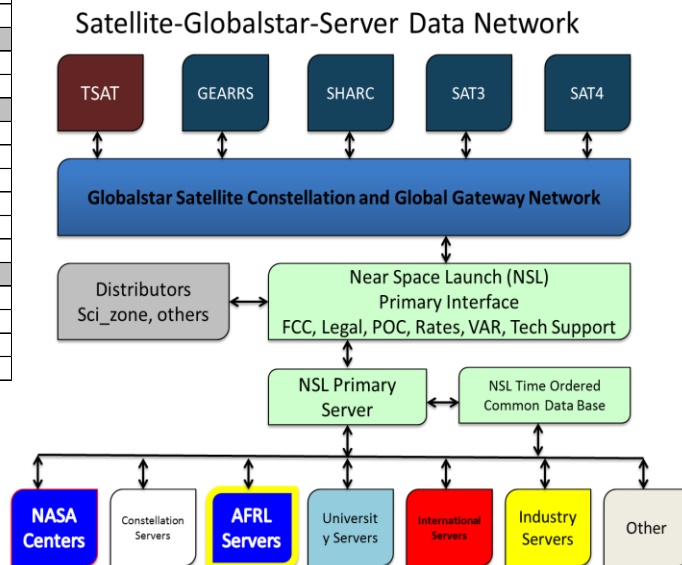

Figure 10: Data flow through the Globalstar network to customer servers

instrumentation preferences. NSL offers a number of other products that include ruggedized CubeSat structures, EPS, and Li-ion/Polymer battery packs. With more competitive options for entrepreneurs, more exciting commercial endeavors are possible in emerging markets.

ELEO ORBITS

ELEO Objectives and Science

Extremely Low Earth Orbit (ELEO) satellites may open up, "A new space region of exploration for understanding our global sun and earth connection". At present the near earth space region between 40 and 300 km is vastly underexplored, since only sounding rocket flights (about 20 min) can take measurements in this region at only one location (see Figure 11). LEO satellites, when orbiting below 300 km altitude, spiral into the atmosphere within several days to weeks and simply are not cost efficient to explore this region of space.

The new class of proposed ELEO satellites will be aerodynamic, with a high ballistic coefficient, so that they can make measurements down to 120 km, and possible lower, relaying their data immediately to a satellite network. Low drag satellite designs with sloped area cross-section and "Thin Sats" that are 3 and 6U long, but only 1 or 2 inches wide, have low drag and can be stabilized by moving the CG forward.

ELEO Sats will be launched between 325 to 425 km altitudes, and will spiral in over a several weeks to months interval, with an earth orbit period of about 90 minutes. By using many low cost and small ELEO CubeSats, 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) ELEO orbits 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, permits data collection above the "black-out" region anywhere on the earth.

In the future, ELEO 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. Furthermore, when an ELEO-SAT enters the reentry region near 80 km, future designs could allow for the heavy exoskeleton and batteries to be jettisoned, while a spring-dampened Kevlar chute would allow instrument reentry and continued measurements as a dropsonde. It is expected that many relatively low-cost rides will become available to ELEO orbits in the future.

The extremely low altitude data set of the S81-1 SEEP satellite flown in 1982 (which required propulsion to retain orbit) provides an example of the rich data available from this region of space. SEEP made some of the first space weather observations (10) (Voss et al)
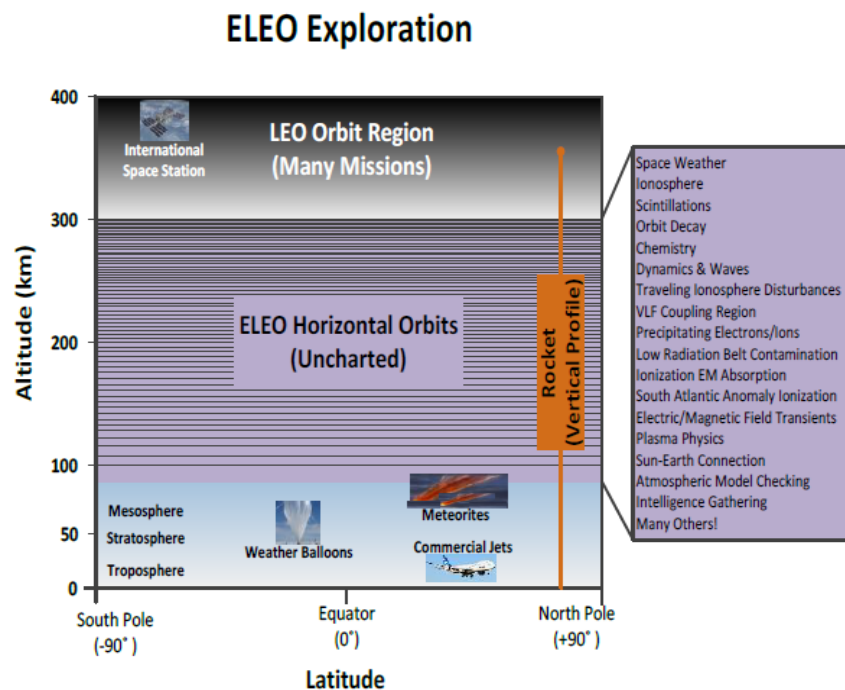

Figure 11: The purpose of the aerodynamic ELEO-SAT is to map and explore the ionosphere and atmosphere in the ELEO region (120 to 325 km). While sounding rockets probe this region (vertical profile at one location) for tens of minutes, the ELEO-SAT will make unique horizontal and global cuts and measurements for over 600 orbits on the order of five weeks.

with unprecedented signal to noise ratios, due in part to the low altitude platform. The SEEP plasma probe data in the TOP panel used the same electrometer design found on TSAT. 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 12; 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 12 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.

Monte Carlo drag simulation

In order to extend spacecraft lifetime in ELEO orbits, the drag coefficient needs to be understood and reduced. For aerodynamic stabilization, the forces and torques also need to be computed in the different flow regimes, from free molecular flow to hypersonic continuum flow below 120 km.

The TSAT simulation results show that as the cross section is decreased and the ram structure becomes more pointed (streamlined), the drag drops significantly. TSAT, with its flat ram direction shape and full surface area of 100 cm^2, was not very aerodynamic, but still had one of the longest lifetimes of the ELaNa-5 CubeSats.
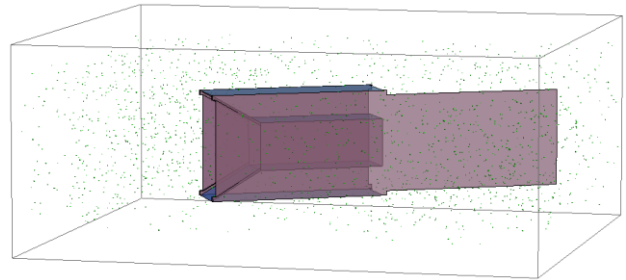
Figure 13: TSAT and ELEO-Sat DSMC Monte Carlo simulation to compute and compare drag, force, and torques.
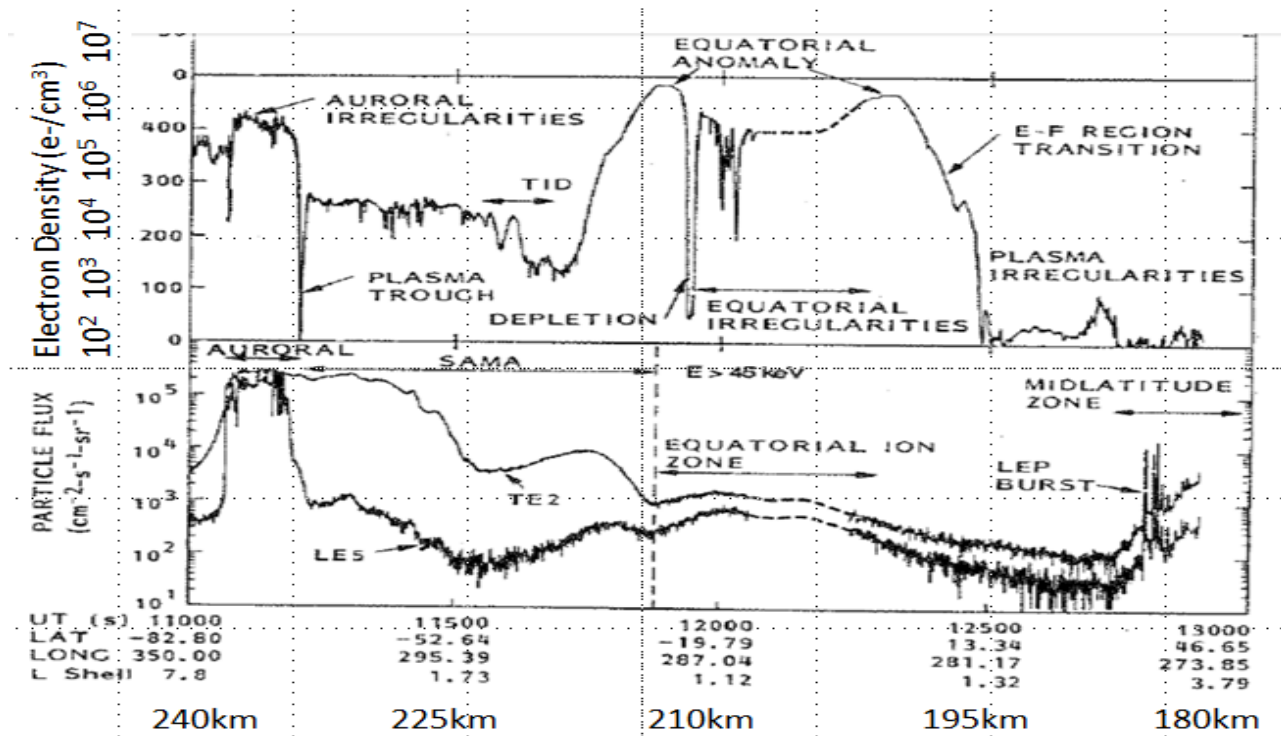
Figure 12: S81-1 SEEP Plasma and Energetic particle Space Weather nighttime measurments in the ELEO region (180-240km). The TE2 detector viewed the trapped flux and LE5 the precipitating flux. The TSAT probe is similar to the SEEP probe mounted in the ram direction. With 200ms byte resolution for three sensors for a half hour pass, the data would be 26Kbytes, which could be trasmitted on one Globalstar simplex link (200 mW).

Table 4: DSMC of TSAT drag and torques

Yaw Angle (deg)	F_x (N)	F_y (N)	F_z (N)	T_x (m-N)	T_y (m-N)	T_z (m-N)
0	-6.37E-19	-3.12E-18	6.00E-06	6.11E-08	-9.55E-09	2.27E-21
15	9.11E-07	-5.50E-16	1.35E-05	1.24E-07	-1.03E-07	1.09E-08
30	-2.83E-06	-2.67E-14	1.38E-05	1.75E-07	-1.84E-07	5.76E-08
45	-7.66E-06	-6.72E-14	1.76E-05	3.02E-07	-3.85E-07	1.14E-07
60	-1.00E-05	-1.63E-13	2.43E-05	4.52E-07	-5.02E-07	1.27E-07

TSAT TLE Orbit and adjustments for below 200km

As a student project, TSAT was not able to include a GPS because of high power requirements of the unlocked GPS units, complex set-up times, and cost. NSL and Taylor University have flown over 600 very low power GPS units that are unlocked for altitude, on high altitude balloons. A high priority for small sat community growth is to facilitate unlocking low power GPS units after installation in the rocket, for security purposes.

The NORAD Two Line Elements (TLEs) were very helpful and critical for TSAT to be tracked during its 40 day mission. It soon became apparent that altitudes derived from the archive TLEs and the Simplified General Perturbations Satellite orbit model 4 (SGP4) package were not intended to be accurate below 180 km, although latitude and longitude were satisfactory. We found conflicting information about the final reentry process, and little detailed, readily accessible documentation on reentry models for small satellites.

To help understand and solve this problem, we developed simulations that included drag and atmospheric density models for the altitude 75km to 325 km. The simulation uses the initial conditions for TSAT to predict its orbit around the earth. Given an initial height and velocity, it shows the satellite dropping in altitude and becoming more circular in its orbit. The simulation is implemented using a polar coordinate system to calculate the satellite height as a function of time, based on the drag equation and Newton's Law of Universal Gravitation. The satellite has a radius vector and an angle vector at every moment in time. By solving the resulting system of differential equations, it is relatively easy to obtain the height of the satellite above the earth. The atmospheric density profile employed comes from the MSIS model for atmospheric density (11). A detailed Monte Carlo simulation was also used, as previously discussed, to compute drag and torques on the spacecraft.

In Figure 14, the archive orbital TLEs from the mission were used with the SGP4 package to generate orbital altitudes, shown in blue. Overlaid in red are the altitude variations based on the TSAT drag model. The thickness of the blue and red bands represents the apogee and perigee variations about each orbit. For
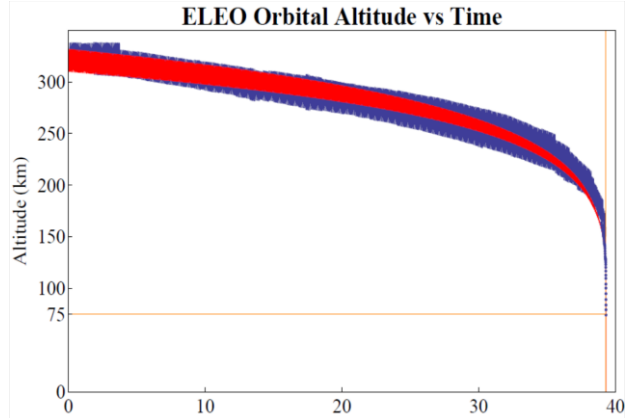

Figure 14: TLE/SGP4 predicted orbits (blue) overlaid by the TSAT drag model (red)

TSAT, 626 orbits were completed. Also conspicuous in Figure 14 is the widths of blue and red bands narrowing with time. This is expected with drag in the model, as the orbits become more circularized. The TLE/SGP4 based blue model altitude did not drop below 160km at the time of reentry burn-up.
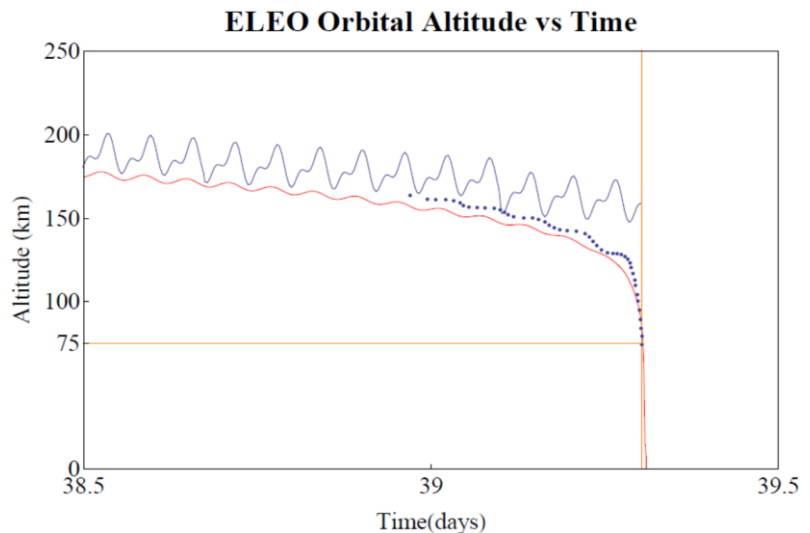

Figure 15: TSAT models for last day orbits. Archive TLE driven SGP4 model (blue solid), TSAT drag model (red solid), and simulations based on Gazley et al. (dark blue dotted) (12).
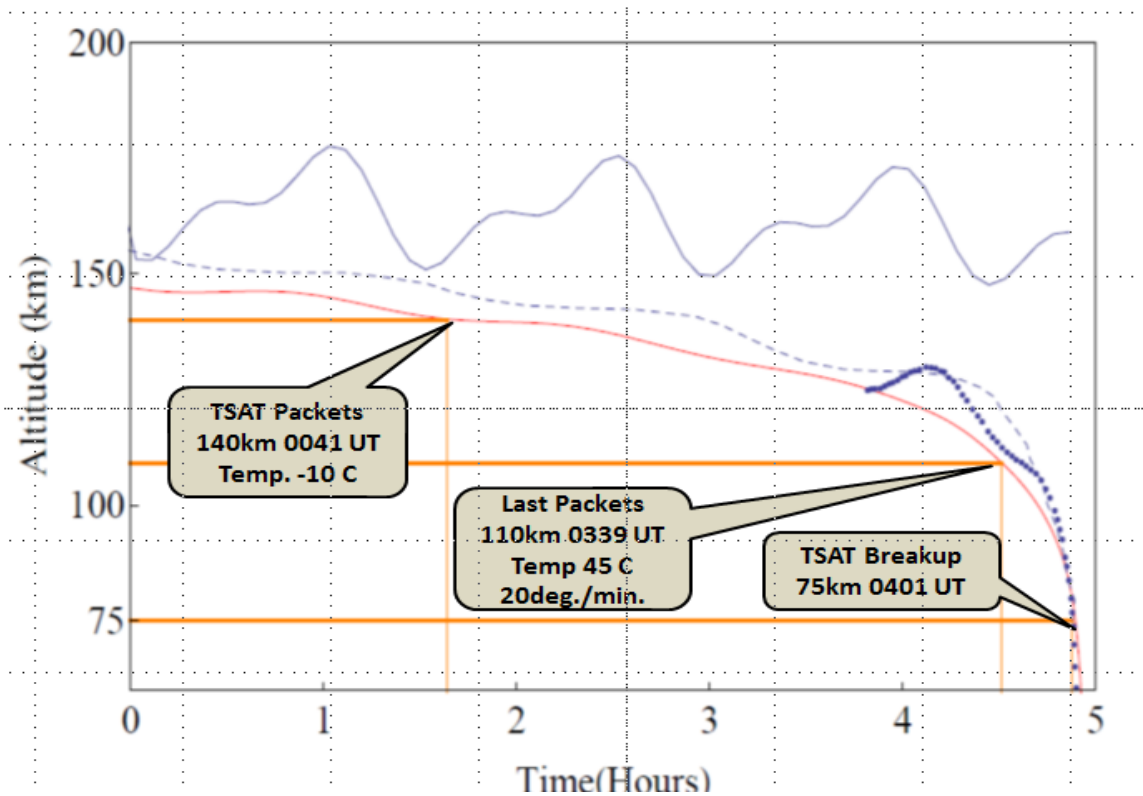
Figure 16: TSAT reentry flight paths: Solid blue line is archive TLEs/SGP4 model, red line is TSAT drag model, dashed and dotted lines are derived from models (11) and (13). TSAT Reentry time at 75 km is 4:01 UT by NORAD, last packet received at 110 km at 3:39 UT, and previous packet at 140 km at 00:41 UT.

The reentry region on the last day is expanded in Figure 15. The individual orbits with apogee and perigee can now be clearly seen. The TLE/SGP4 based orbital predictions in blue do not show the reentry phase, while the TSAT drag model clearly shows the apogee and perigee amplitudes are much less pronounced and stable all the way down into the meteor region at 75km. Independent work by Gazley et al. in 1965 (12) shows a very similar profile to the TSAT drag model for the reentry phase down to 75 km.

The last three orbits are expanded in Figure 16 so even greater detail of the reentry predictions can be clearly seen. The blue line represents the archive TLE/SGP4 based predictions for reentry, while the red line represents the TSAT drag model. The dashed blue line illustrates the simulations by Gazley et al. applied to TSAT's ballistic coefficient, and the dotted blue line represents a simulation follwing Strizzi (13). The TSAT drag model simulations track reasonably well with the results from both Gazley and Strizzi. The horizontal orange line at 109 km shows when the last message burst was received at 3:38.5 UT. The horizontal orange line at 140 km denotes when the second-to-last packet was received at 00:41 UT.
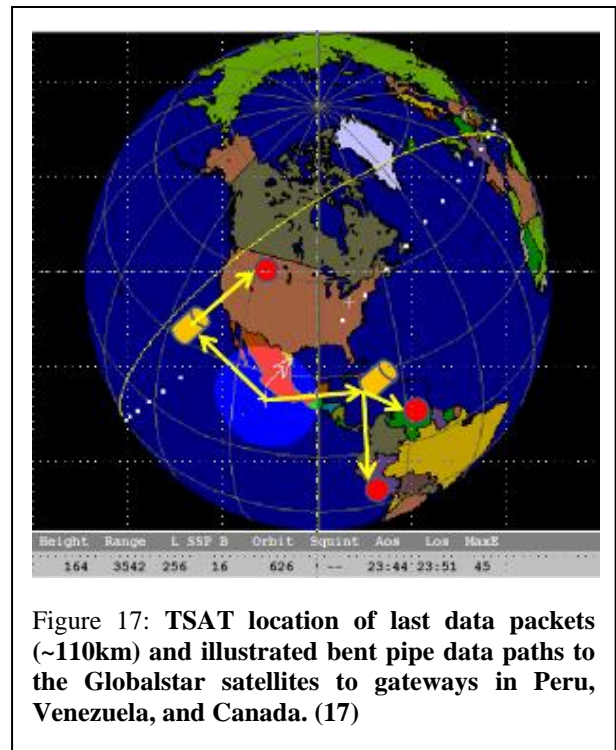

Figure 17: **TSAT location of last data packets (~110km) and illustrated bent pipe data paths to the Globalstar satellites to gateways in Peru, Venezuela, and Canada. (17)**

The orbit geometry for the last packet (highlighted area just west of Mexico on the night side) is shown in Figure 17 using the SatPC32 tracker map (17). The final reentry location and burn-up was projected by NORAD to be over Italy at 4:01 UT. Our last sequence of packets at 3:39 UT is consistent with data being transferred through the Globalstar satellites to ground stations in Venezuela, Peru, and Canada. Predictions from the TLE/SGP4 orbits also placed TSAT over Italy at time of reentry burn-up.

TSAT Reentry heating near 110 km

Around the final data packet transmission at 3:39 UT and near 110 km, TSAT began heating up very quickly as predicted on its approach into the meteor region at 75km (14, 15). During this time, the PCB board temperature increased to 45 degrees C and was rising at about 20 degrees/minute. On previous packets, the temperature averaged -10 degrees C, so the temperature increase was about 55 degrees from the previous packets, and was increasing rapidly. TSAT was still functioning at this point in its mode of conserving electrical power.

OTHER TSAT DATA

In Figure 18, the top panel shows the orbital temperature variations of the solar panel walls. The temperature sensors were located on the back side of the copper clad PCB. (Figure 1)

Solar panel #2 (red, Figure 18) has the lowest amount of thermal mass attached to it. The red line for solar panel #2 shows high points at 13.5 hours and 19.5 hours. The three red peaks at 15, 16.5, and 18 hrs are observed to increase in amplitude. This change in intensity is consistent with a slight roll period of four orbits or 6 hrs.

The internal temperatures of the battery pack, communication board, and plasma PC board are shown in the center panel. Their respective average temperatures are 10 C, -2 C, and -10 C.
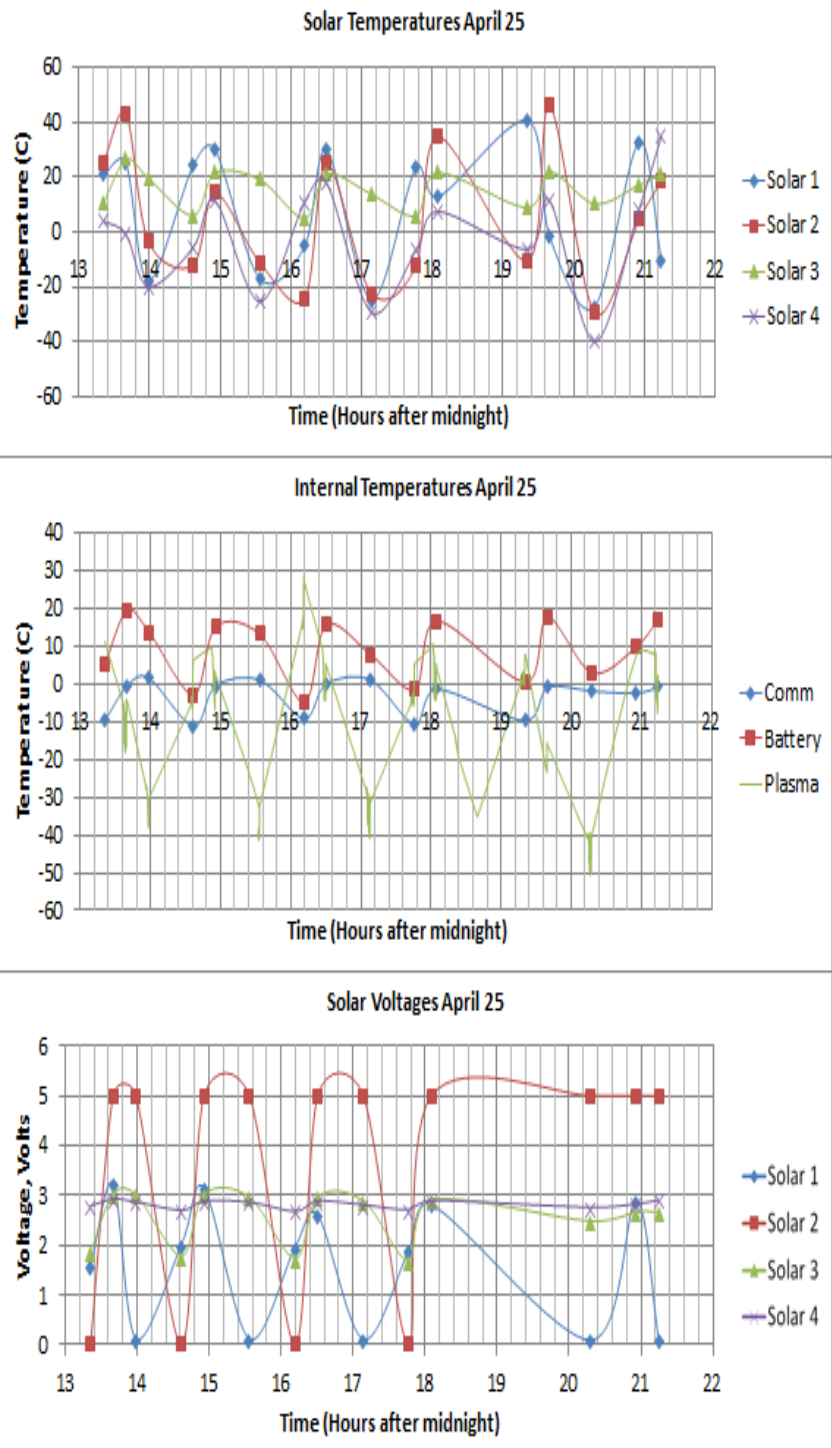

Figure 18: TSAT solar array temperatures (top panel), internal temperatures (center panel) and solar voltages (bottom panel)

The solar voltages for the four solar panel walls are shown in the lower panel of Figure 18.

TSAT also included a precision 3-axis flux-gate magnetometer. One of the three channels is weak, and shows an offset, so it may not be useful. The other two channels appear to work well, but have not been analyzed in detail. The magnetic field variations show no strong spinning motions.
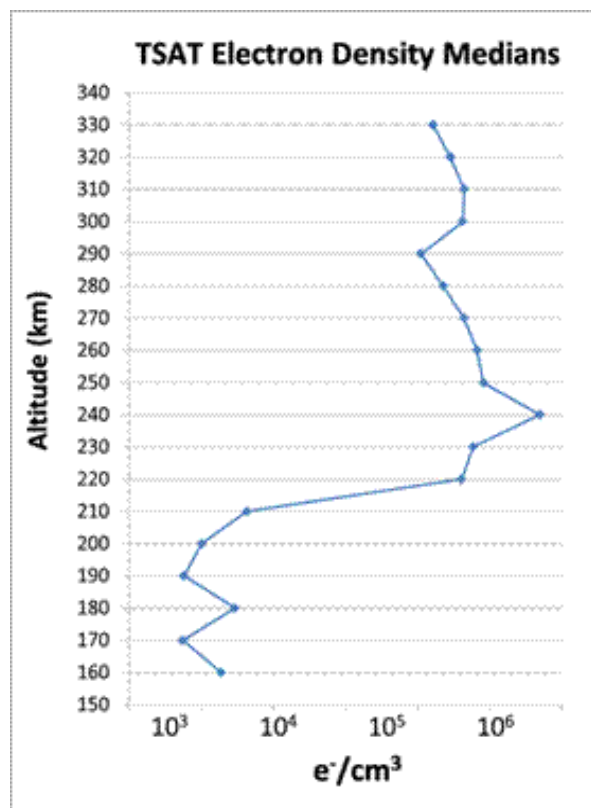

Figure 19: **Mission medians of electron density for various orbit altitudes (10km bins). The higher density in the F-region transitions to the lower density in E-region at about 215 km.**

Finally, the Plasma Probe instrument operated at a fixed voltage most of the time, but was also programed to sweep in voltage from 0 to 5 volts. A preliminary plot of electron density is shown in Figure 19 as a composite for the entire mission. For each 10 kilometers of altitude, the median plasma density was calculated. Figure 19 is essentially a "quick look" graph representing plasma probe median electron density by altitude for the entire mission. Further analysis and correction for other factors such as temperature variation will be conducted in the coming weeks. The ionospheric E-F boundary is the most prominent feature at 200 to 220 km. The F region median density is about 10^6 electrons/cm^3, while the E region is about $2*10^3$ electrons/cm^3. The electron density profile may be extended down to lower altitudes, now that the

TSAT drag model has provided a clearer picture of the altitude versus time profile. The plasma data was collected in small batches because of the duty cycling of the instrument, in order to conserve power as illustrated in the packet coverage map (Figure 4).

GEARRS SATELLITE

The Globalstar Experiment and Risk Reduction Satellite (GEARRS, figure 20) is an exploratory mission by NSL to provide detailed analysis of the global extent of coverage for simplex and duplex TT&C. AFRL has funded the analysis which will experimentally gather information on rates, latency, and signal strength using a 3U cubesat platform. These data products will help further inform the small satellite community about the potential of the Globalstar Network as an operations alternative or a helpful augment to the traditional operations paradigm.

GEARRS is manifested for launch on the Orbital Sciences ORB-2 resupply mission to the ISS via the Space Test Program who contracted the commercial launch services provider NanoRacks LLC. In the 1-3 months following the ORB-2 mission, GEARRS will be deployed out of the NanoRacks LLC Cubesat
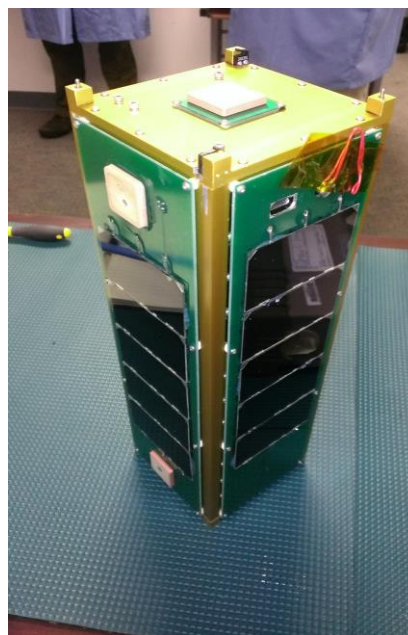

Figure 20: GEARRS at delivery showing a simplex patch antenna on the solar array panel and the plasma probe on the end cap. The second simplex unit is on the down facing end cap, and the duplex antenna is not shown.

Deployer (NRCSD). The mission has three stated objectives: 1) provide a geographic contact coverage

map based on the latitude and longitude to successful data relays to the host Globalstar spacecraft, 2) characterize the health of a relay link versus spacecraft attitude state, and 3) demonstrate rapid command and control response through the Globalstar IP data services.

The design and build mission in its entirety from concept to NanoRacks integration delivery lasted 94 days. This speaks to the responsiveness of a highly integrated team willing to assess and execute the mission success criteria. To that end, it also speaks to the ability of the launch services providers STP and NanoRacks providing a clear closed-form process to follow enabling a quick turn mission.

Similar to TSAT, GEARRS includes a Langmuir Plasma Probe for measuring electron density. The input electrometer covers 6 orders of magnitude using a log amplifier. Four calibration resistors can be switched on to give known currents. The log amp temperature is monitored. Eight temperature sensors are included, along with normal health and sat safety voltage and current monitoring. In addition, duplex status is also transmitted.

The driving data products required 3 radios on the GEARRS space vehicle. A simplex radio provides engineering telemetry feedback at a constant cadence for the GEARRS team to analyze simplex throughput around the globe. A duplex radio connected to a separate simplex beacon enables characterization of duplex connectivity to the network, and coarse signal strength. Also having the duplex unit allows for an assessment of uplink command authority to the space vehicle around the globe from the IP based ground terminals.

GEARRS will have a nominal mission lifetime of nine months before re-entry, during which time it will build upon the success of TSAT and provide a more comprehensive characterization of the Globalstar network for ELEO satellites.

UNP-8 ELEO Sat

Taylor University's next student developed nanosatellite is ELEO-Sat (Figures 21 and 22). As a part of the UNP-8, ELEO-Sat will complete its design phase in January 2015. The primary mission of ELEO-Sat is to explore the 120-350 km region of the ionosphere (16). The ELEO-Sat mission may be broken
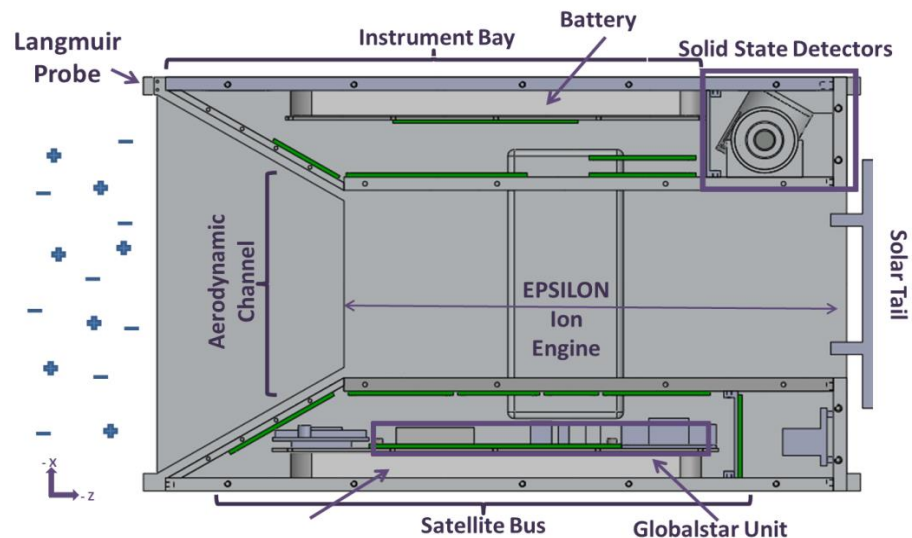
Figure 21: Student AFRL UNP-8 ELEO-Sat aerodynamic design with electric field Epsilon drive, Spacecraft bay, and instrument bay layout

down into scientific and technical objectives of 1) developing an open source database of in-situ wave, particle, and plasma ionosphere measurements, and 2) demonstrating new and innovative spacecraft technologies. ELEO-Sat's mission is very similar to TSAT's, and is designed a continuation of the impressive student work accomplished on TSAT. Unlike TSAT, however, ELEO-Sat development is made possible through the University Nanosatellite Program (UNP) through the Air Force Research Laboratories. Key features of the satellite are the science instrument bay, the aerodynamic craft structure, the exterior boom

Figure 22: ELEO-Sat fully deployed

design, the Globalstar communications unit, and a novel in-situ ion engine.

THIN SATS

NSL is also supporting a new product called Thin Sats to help extend mission life for ELEO orbits and make multi-point measurements in constellations. The basic spacecraft bus includes the structure (with 3U and 6U, Figure 23), the new low power EyeStar product for
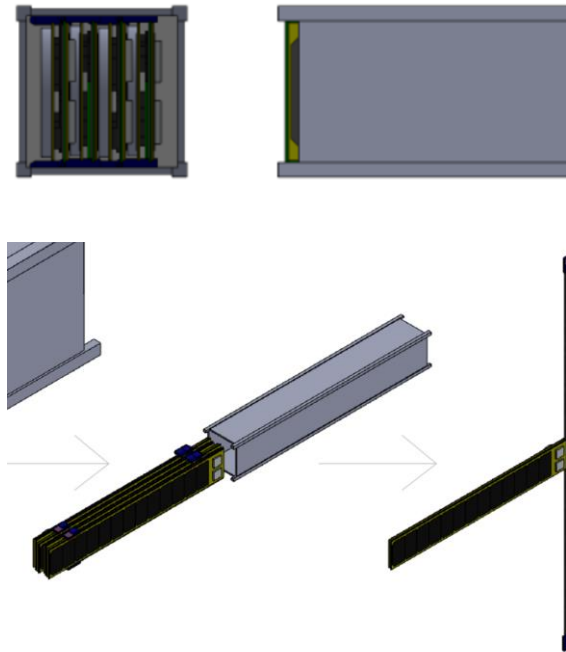

Figure 23: Thin Sat design concept using PCB satellites with solar cells on both long sides. Designs for two and four Thin Sats launched from mother 3U or 6U cube configuration.

Globalstar communication and electrical power system (EPS), the EyeStar communication options, and some basic sensors. About 70% of the Thin Sat volume is available for various experiment applications. Other options include boom deployment and custom modifications.

CONCLUSIONS

The first results from TSAT demonstrate the research grade quality of the Globalstar commercial network for new satellite data, without the need for a ground station. The new paradigm is satellite download visibility anywhere and anytime, with command capability. The simplex link worked well with the wide field of view patch antenna. The new Globalstar capability is now available to others through the NSL EyeStar radio product. Additionally, new measurements have been made in the relatively uncharted ELEO region of the ionosphere from 110 km to 325 km. Below 200 km, the TLE/SGP4 derived altitudes are modified for better trajectory predictions of reentry. TSAT's last packet at 110km indicated the rapid heating of the internal electronic PCB. TSAT has helped to pioneer the way for constellations of small satellites.

Some TSAT firsts include the following: first approved Globalstar modem in space for testing (FCC, Globalstar, & other approvals), first Taylor University satellite in orbit, first Indiana satellite in orbit, first CubeSat packet received in less than 11 sec after RF turn-on, and new low altitude measurements down to 110 km altitude.

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