Globalstar Link: From Reentry Altitude and Beyond

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ABSTRACT

Three CubeSats flown in the past two years have successfully mapped Globalstar performance over the altitude range 100 km to 700 km. The Globalstar constellation provides "Anywhere and Anytime" visibility to satellites and is ideal for CubeSats, constellations, and formation flying missions. Globalstar capacity is designed for 2500 channels per Globalstar satellite, potentially enabling hundreds to thousands of simultaneous communication to satellites. Capacity would then extend from the ground to potentially above the Globalstar LEO constellation at 1400km. TSAT (2U) made real-time plasma density and diagnostic measurements in the Extremely Low-Earth Orbit (ELEO) ionospheric region 350 to 110 km for new in-situ Space Weather mapping. TSAT heated at a rate of 20 degrees/min. on reentry at 110 km (reentry physics), yet it maintained a good real-time link with ground stations in Canada and Venezuela where it is believed to have re-entered. The NSL Globalstar flight products now permit new experiments to ELEO orbits in addition to releasing drop radiosondes to explore the Upper Atmosphere (Mesosphere) coupling with the lower atmosphere. Preliminary results are presented from the Globalstar Experiment and Risk Reduction Satellites (GEARRS1 and GEARRS2). GEARRS1 (3U) was launched from the ISS and verified the Globalstar CDMA protocol and Duplex SMS messaging. GEARRS2 (3U) was launched with an Atlas rocket on May 20, 2015 into a 350 by 700 km orbit and the Simplex communication and instrumentation operated well for 9 months beyond the mission expected lifetime (high TRL and radiation tolerant). Improved global coverage maps of the Simplex and Duplex performance are presented. Global maps of Duplex RF pulse data indicate that the Duplex may have good global coverage when on a 3 axis stabilized satellite to permit necessary connect time. Using a small permanent magnet for attitude control, the two patch antennas (1.616 GHz) and loss-cone energetic particle detector point up and down the earth's magnetic field lines. The three SSD detectors mapped the precipitating and trapped particle flux in the aurora zone, the SAMA, the trapping boundary, and the internal penetrating radiation dose. Several new Globalstar flight radios are manifested for launch with three axis stabilization, so that Duplex large file transfer can be characterized. TSAT and GEARRS data indicate a strong side lobe link that may reach to high MEO altitudes

INTRODUCTION

This paper reports on the new capabilities and applications of the NSL-Globalstar Simplex and Duplex flight communication links for new space investigations. The first Globalstar flight results and coverage maps were presented (1) on TSAT which was launched on April 18, 2014. Preliminary results from the recent Globalstar Experiment and Risk Reduction Satellites (GEARRS1 and GEARRS2) are reviewed and the analysis augmented from the previous presentations on GEARRS1 (2) and GEARRS2 (3). Figure 1 summarizes aspects of these pioneering flights. In addition, an effort is made to present information and products so that other researchers and students can efficiently implement Globalstar space flight and ground segment products into their space systems in a matter of weeks.

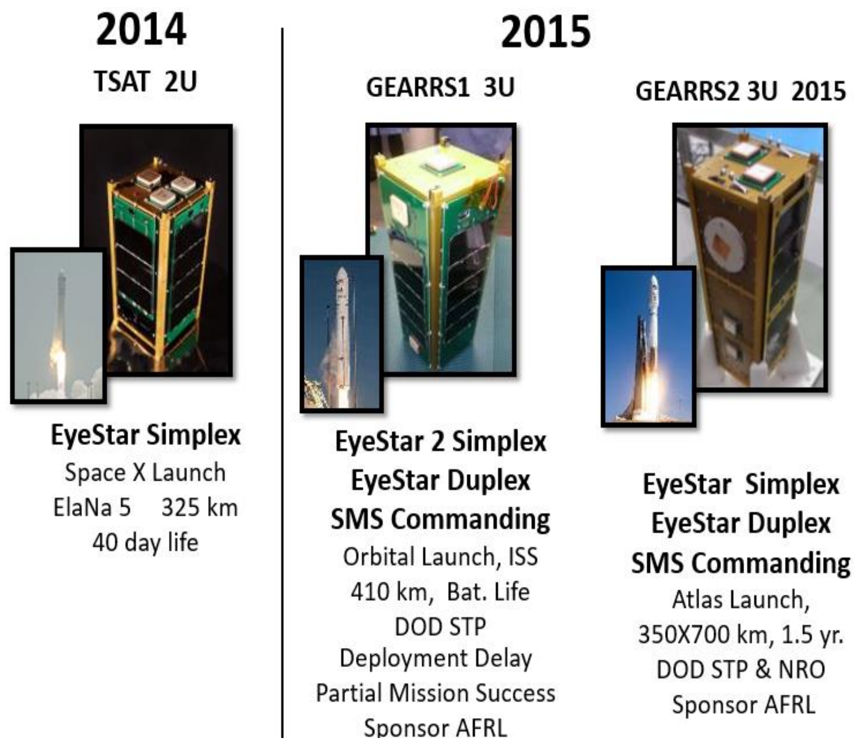


Figure 1: Three successful student and commercial CubeSats that used the Globalstar Simplex and Duplex links for the first time. Mission success is assured, performance increased, and minimal resources required.

The $2B Globalstar Constellation of over 32 LEO satellites (4) at 1400 km provides terrestrial global data and voice services (Duplex) for ~300,000 customers. The Simplex units monitor data (e.g. facilities, wildlife, oil rigs, gas pipe-lines, shipping containers and endangered animals).

NearSpace Launch, Inc. (NSL) advanced the EyeStar flight modem processor product for TSAT, GEARRS, and other satellites & the EyePod product for high-altitude ballooning. NSL developed a relationship with Globalstar engineers and management and is an official Value Added Reseller (VAR) for the past several years with its flight approved and FCC approved satellite radios and ground segment. NSL has flown six EyeStar units with 100% success and now > 370 balloon EyePod launches with over 99% data/recovery success.

Data links include the Globalstar and NSL network (Simplex and Duplex). Globalstar Code Division Multiple Access (CDMA) provides extremely high signal to noise ratio using a wide bandwidth and a pseudorandom noise (PN) code that is suitable for high velocity satellites and encryption. Satellite commanding and data downlinks are maintained by the Globalstar professional ground stations.

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 for 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 in near real-time, the EyeStar radio system does not need store and forward data with associated long delays. This is very important in the forecasting and in the reentry ELEO region.

Communication Priority

Communication problems dominate in the small satellite development phase and are responsible for many flight failures. Communication considerations include:

1) Simplifying the complexity of the communication system; a sub-system that involves low power transceivers with low mass and size and RF connectors and cables.

2) Exclusion of spacecraft protruding antennas, and risky deployment mechanisms.

3) Remove requirement for high-gain, expensive tracking ground stations with associated software and operations cost for a research grade ground segment.

4) Infrequent and short line-of-sight overpasses for conventional ground stations.

4) Maintaining a commercial and research grade FCC license versus a limited Ham amateur approval.

5) Difficulties associated with international radio community coordination and licenses.

6) Waiting hours to days after initial turn on to react to health and safety data.

7) Inability to observe a tumbling satellite after initial turn on and command it in emergencies.

8) Need for 24/7 commanding and satellite visibility.

9) Difficulties of operating a constellation of satellites with multiple ground stations and disjointed data base.

10) Rapid identification of satellite number from conflicting Two Line Elements (TLE) series for analysis and tracking.

New Paradigm

The TSAT, GEARRS1, and GEARRS2 spacecraft introduced a new paradigm using the existing Globalstar network of phone satellites to initiate satellite-to-satellite cross-links. The Globalstar-NSL ground segment also unifies the various Globalstar EyeStar radios into a common and synchronized dataset. It is essential that the data from all satellite ground stations be unified and time-synchronized for multipoint measurements. The EyeStar radios and Globalstar-NSL ground network greatly simplify 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 mission specific ground infrastructure beyond a data server.

In Figure 2 the Globalstar constellation is shown giving 24/7 connectivity to a small constellation of four CubeSats. With its few second latency, the Globalstar network can assume much of the direct control of constellations from ground operations. This can significantly reduce the risk of orbit operations with adaptability, optimization, and at much lower cost.

Globalstar Data Capacity

A diagram of the Globalstar constellation in relation to other satellites and important space regions is shown in Figure 3. The red arrows indicate the link directionality and the dashed links show unknown limits. With low cost aerodynamic CubeSats, ion engines, and the Globalstar low data latency, the new underexplored regions listed with a question mark are open for detailed study.

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

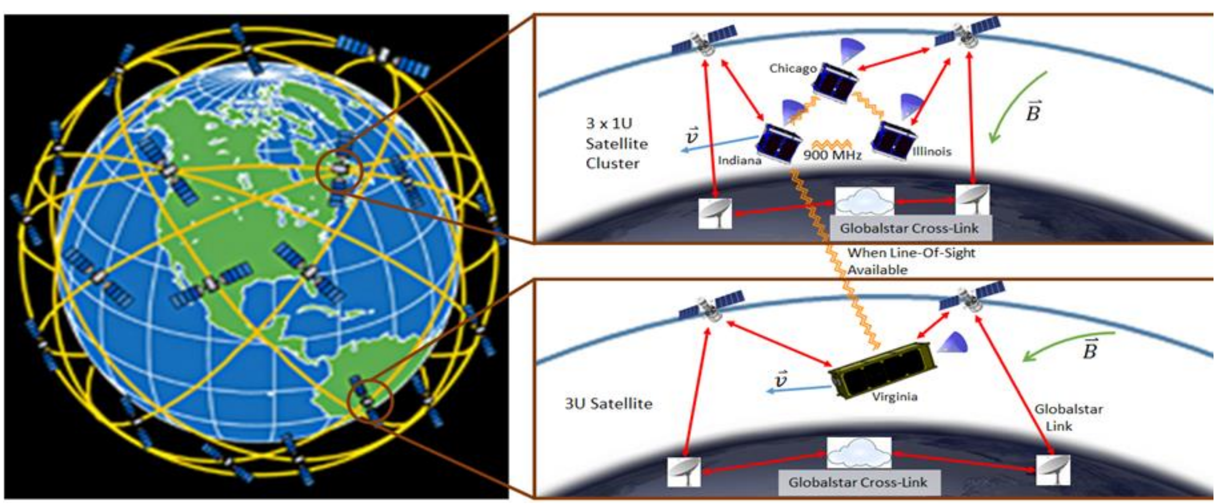


Figure 2: Example of four CubeSat constellation using the Globalstar communication and GPS networks for near real-time and absolute position determination. Constellation control is managed on the ground segment.

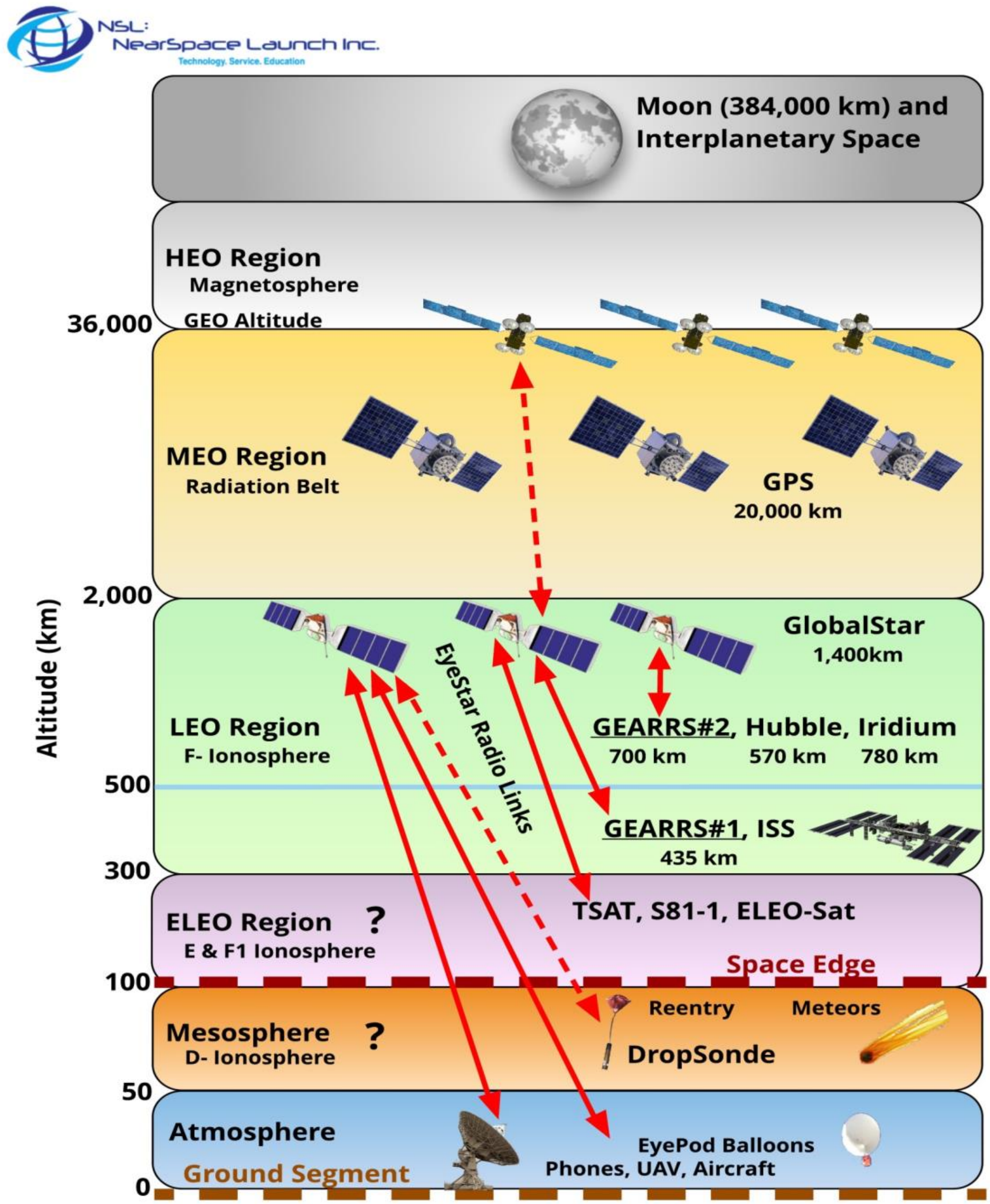


Figure 3: Visual nonlinear scale of the Globalstar constellation in relation to orbit regions, ionosphere regions, atmosphere regions, other satellites, and ground operations. Globalstar links are shown with red arrows indicating Simplex and Duplex directionality. The dashed links show new link investigations. The question marks indicate uncharted regions near earth for fruitful CubeSat study.

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 currently no capacity issues at any individual gateways, nor are there anticipated to be any future capacities due to the addition of CubeSats. The Globalstar system appears to have capacity to handle many CubeSats transmitting thousands of packets per day.

DATA OPERATIONS

The NSL ground station technology (Figure 4) is comprised of the following elements:

- The Globalstar communications network
- The NSL server
- The web console
- The web Application Program Interface (API)
- The Front End Processor (FEP)

The Globalstar communications network provides the actual ground-to-space link. All the normal radio link management issues are delegated to Globalstar.

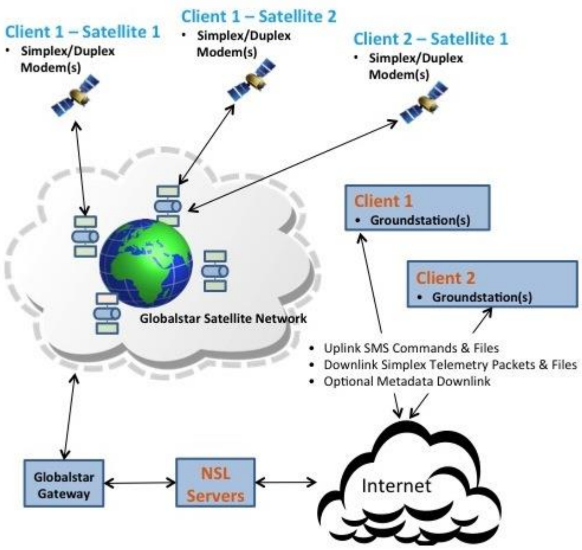


Figure 4: Overall Communications Architecture.

The NSL server communicates via the Globalstar network to send and receive satellite data. All data is logged and archived on the server. The server database performs real-time replication to a backup server. The typical full path latency for Simplex data from satellite to the NSL server is under 30 seconds.

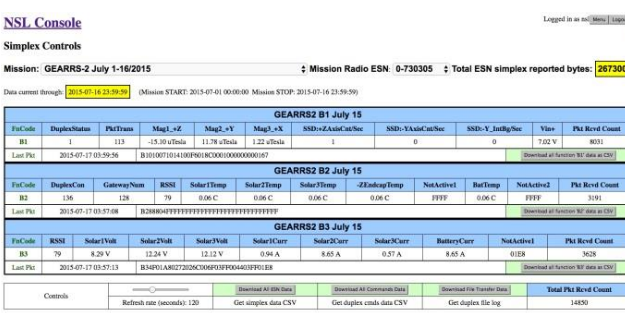


Figure 5: Web Console Simplex Telemetry Display.

For those who desire, the NSL web console (Figure 5 & 6) permits viewing, graphing, zooming, translation, and downloading Simplex telemetry data (commonly, 36 or 45 bytes per packet). In order to display and download meaningful Simplex telemetry data fields, the web console code performs packet decommutation and reverse quantization on the raw bytes to convert the Simplex field values back to an approximation of the original engineering unit values. The first byte of each Simplex packet identifies the packet type and dictates how the rest of the packet is to be processed, in a secure manner, leveraging best industry practices.

The web console also handles interactive uploading and downloading of files via the Duplex file transfer link, as well as sending short commands (1-35 bytes) via the SMS channel. Last, real-time tracking of balloon flight locations and plotting on maps is also available using the web console.

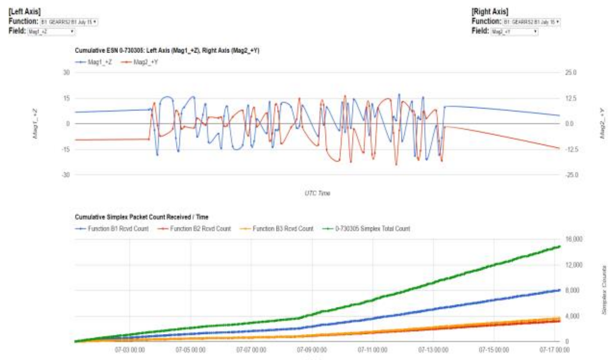


Figure 6: Web Console Simplex Telemetry Graphing.

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.

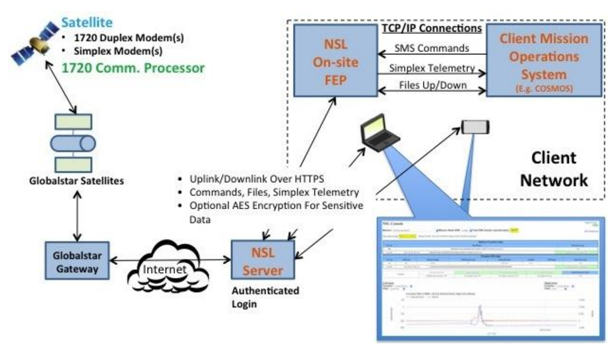


Figure 7: Client Using FEP and Web Console.

The Front End Processor (FEP) provides the client with TCP/IP-based sockets as a means for communicating with a satellite (Figure 7). The entire communications path is simplified to reading and writing using specified ports on the FEP. The FEP uses the web API to perform all communication with the NSL server, thus relieving the client of a significant amount of programming. The FEP also stores archival copies of the data and performs optional encryption and decryption of data.

When interfacing with the FEP, the client configures their client mission operations system (e.g., COSMOS) to read and write the appropriate TCP/IP ports on the FEP. This approach is similar to the traditional approach that reads and writes serial lines to communicate with a FEP, except that TCP/IP ports are used instead. Multiple FEP configurations are possible: at the low end, the FEP is configured for one mission with just one Simplex or Duplex link. At the high end, a FEP can be configured for multiple missions, each with a mixture of multiple Simplex or Duplex units. Additionally, the FEP architecture permits multiple FEPs to run in parallel without interference for the same mission. This architecture permits clients to easily run one or more FEPs as hot backups as well as providing distributed mission command and control.

Encryption

FIPS 140-2 validated cryptography must be used by private-sector vendors who provide encryption for sensitive but unclassified data in certain regulated industries and branches of the United States and Canadian governments (Ref. 7). FIPS 140-2 specifies procedures for validating encryption tools on specified platforms. The NSL Front End Processor (FEP) uses an embedded OpenSSL FIPS 140-2-validated cryptographic module running on a RHEL 6 platform per FIPS 140-2 Implementation Guidance Section G.5 guidelines. Consequently, the NSL FEP has the capability of processing sensitive, unclassified data for NASA, DOD, and other federal units.

The FEP encrypts serialized data going from the customer to the satellite, and decrypts data going from the satellite to the customer. Unencrypted data is held only briefly in memory and on the data connection to the customer software. At no point is sensitive data held unencrypted on the NSL file system.

TSAT REENTRY REGION PROBING

CubeSats and constellation CubeSats using Globalstar 24/7 communication are now capable of unprecedented low-altitude data and location tracking below 350 km and in the reentry region.

TSAT Reentry results

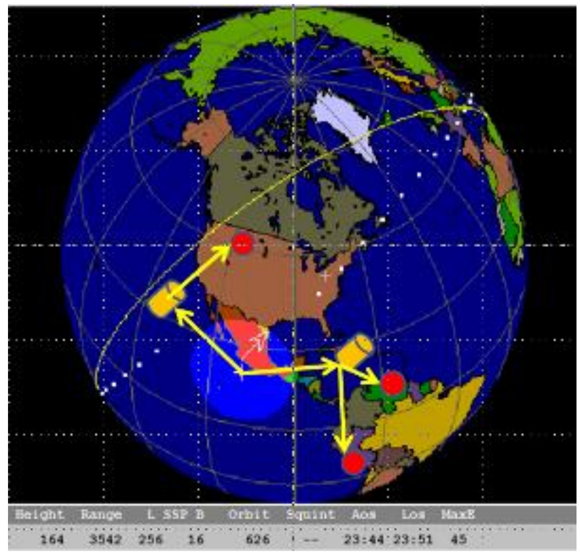


Figure 8: TSAT location of last data packets (~110km) and illustrated bent pipe data paths to the Globalstar satellites to gateways in Peru, Venezuela, and Canada. (Ref. 15)

At a TSAT location just west of Mexico (See Figure 8), the CubeSat nose endplate surface temperature was observed to be increasing at 20 deg./min. In Figure 9 the last TSAT packet was transmitted in real time at 110 km and sent through two Globalstar satellites. Three ground stations received the data (Canada, Chile, and Venezuela) and transferred it to the NSL servers for console display.

TSAT TLE Discrepancy

Also shown in Figure 9 is the TLE altitude variation (purple top curve). The 90 min oscillation of this curve is due to the predicted apogee and perigee variation. TSAT, a low priority tracked object, also found a discrepancy and little information on the low altitude near reentry compared to predicted TLEs (top purple curve). The derived decay trajectories below 250 km are also shown. The conclusion here is that because of drag the TLEs do not reflect the actual altitude below 250 km, but the latitude and longitude are consistent with the TSAT data.

TLE Identification Using Sensor Data

As a side note the TLE CubeSat identification can be a long and tedious process when many CubeSats are launched together without GPS. For TSAT and GEARRS we were able to use in situ and remote sensor data to identify our satellite in a cluster. In Figure 10 the GEARRS satellite was identified by plotting our

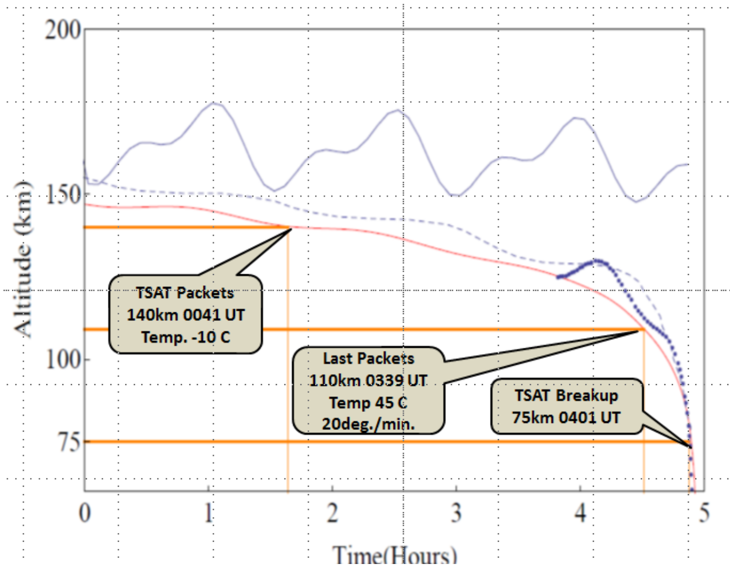


Figure 9: TSAT reentry flight paths: Solid blue line is archive TLEs/SGP4 model, red line is TSAT drag model, dashed and dotted lines are derived from models Ref. (10) and Ref. (12). TSAT Reentry time at 75 km is 4:01 UT by NORAD, last packet received at 110 km at 3:39 UT, and previous packet at 140 km at 00:41 UT.

energetic particle or other sensor data with the TLEs of the eight other satellites in our cluster. As shown in Figure 8 the bottom panel tracks well with the known particles in the South Atlantic Magnetic Anomaly (SAMA) and the auroral oval seen prominently in the south polar region.

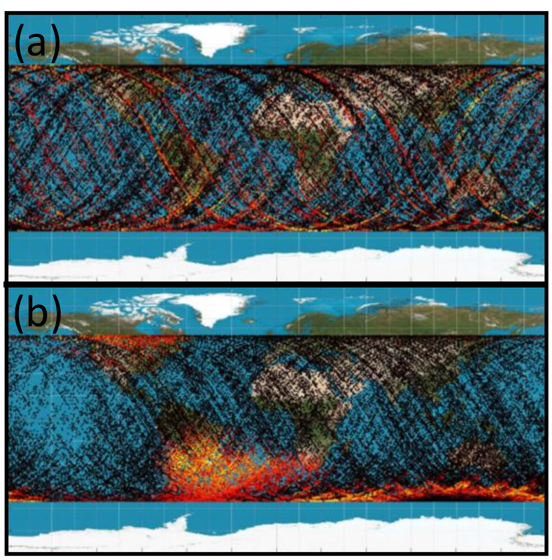


Figure 10: The upper panel shows GEARRS2 satellite for one of the eight TLEs in our cluster. After a day or so our particle data (bottom panel) lines up best (SAMA and Oval) with our now identified TLE.

Future satellites will use GPS (as prices drop and interface complexity improves) with the Globalstar network to quickly identify satellites seconds after the RF is allowed to turn on.

Dropsonde Exploration of Mesosphere

As Radiosondes have revolutionized our understanding of the atmosphere over half a century, a plethora of "Dropsondes" may also revolutionize our understanding of the Mesophere. A cluster of small Mesosphere probes may be released near the CubeSat reentry point after the main CubeSat shell has taken the brunt of the deceleration and heating. The idea here is to then release an autonomous Mesospheric probe that maintains some of the main bus systems (e.g. Globalstar radios, GPS, fresh battery, temp sensors, plasma probe, energetic particles) and freefalls and glides to the lower atmosphere while transmitting data and being tracked. This idea has been implemented by the early ELEO region DOD satellites (Corona, 1960's) to drop film packages to earth.

As illustrated in Figure 11 the aerodynamic CubeSat (much like TSAT) decelerates and heats in the reentry region. It includes a thermal heat shield and insulation before the Dropsonde located in the rear as shown.

Because the ionization wake and antennas are in the rear, the link should remain connected to the Globalstar network during most of the blackout region. Then at a predetermined point based on acceleration and/or temperature, the Dropsonde is released with a mechanism to deploy a Kevlar drag chute on stiff Carbon fiber tubes which will also act as an atmospheric parachute for safe landing. See the right two drawings in Figure 11 of the Dropsonde package and the Dropsonde as it is deployed. The probes could continue to operate as a ground or ocean probe. Of course much more analysis is required and a prototype could be flown to test some of these concepts.

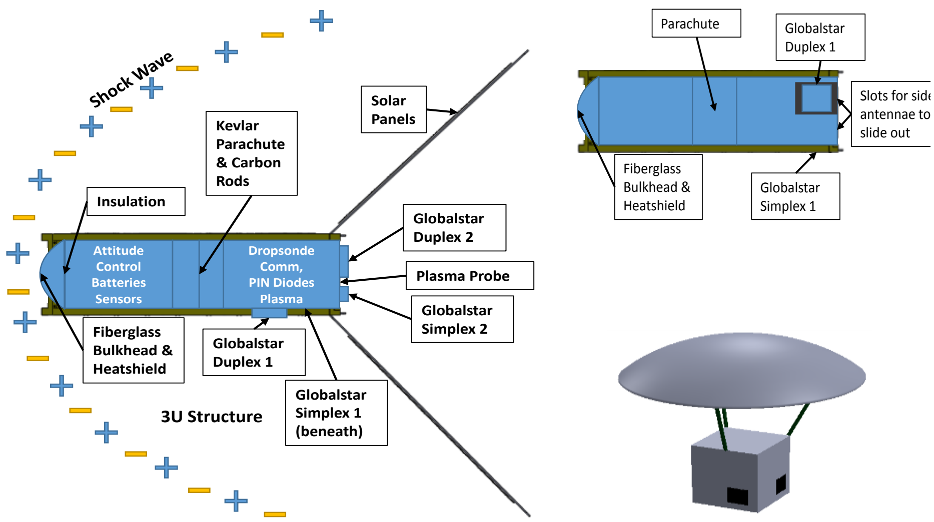


Figure 11: Concept Dropsonde released from 3U CubeSat for exploring the Mesosphere.

GEARRS1 LAUNCH AND ACCOMPLISHMENTS

Globalstar Experiment and Risk Reduction Satellite (GEARRS, Figure 12) was an exploratory mission by NSL and the AFRL to provide detailed analysis of the global extent of coverage for Simplex and Duplex TT&C. First results were given at the Cal Poly workshop in 2015 and the Small Sat conference in 2015 (2). GEARRS data products 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.

GEARRS1 was launched 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. Launch from the ISS was delayed until Feb of 2015 due to a launcher problem. 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.

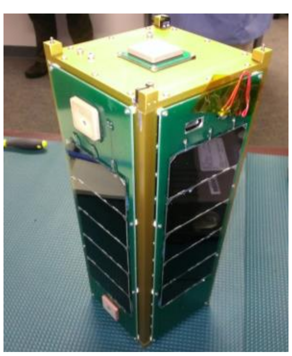


Figure 12: GEARRS1 at delivery showing a Simplex patch antenna on the solar array panel and the plasma probe on the end cap. A second Simplex unit is on the down facing end cap. The Duplex antenna is not shown.

Similar to TSAT, GEARRS1 includes a Langmuir Plasma Probe for measuring electron density. The input electrometer covers 6 orders of magnitude using a log amplifier. 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 three 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 IP based ground terminals.

The Globalstar Experiment and Risk Reduction Satellite (GEARRS1) was designed to completely run off battery for a short 2-3 day mission life to prove the EyeStar Duplex performance in space and reduce risk on many flight components (EPS, new Globalstar links, hybrid antennas, new ground control system, and flight software) for other missions. After GEARRS' successful ISS launch at 8:20PM ET or 6:20 MT on Tuesday March 3 (1:20 UT March 4) the first Simplex packet was received at 2:48 UT and arrived 58 minutes later than expected. This hour delay was likely due to the battery charge below the 6.2 V battery trip off point. All GEARRS systems appeared to become operational and without resets to the flight processor sequence counter. After several hours of solar cell charging the weak battery tripped on. On orbit 3 the Duplex received 19 SMS commands over a 55 min period mostly in eclipse and 12 of them were validated (63%) Although the amount of data received was lower than expected due to a one-year aged battery, almost all of the GEARRS main objectives were achieved (hardware risk reduction) and impressive Duplex and Simplex performance observed for the first time. Fortunately, GEARRS2 was scheduled to launch a few weeks later.

Preliminary GEARRS list of accomplishments and Risk Reduction:

1. GEARRS complete system worked as an integrated unit in space with much valuable data in spite of the very low battery voltage at turn-on due to an unexpected one-year delay without battery charging. (All inhibits, EPS, three processors, two EyeStar Globalstar Simplex units, one EyeStar Globalstar Duplex unit, solar array panel, instruments, flight software, and ground system).

2. For the first time the Globalstar Duplex unit works in space with a high-gain active hybrid antenna. It was tested for commanding and data quality with validation of command and backhaul of command on Simplex. Valuable data obtained on Duplex initialization times, CDMA operation, and Gateway handoffs.

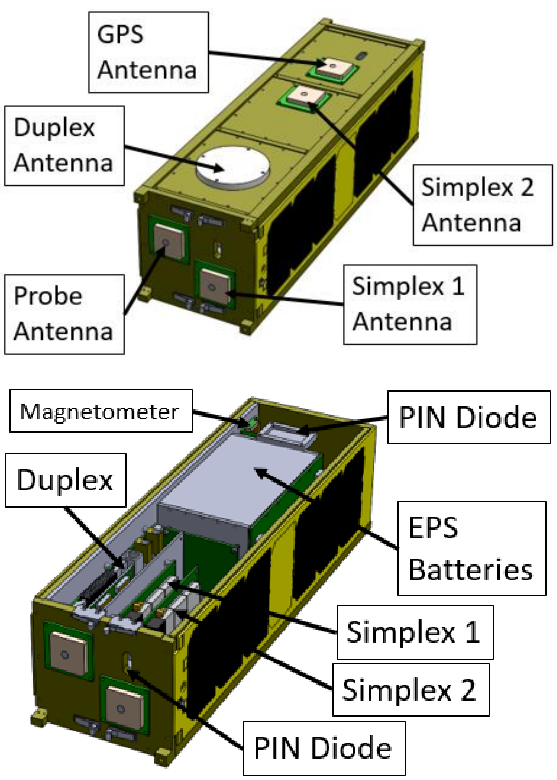


Figure 13: GEARRS 2 Subsystem Layout.

3. In one hour 12 of 19 sequential commands were received and validated (63%) by the Duplex unit at low power over all latitudes.

4. First dual EyeStar Globalstar Simplex units in space with dual patch antennas working well.

5. CONOPS end-to-end real operations and testing validated.

6. Solar Arrays added by NSL worked and kicked the satellite on in first orbit with its much depleted batteries and continued to add power to the batteries during flight.

7. All flight Beacon, Duplex, and EPS processor hardware and software working and flight tested for AFRL missions.

8. All data transfer ground segment paths were validated through Satellite-to-satellite, Satellite-to-Gateways, Gateways to NSL backup servers, data storage, ground software displays, and AFRL near real-time data access.

9. Ground segment and Commanding Script data software tested and working on orbit.

10. Visualization software for GEARRS data was tested and improved.

11. Much more information obtained on Globalstar Duplex efficient modes and network tuning.

12. GEARRS went into low power mode as programmed. All sequences worked as programmed.

13. Indiana's first commercial satellite

14. Passive permanent magnetic (0.3 Am2) attitude observed to rotate spacecraft along B field direction in correct direction after release from spacecraft

GEARRS2:

First results of the GEARRS2 mission were presented at the Small Sat Conference 2015 (1).

The GEARRS2 Satellite was built on a quick 45 days turn-around to back up the low battery on GEARRS1 mission and add some new data software and features.

GEARRS2 used the standard NSL 3U FastBus product (Appendix 1): (Structure, EPS, G* links, mag., solar, EMI enclosure, Thermal short, passive magnet). The GEARRS2 photo in Figure 1 shows the Simplex and Duplex patch antennas and the plasma probe on the end cap.

In Figure 13 a CAD cutaway is shown of the external and internal subsystems of GEARRS2.

GEARRS2 operated for 9 months from launch in LEO (700 by 350 km orbit) with end-to-end space testing and ground segment operations.

GEARRS DATA COVERAGE MAPS.

Raw data coverage maps are shown for the Simplex Radio on GEARRS2 in Figure 14. In Figure 14 a comparison is shown of the recent Globalstar ground phone coverage map with the new Africa Ground Station (first panel), the TSAT coverage map (second panel), the GEARRS2 Coverage (third panel) and energetic Particle data received on several passes. Note improvement with high altitudes and a new Ground station in Africa. Bottom panel: Example of STX-2 Simplex energetic particle data from several orbits of GEARRS2. Small gaps in track show duty cycle of transmitter and long gaps due to sun sync of 78 packets of data sequence to save system power. Note the South Atlantic Magnetic Anomaly (SAMA) and the Aurora Oval. GEARRS Simplex coverage maps (Figure 15) are very uniform over the entire earth with a weaker coverage area in the Pacific Ocean. The 53 deg. latitude cutoff is due to the GEARRS Sat. inclination and not due to the Globalstar link.

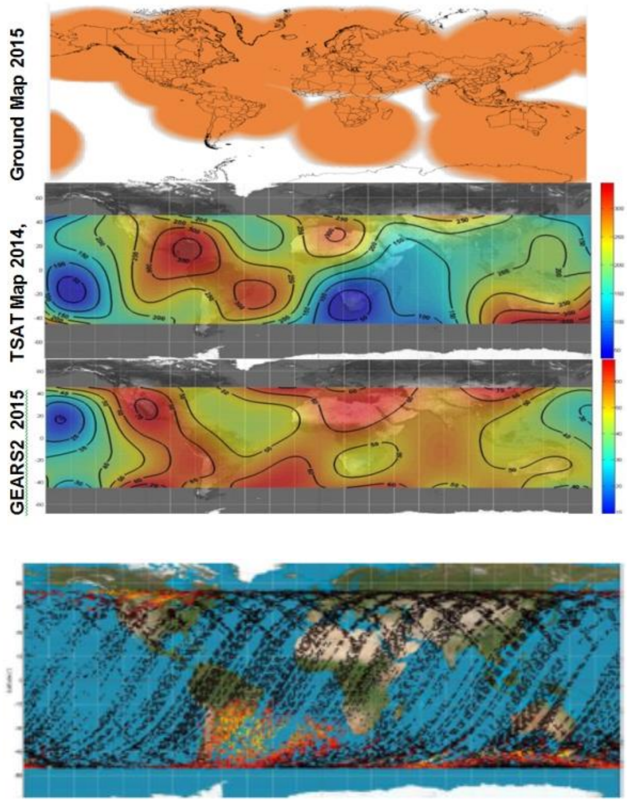


Figure 14: **Simplex coverage maps from ground from Globalstar, TSAT 2014 map, and GEARRS2 2015 map. GEARRS2 particle map showing aurora and South Atlantic Magnetic Anomaly.**

In Figures 16-17, the top panel shows the Globalstar Duplex ground coverage and the Duplex connects /Signal strength connects for the Duplex unit when the satellite was spinning at 2 RPM and pitching at 1 RPM. The second panel shows the Globalstar Duplex ground map and the SMS Duplex Commanding. It was very hard for the Duplex unit to get long enough

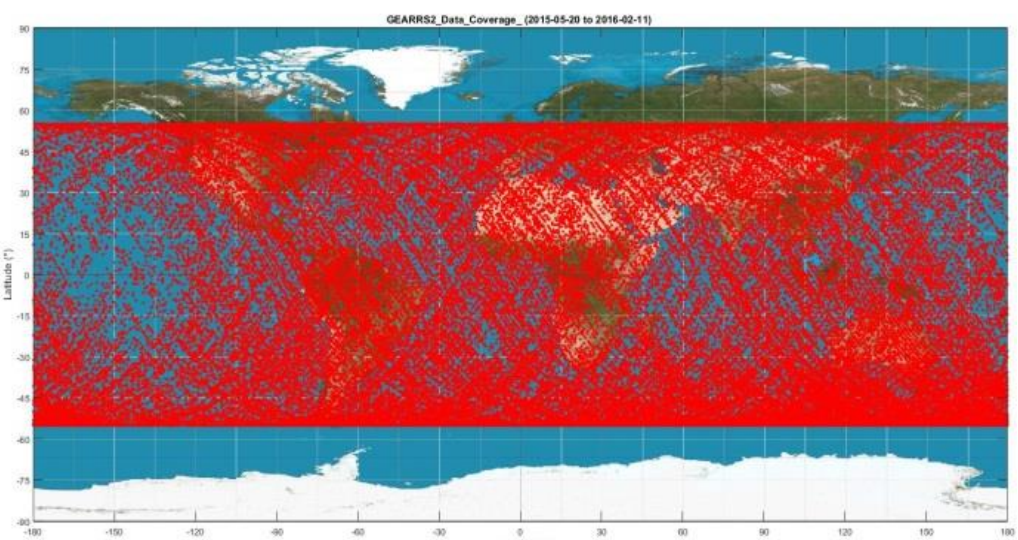


Figure 15: Simplex raw data packets received showing the unweighted but still very uniform coverage. Note some of the weaker coverage areas over the oceans but is much better than the Globalstar and coverage maps.

connections except when it was over the major ground stations because GEARRS was spinning at a 2 RPM rate. GEARRS2 actually became locked on the magnetic field with its passive magnet in the third month of its flight but the Duplex units were not operational at that time.

The lower panel shows RF binary files transmitted by the Duplex based on a registration command received by the Duplex unit from the Globalstar satellite. Since the RF binary files were sent in a fraction of a second the spin motion was not an issue. Fast RF Duplex Connects give a uniform coverage around the earth.

The fact that the fast RF Duplex transmission were initiated by the Globalstar satellite during the registration process and are evenly spread out over the entire earth similar to the Simplex coverage it is anticipated that when a CubeSat is stabilized and in constant contact with the Globalstar satellite that the Duplex unit will have uniform Global coverage! This will have to be verified on a non-spinning spacecraft.

EyeStar radios are now planned for an upcoming AFRL mission and upcoming DARPA mission.

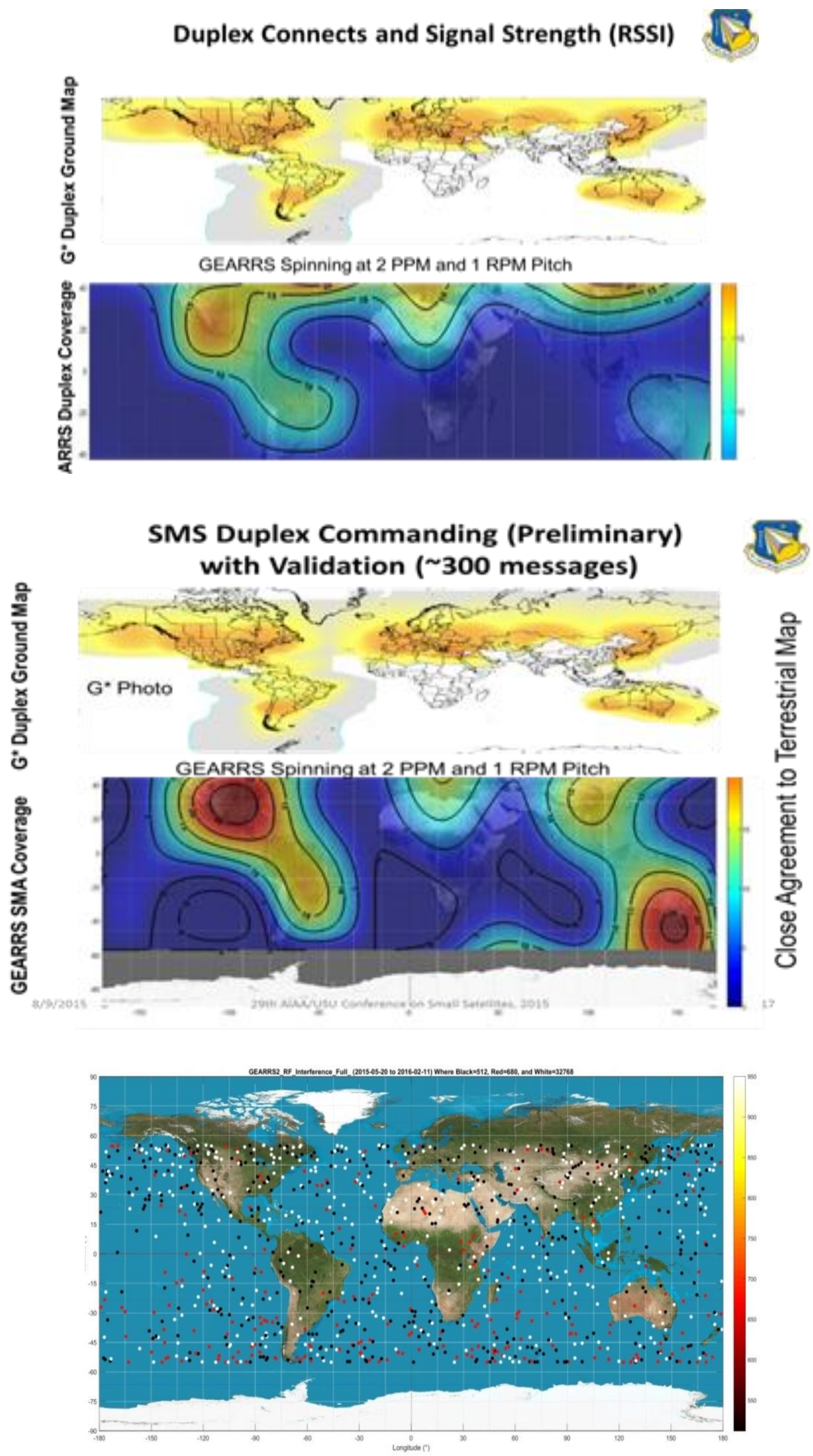


Figure 16-17: Top Panel first shows the Globalstar Duplex ground coverage and the Duplex connects/Signal strength connects for the Duplex unit when the satellite was spinning at 2 RPM and pitching at 1 RPM. The second panel shows the SMS Duplex Commanding. The lower panel shows RF binary files transmitted by the Duplex based on a registration command received by the Duplex unit from the Globalstar satellite. A uniform Duplex coverage map is expected for a non-spinning satellite.

CHARACTERIZING THE GLOBALSTAR GSP-1720 MODEM: TERRESTRIAL TESTING

Investigation of the Globalstar GSP-1720 Duplex modem capabilities has proceeded with both ground characterization and testing in space via the GEARRS1 and GEARRS2 LEO flights. In all test environments, NearSpace Launch's (NSL) GSP-1720 EyeStar configuration (featuring an ARM processor running a minimal Linux OS) has been characterized for both the Simple Messaging System (SMS) and download file transfer (communicating via TCP/IP over a PPP data-link). The default configuration of the modem was modified to accommodate separate data and control channels so that simultaneous commanding and data transmission are possible.

Call Connection Time

Testing to determine call connection elapsed time was accomplished by running back-to-back call attempts whenever a suitable signal strength was indicated by the modem (Received Signal Strength Indicator of 4, or 2 or 3 and rising over time). During a three-hour period, utilizing the original Duplex patch antenna (no longer offered by Globalstar), 210 call attempts were made (1.23 attempts per minute), with connected calls resulting 192 times (91% connection rate). Connected calls took an average of 15.51 seconds from initiation of the call to connection, with a standard deviation of 1.95 seconds. During a one-hour period, utilizing the new Duplex patch antenna (now the only antenna available with the GSP-1720), 86 call attempts were made (1.43 attempts per minute), with connected calls resulting 82 times (95% call connection rate). Connected calls took an average of 15.53 seconds from initiation of the call to connect, with a standard deviation of 2.45 seconds. Call connection time appears to be a rather stable component of the entire file transfer process. Data link establishment via PPP averaged 6.8 seconds, with a standard deviation of 2.3 seconds. Expected time from initiation of a call to establishment of the data link, before file transfer protocol negotiation may begin, is generally around 22 seconds.

File Transfer Rate Mission Simulation

File transfer data rates have been characterized in a number of ways. Preliminary results from a test of file transfers (almost 2200 files of mixed, but unspecified, sizes, sometimes sent intermingled by size, others times grouped, in simulation of expected mission data transmission) by an NSL customer resulted in a range of transfer data rates (Figure 18), largely due to varied file sizes and batch sizes. In this figure, the wide variation of effective data rate includes the overhead of the file transfer protocol. The number of bytes transferred for very small files carries proportionally greater overhead from the file transfer protocol, compared with larger files. Effective data rates for various file batch transfers ranged from 8 to 900 Bytes/second. Precise measurement in this simulation was hampered by the granularity of the recorded time (to the nearest second) which obviously skewed results for batch transfers with few files of small size.

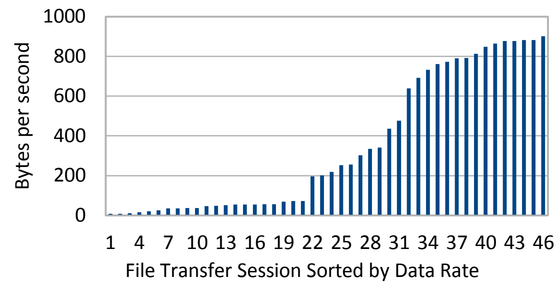


Figure 18: Range of Data Rates for Simulated File Batch Transfer Sessions.

SMS Message Delay

In order to characterize typical SMS message delay, 244 messages were submitted for transmission via an automated script at three minute intervals for a 12-hour period. Time of transmission was recorded in a database, and timestamped receipt acknowledgements were processed and matched with the original messages in the database. The average time from message transmission to receipt by the terrestrial test modem was 28.1 seconds, with a standard deviation of 66.9 seconds.

Modem Data Rate Characterization

More recent ground-based testing has confirmed that the capability of the Duplex modem largely matches Globalstar's specification with regard to potential data rate. An advertised modem data rate of 9600bps, when protocol overhead is considered, appears to be supported by testing. Data files consisting of randomly selected alphanumeric characters were generated for four file size ranges: 256Byte (5341 file totaling 1.37MB), 1KByte to 16KBytes (1423 files totaling 12.4MB), 16KBytes to 32KBytes (308 files totaling 7.6MB), and 32KBytes to 64KBytes (96 files totaling 4.7MB). Downloads of these randomly generated files were tested continuously for each of these data ranges, for several hours per range. Time related to the file transfer protocol negotiations was factored out of the timing measurements. These four ranges were chosen based on interest from launch clients. Kuroda (Ref. 5) from Ames Research Laboratories has presented additional extensive characterization of the GSP-1720.

A single point test was also run to estimate download time for a file of 10MB (again, randomly selected alphanumeric characters). This download took about 18 hours and 20 minutes of elapsed time (5.2 hours of actual file transfer time), over a series of 140 call connections, yielding an effective transfer rate of 575 bytes per second, and an average of 77.2KBytes transferred per call session segment (standard deviation of 89.5 Bytes/second).

Figure 19 illustrates the effective data transfer rates for the four file size categories, plus the 10MB file transfer.

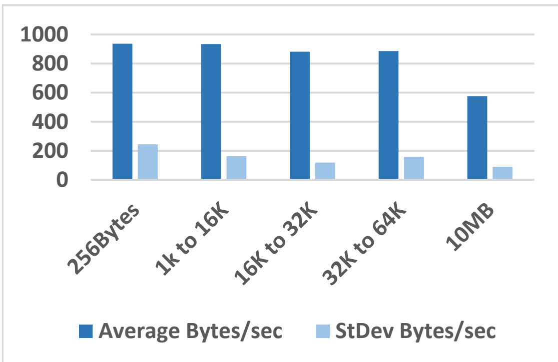


Figure 19: Data Transfer Rates for Four File Size Ranges.

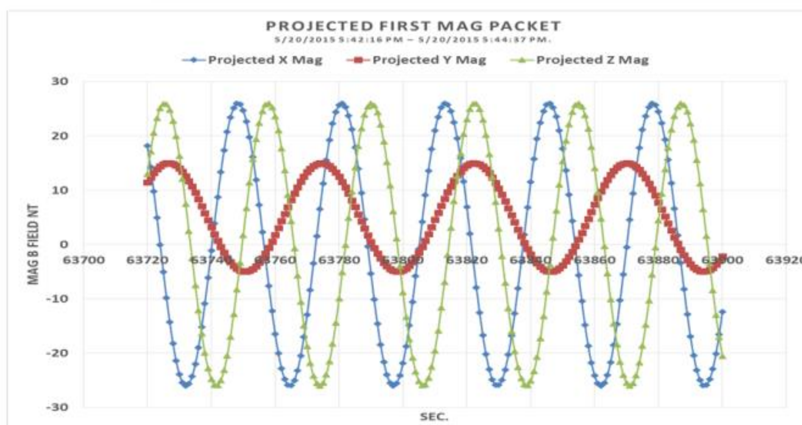
In general, there is a trend of higher data throughput for smaller file sizes. Additional testing for optimization of file size for data throughput will be carried out for additional file size ranges, and in future orbital experiments.

GSP-1720 MODEM IN LEO

The performance of the Duplex modem in LEO orbit was anticipated to be comparable to performance obtained through terrestrial tests. Earlier concerns about Doppler shifting causing unacceptable signal loss was calculated to have only a minor impact on the transmission capabilities of the modem. Given the reduction of distance between the Duplex modem in space and the Globalstar satellite constellation, the consequent reduction of most atmospheric interference, and the potential for the orbital path of the Duplex modem satellite to often partially correspond to one or more of the Globalstar constellation satellites (thus resulting in longer duration signal lock), it was expected that file transmission throughput would at least match, if not exceed, throughput experienced in terrestrial tests.

GEARRS

GEARRS (Globalstar Experiment and Risk Reduction Satellite) was the first NSL orbital test of the GSP-1720 Duplex modem. GEARRS was a 3U CubeSat, with 2 Globalstar STX-2 Simplex radios and one GSP-1720 Duplex modem, purposed for SMS commanding, but not for file transfer. GEARRS launched from a Nanoracks launcher aboard the ISS on March 4, 2015. Because of repairs that needed to be applied to the ISS Nanoracks launcher before GEARRS could be deployed, GEARRS was in storage for nearly a year without the possibility of recharging, and the batteries were almost depleted when the satellite was deployed. Despite this setback, there was enough power to send 204 science mission data records via the Simplex unit, and 12 of 19 SMS messages from the ground were received and acknowledged by the GEARRS GSP-1720 Duplex modem before the satellite went power negative. Results of the GEARRS mission were presented at the Cal Poly CubeSat Workshop in April, 2015. In short, GEARRS demonstrated the ability of the GSP-1720 Duplex modem to receive SMS messages while in low earth orbit.



Axis	Frequency_Hz	Rate_rpm	Period_sec	Phase Shift_degree
x	0.0308	1.848	32.46753247	-71.61972439
y	0.0209	1.254	47.84688995	-229.1831181
z	0.0309	1.854	32.36245955	48.70141259

Figure 20: GEARRS2 Spin Shortly After Deployment.

GEARRS2

GEARRS2 was a 3U CubeSat with 2 Globalstar STX-2 Simplex radios and one GSP-1720 Duplex modem, purposed for SMS commanding and file transfer, launched in May of 2015 from a P-POD launcher on an Atlas rocket. GEARRS2 achieved an elliptical orbit of approximately 350 to 700 kilometers. GEARRS2 results were hampered by the flight dynamics of the satellite, as both pitch and roll were apparently imparted to the satellite upon deployment from the launch vehicle. Figure 20 depicts magnetometer instrument readings plotted over time, pointing to an apparent roll rate of about 2 RPM and a pitch rate of about 1 RPM. In order to understand possible effects of these flight dynamic disturbances on the communication effectiveness of the GSP-1720 Duplex modem, a physical 2 axis flight dynamics simulator was built to house and test the Duplex modem. Figure 21 depicts the simulator unit. The simulator was activated for several hours, and data for the number of connection attempts and connection durations were collected. Figure 22 illustrates the results of testing, clearly demonstrating the combined pitch and roll of the satellite made signal acquisition of a sufficient duration required for successful call placement, let alone establishment of a data link, practically impossible. In general, a duration of about 40 to 50 seconds is needed to place the call, establish the data link, and initiate file transfer. Although a single call was received from the GEARRS2 GSP-1720 just after satellite deployment (personal correspondence with Globalstar), the combined roll and pitch of the satellite prevented data link establishment, and also prevented any additional calls from being received from the modem. File transfer was essentially eliminated by the satellite's flight dynamics. However, SMS commands were still received by the Duplex modem, probably due to the short duration terrestrial SMS transmission which would occasionally align with the brief reception window, sporadically presented by the rolling and pitching satellite.

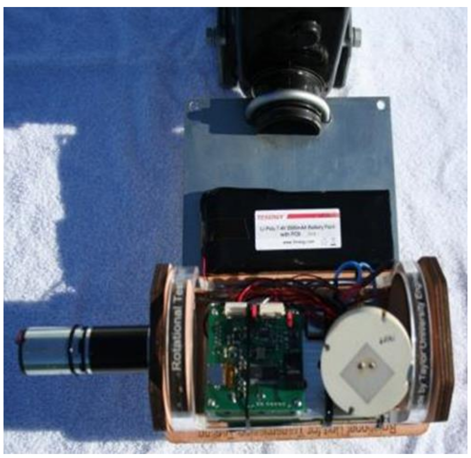


Figure 21: 2-Axis Test Platform for GSP-1720 with pitch and roll motion.

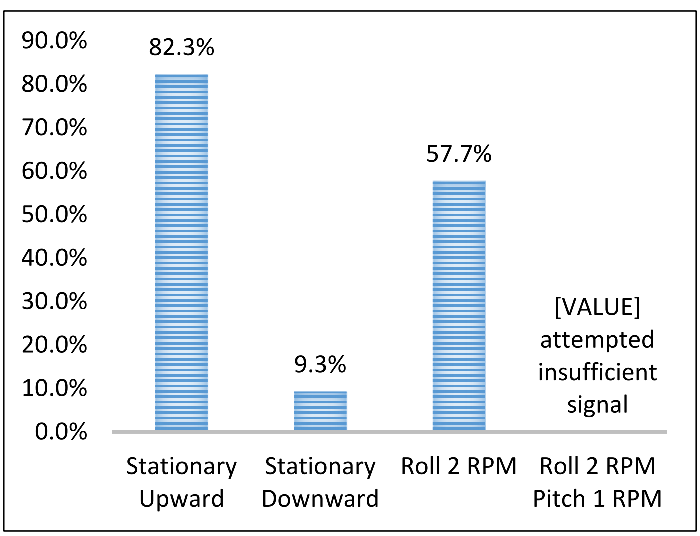


Figure 22: Results of 2-axis Rotation Simulation.

At 24 days into the mission, the communications processor (but not the Duplex modem) ceased functioning. This failure occurred after the spacecraft had rebooted over 50 times due to low power shutdown/solar insolation/restart cycles. The communications processor failure prevented any additional testing of the Duplex modem file transfer capability, as it was anticipated that the modem might be expected to start transferring files with the achievement of more stable flight dynamics over time. However, subsequent to the communications processor failure, SMS messages were still being received by the modem. Over the course of 56 days, 261 of 308 SMS messages were received (84.7%). Average time from transmission to acknowledgement of receipt was unacceptably long due to the disturbed flight dynamics and resultant disruption of communication with the Duplex modem, and the increasingly intervals between SMS retries employed automatically by the Globalstar SMS transmission system. SMS reception of the Duplex modem was exceptional under the circumstances, although timely receipt was greatly reduced (hours-days delay versus normal seconds-minutes delay).

SCIENCE: ENERGETIC PARTICLES

Survey Data

Figure 23 shows a survey plot of most of the raw sensor data collected on GEARRS2. The subplots show the 3 magnetometer axes (Mag X, Mag Y, and Mag Z), three energy particle detectors (SSD Y external, SSDY internal, and SSD Z), the voltage of the solar arrays, packet count, and altitude. The energetic particle detectors are three solid state detectors, two facing the +y direction, one in the +z direction. In the +y direction, one detector has no shielding in front, earning it the “external” tag, while the other lies behind the aluminum frame, giving it the “internal” tag. These differences allow the measurement of all particles, along with highly energetic particle that must penetrate the aluminum shield.

Observing the three magnetic subplots, the satellite is shown to be magnetically locked in the +x and +y axis, and rotating slowly about the +z axis. The particle detector data shows the satellite passing over the auroral oval. This is shown from the two large peaks seen in each of the three particle plots. The satellite passes through the oval and into the polar region, then passes back through it on its way back to the equator. Each crossing of this auroral oval causes a large peak in these plots.

Particle plot

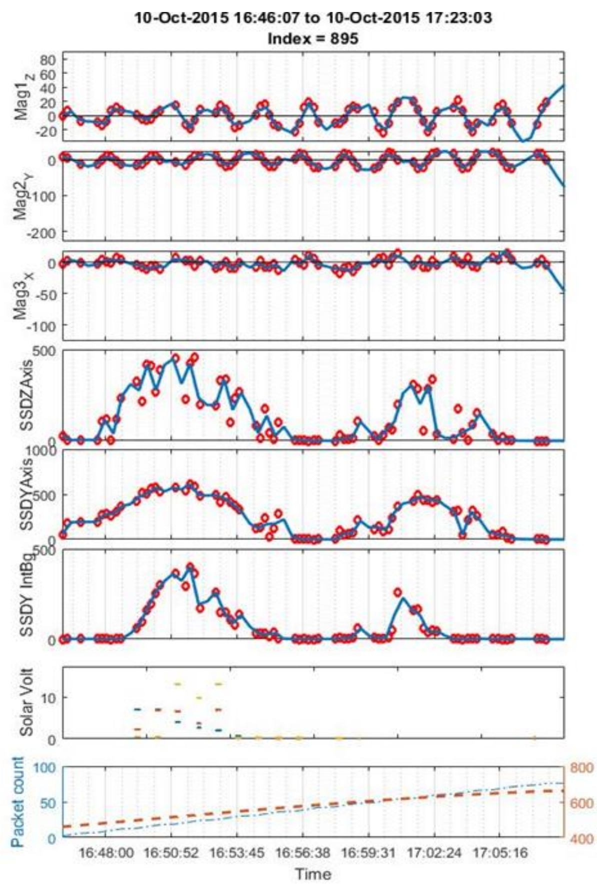


Figure 23: Example of existing survey plots for GEARRS G* data received on 10 October 2015. Top three panels show Magnetometer x,y,z with the X axis locked on the magnetic field line. Two Aurora Oval particle precipitation peaks shown on either side of the polar cap. Lower panels voltage & altitude.

The longitude and latitude of each SSD Y external point can be seen plotted in Figure 24. The South Atlantic Magnetic Anomaly shows prominently, as well the auroral oval south of Australia. Also observed is the high particle flux over North America. This plot was used to determine which TLE corresponded to the GEARRS2 satellite, as it clearly shows the known high flux regions.

Spectrum Plot

The ratio of the SSD Y external to SSD Y internal can be seen in Figure 25. This plots demonstrates the ability of these sensors to investigate the particle energy spectrum. In darker areas, we see a much “harder” spectrum, as there a low ratio of low energy particles to high energy particles. However, towards the southern end of the SAMA, we see a region of “soft” spectrum as the vast majority of these particles are lower energy, thus giving a high ratio of low energy to high energy particles.

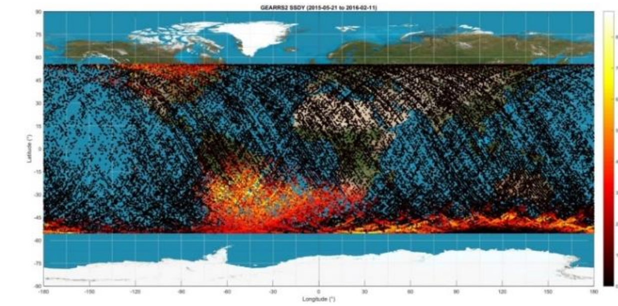


Figure 24: GEARRS2 Solid State Detector data, for the external +y facing detector. Color indicates particle counts per 1/4s. Note the high count region over North America, the South Atlantic Anomaly, and the aroural oval region.

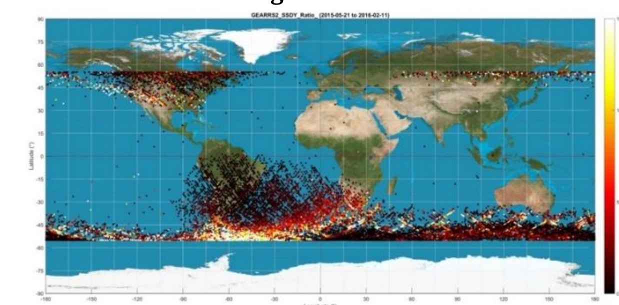


Figure 25: GEARRS2 Solid State Detector data, for the external and internal +y facing detector. This shows the ratio of external/internal. Color indicates the particle energy spectrum, ranging from heavy “hard” spectra, to softer particles.

LIMB AND HIGH ALTITUDE LINK

Simplex Link Efficiency with Spin Motion

One of the interesting observations we made with the Simplex on the spinning GEARRS2 satellite and on the other satellites was the antenna pattern sensitivity did not have gaps in it as it was spinning and pointing away from or towards the Globalstar satellites. This suggest that the radiation pattern of the receiving or transmitting antenna was more omni-directional with side-lobes or perhaps the CubeSat small area and patch antenna were acting as a combined antenna, or there were reflections of some sort or other explanation. Another indirect indicator was that when testing the Simplex in the thermal vacuum chamber in a metal building with some high-bay windows the Simplex unit made some connects with the Globalstar satellites while it was being tested in the steel vacuum chamber with an observing window, which surprised us.

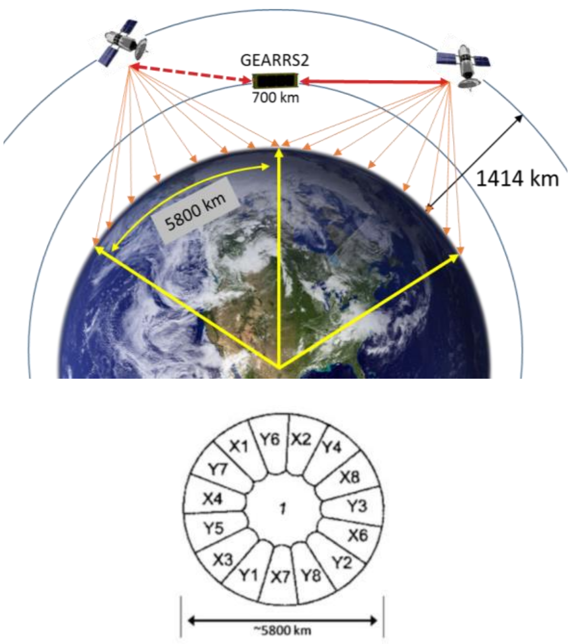


Figure 26: Globalstar 16 L-Channel and Beam configuration with projection on earth.

Globalstar Beam Pojections on Earth and Satellites

A conceptual drawing of the Globalstar geometry is shown Figure 26. The projection of the beam on the earth covers about 5800 km or nearly an earth radius. Note that for a satellite in a 700 km orbit, as shown, the beams do not always intercept the CubeSats so there could be weak link regions between the Globalstar satellites. On the other hand, the CubeSats are closer to the Globalstar satellites and do not have atmospheric loss. Whatever the case, we did not have any significant drop outs in signal on most of the earth except over the Pacific Ocean since there were fewer gateways for the satellites to connect to.

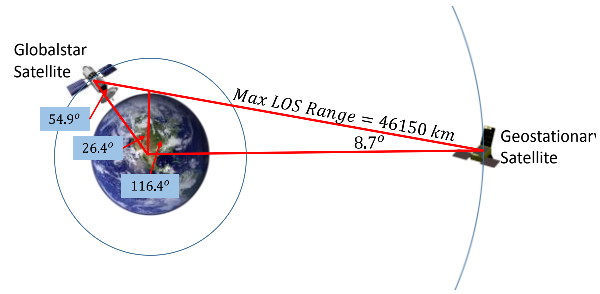


Figure 27: High-altitude links above 2000 km may be possible near the limb of the earth and should be investigated out to GEO with a transfer type orbit.

Limb pointing diagram with water reflection and RO

At this time, we are encouraging groups to fly the Simplex to higher orbits to help map out the link margin for orbits nearer to the Globalstar constellation and beyond. Some basic analysis shows that the link may be viable to high altitudes if there is more antenna gain and good side lobe access.

When the Globalstar satellites are near the limb of the earth as shown for a GEO satellite in Figure 27, they are closest to the side lobes and more sensitive to small angle reflections and refractions.

Measurements by Ref. (6) show ocean refection coefficients for small angle scattering (1.6 GHz waves). Another small Limb effect is the bending of 1.6 GHz waves by Radio Occultation (RO) as discussed by Ref. (17) and (19). As shown in Figure 28 the ray paths are shown for 1) Direct side lobe pick-up with no atmospheric loss, 2) for direct small angle ocean reflection but is attenuated through two passes through the atmosphere and loss of reflection, and 3) Radio Occultation refractive bending. These various paths into the downward pointing L-Band Globalstar antenna will continue to be simulated and tested with a prototype to explore these and other limits on the link (possible ways to mitigate losses with Globalstar and FCC approvals). Great care needs to be taken regarding Radio Astronomy and other interference even though the power levels on Globalstar are low (Simplex 0.2W ERP) with CDMA.

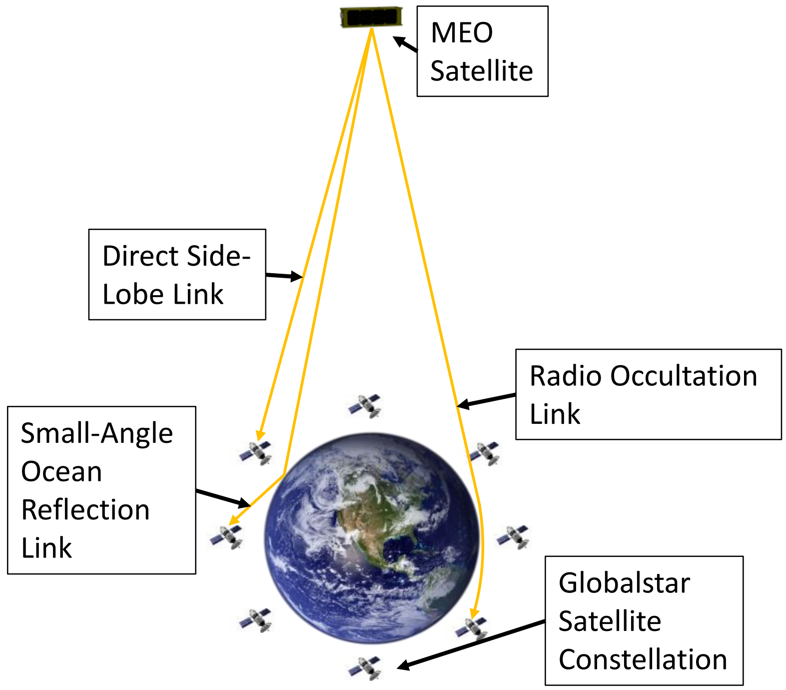


Figure 28: Range of Globalstar link paths for direct, reflected, and refracted waves.

CubeSat High Gain Antenna

An example of a High gain multi-patch antenna is shown in Figure 29. A linear CubeSat array using the MatLab Antenna Toolbox for 1.6 GHz demonstrates high gain for distant viewing MEO and GEO orbits.

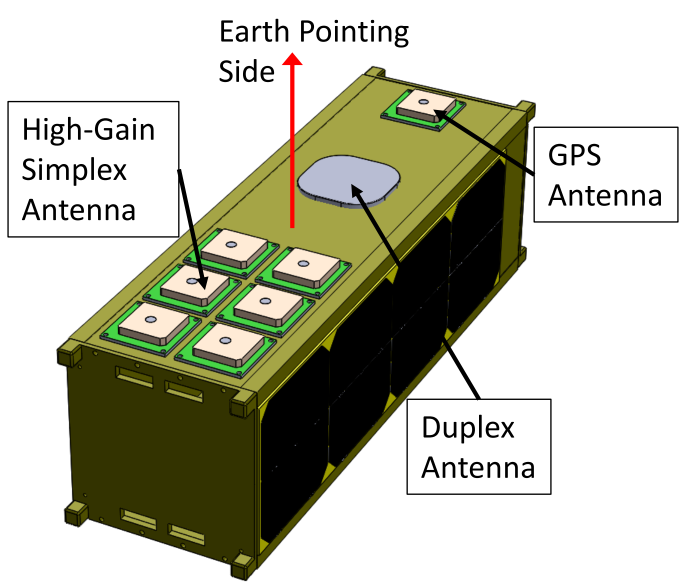


Figure: 29: CubeSat stationary MEO High Gain Array designed for distant Globalstar link testing.

Globalstar has recently launched the Next Generation with 256 kbps in a flexible Internet protocol multimedia subsystem (IMS) configuration linking satellites with many additional features. Several new products are in development that will greatly improve CubeSat constellation links.

Acknowledgments

We would like to thank the Air Force Research Laboratory's Small Satellite Portfolio for their sponsorship and support of the GEARRS mission.

Thanks to NSL employees who worked tirelessly and innovatively developing all three CubeSats: TSAT, GEARRS1 and GEARRS2 and flying them in a two-year span. Thanks to students, faculty, and staff at Taylor who worked many volunteer hours to make the student part of TSAT successful.

Many thanks to the team at Globalstar Inc. for their patience and creativity in the work they did to help us advance electronics, computer server transfers, legal challenges, FCC approvals, satellite testing, and creating the EyeStar VAR product. Their willingness to take some risk and work with a small group was inspiring.

Gratitude is also expressed to: Scott Higginbotham, Ryan Nugent, and Perry Ballard for their efforts working with us on the GEARRS AFRL and NASA ELaNa 5 programs and launch preparations, the NASA INSGC Space Grant for student program support.

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APPENDIX: REFERENCE NSL PRODUCTS

Research/Commercial Grade:

<u>EyeStar-S2: Satellite Simplex Radio</u>: Features Anytime-Anywhere Globalstar connectivity, with 200 Kbytes/day and 9 Bytes/sec, antenna, flight ready, no need for a ground station, microchip flight micro-controller, and STX2 or STX3 radios. With FCC and Globalstar approval, this is ideal for Beacon, GPS, and summary data with single or multi-satellites. (availability: <2 weeks). See Product Sheet.

<u>EyeStar-D2: Satellite Duplex Radio</u>: Features Anytime-Anywhere Globalstar connectivity, with 20 Mbytes/day and 700 Bytes/sec, antenna, flight ready, no need for a ground station, and ARM comm/flight processor. With FCC and Globalstar approval, this is ideal for Beacon, GPS, and summary data with single or multi-satellites. (availability: <4 weeks). See Product Sheet.

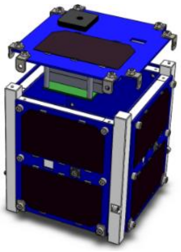
<u>DATA Systems: Local Servers, Console Operations and Data Analysis Software</u>

Complete your total satellite Ground Segment requirements using near real time (latency a few seconds) Globalstar commercial Ground Stations and NSL VAR certified software. See Product Sheet.

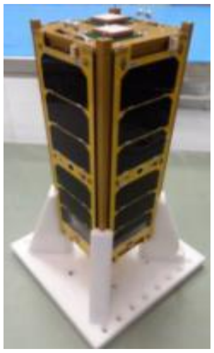
<u>Radio Options include</u>: FCC and Globalstar license, Energetic PIN particle detector, 3-axis mag, Inertial Measurement Unit (IMU), GPS, Plasma Probe, & Ground Data Console.

FastBus All-In-One CubeSats:

<u>FastBus-1U:</u> All-In-One Complete Satellite Bus ready for flight! Structure, Solar Arrays, Electrical Power System, Certified LiPoly Batteries with protection, Globalstar 24/7 Simplex Radio and antenna, Ground Station, Harness, Inhibit Switches, TRL=7-9 for subsystems, support, customization, and options. PC104 and Pumpkin form and Fit (availability: <6 weeks). See Product Sheet.



<u>FastBus-2U to 6U:</u> All-In-One Complete Satellite Bus ready for flight! Structure, Solar Arrays, Electrical Power System, Qualified LiPoly Batteries with protection, Globalstar 24/7 Simplex Radio and antenna, Ground Station, Harness, Inhibit Switches, TRL=8-9 for subsystems, support, customization, and options. PC104 and Pumpkin Form and Fit (availability: <6 weeks). See Product Sheet.



<u>FastBus Options include</u>: FCC and Globalstar license, Energetic PIN particle detector, 3-axis mag, Inertial Measurement Unit (IMU), GPS, Plasma Probe, Ground Data Console, 900 MHz Crosslink, and Flip-out Solar Arrays.

For more information and costing, see www.nearspacelaunch.com, or contact us at nsl@nearspacelaunch.com or 765-998-8942.