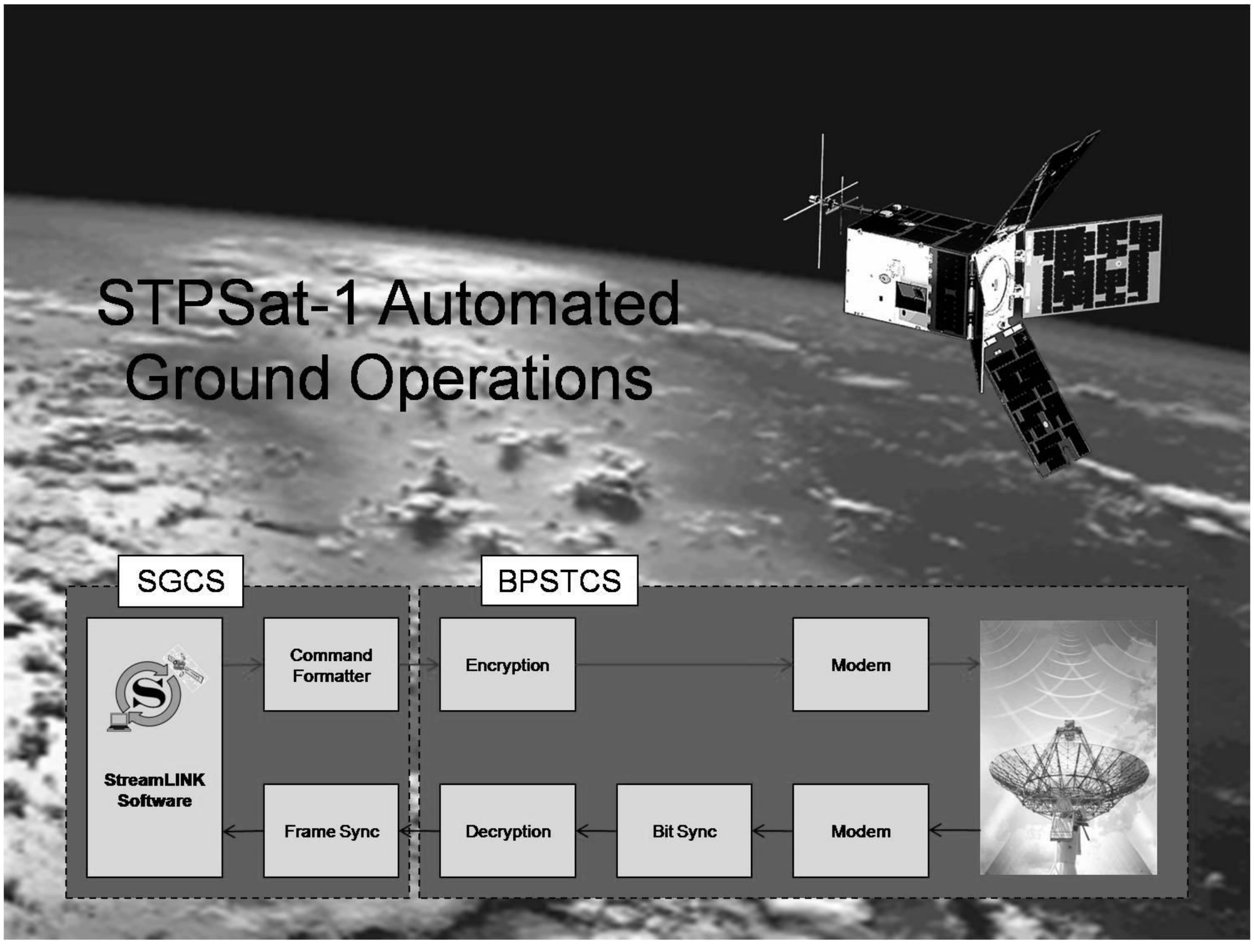

Low-Cost, Automated Ground Station for LEO Mission Support

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ABSTRACT

The STPSat-1 spacecraft is a low Earth orbit (LEO), small satellite (total mass: 156 kg) built by AeroAstro Inc. for the US Air Force Space Test Program. It carries two payloads: The Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER) and the Scintillation and Tomography Receiver in Space (CITRIS). The satellite bus and its payloads were designed for a 13 month mission. After the successful completion of the one year nominal mission, the payload teams desired to continue satellite operations for at least an additional year to achieve additional scientific objectives. To meet this new mission goal within the available, but limited funding, Tiger Innovations successfully designed, built, and integrated an automated ground system solution for a low cost mission extension. Automating a LEO ground station presents a number of unique challenges, including equipment setup, health and safety monitoring, payload interfaces, and anomaly reporting and resolution. The successful STPSat-1 mission extension serves as a powerful demonstration of the tools and procedures necessary to operate comparable future missions in the same manner. Moreover, the entire development cycle from concept to on-orbit commanding was accomplished in less than 6 weeks. Such aggressive schedules are particularly important for operationally responsive space missions.

1. INTRODUCTION

The STPSat-1 (Space Test Program Satellite-1) spacecraft is a low Earth orbit (LEO) small satellite (total mass: 156 kg) built by AeroAstro Inc. for the US Air Force Space Test Program. The vehicle launched in March 2007 as part of the STP-1 Atlas-V launch on board the EELV ESPA ring [1]. The primary payload, the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER), is a high-resolution ultraviolet spectrometer based on the novel optical technique known as Spatial Heterodyne Spectroscopy (SHS) [2]. SHS facilitates the design of low mass, low power, high throughput spectrometers for space-based remote sensing. The main SHIMMER objectives for the nominal mission were the demonstration of SHS for long term UV remote sensing of the atmosphere and the measurement of vertical hydroxyl (OH) profiles in the mesosphere [3]. The secondary experiment, the Computerized Ionospheric Tomography Receiver in Space (CITRIS), investigates irregularities that affect propagation of satellite-to-ground links for GPS (Global Positioning System) and communications [4]. Both payloads were provided by the Naval Research Laboratory (NRL).

The STPSat-1 mission was designed for 13 months of on-orbit operations at which time the vehicle would be turned off. After meeting the nominal mission objectives for the first year of operations, the NRL payload teams explored several options to extend the satellite operations for an additional year in order to gather additional scientific data. To stay within the constraints of the available funding for the mission extension, a new operations approach that could be developed quickly enough to meet a six week transition deadline and that could drastically reduce cost, was needed. Tiger Innovations proposed the development of an automated ground station and operations approach using the Tiger Innovations StreamLINK ground control system coupled with existing ground station resources at the NRL's Blossom Point satellite tracking facility. The most significant cost reductions are achieved by integrating StreamLINK with the Blossom Point ground system and elimination of much of the staffing requirements by fully automating virtually all normal STPSat-1 operations activities.

Figure 1: SGCS Equipment Rack

1.1 StreamLINK Ground Control System

Tiger Innovations' StreamLINK is a highly capable spacecraft ground control software package for use during simulation, I&T, and on-orbit operations. The StreamLINK system is modular, and is easily adaptable and extensible. StreamLINK uses database-driven commanding, telemetry de-commutation and display, and automation via the Tcl scripting language. For the STPSat-1 mission extension program, StreamLINK was integrated into a small mobile equipment rack (16U, 19" rack) that allows it to interface with the host facility and performs frame synchronization and command formatting functions. Tiger Innovations' StreamLINK Ground Control System (SGCS) has been used on multiple programs including HXS, HENEX, STPSat-1 and STP-SIV (STPSat-2).

1.2 Blossom Point Satellite Tracking and Command Station

The Blossom Point Satellite Tracking and Command Station (BPSTCS) is a fully automated command and control facility capable of supporting multiple satellites concurrently. The system currently supports 13 spacecraft in a wide variety of orbits 24 hours a day, 7 days a week, taking approximately 186 contacts per day. The BPSTCS is manned eight hours per day, five days a week and operates with a high degree of automation. STPSat-1 is operated solely from Blossom Point, which supports approximately five STPSat-1 contacts per day. During normal operations, STPSat-1 support is limited to approximately one man hour per week, with engineering staff available to support anomaly resolution as needed. The software system is based on the Common Ground Architecture (CGA) developed by NRL to support all aspects of the satellite development lifecycle from box level testing through operations. The Automated Ground Operations software (AGO) allows the system to run automatically without any operators required.

2. AUTOMATED LEO OPERATIONS CHALLENGES

Operating a low Earth orbit satellite using an automated ground system presents many challenges. Generally, these challenges can be characterized into three groups: equipment setup, real-time operations, and anomaly resolution.

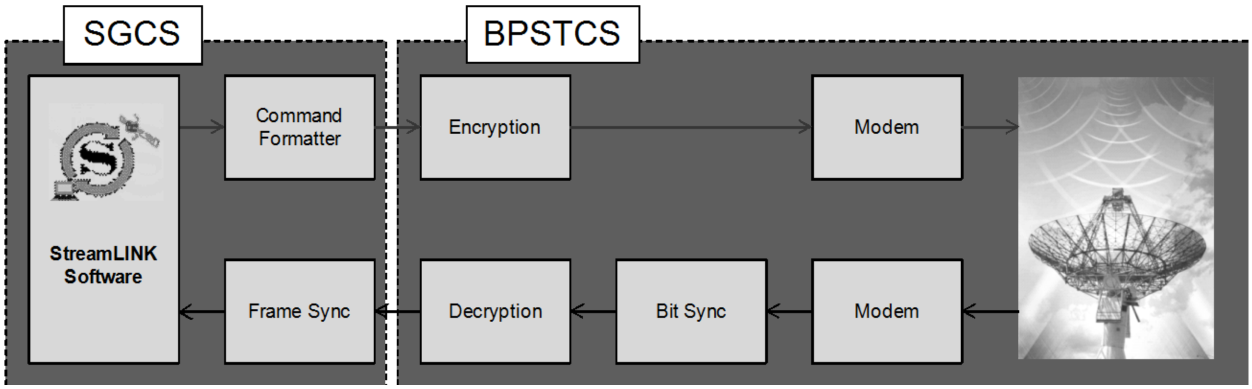

Figure 2: Equipment Block Diagram

Equipment setup: The STPSat-1 ground support system is hybrid between the CGA system and the SGCS. To control STPSat-1, the existing antenna, RF (Radio Frequency), and encryption equipment at the Blossom Point facility was interfaced with the StreamLINK Ground Control System (SGCS) equipment that houses the frame sync, command formatter, and control software. The SGCS telemetry interface accepts a synchronous RS-422 serial link and provides command output in ternary format. The tracking facility provides the RF, bit-sync, and encryption hardware, and passes telemetry clock and data to the SGCS. Inside the SGCS, a Tiger Innovations frame sync module receives the serial stream, identifies telemetry frames, performs a cyclic redundancy check (CRC), and passes valid frames to the backend computer for decommutation. In addition to the electrical interface, the network interface was developed to enable the tracking facility to share information regarding pass AOS/LOS (acquisition and loss of signal) times, and to transfer commands, telemetry, and payload data to and from the SGCS. A sequence of pre- and post-pass processing scripts was developed to query servers and transfer data files to the appropriate destinations. To send commands to the spacecraft, the payload teams simply place their upload files on a secure server, and at the next opportunity, the files are autonomously transferred to the SGCS for parsing and upload. Likewise, following each pass the SGCS processes payload and housekeeping telemetry, generates data products and sends those files to the payload engineers. This architecture allows all parties to access their data remotely and eliminates the operational middle man required to generate command uploads and distribute data products.

Automated real time operations system: For any given pass, Blossom Point's CGA generates antenna pointing angles and AOS/LOS times from daily ephemeris updates. This information is used to schedule antenna and equipment resources and is transferred to the SGCS for pass planning. Prior to AOS, CGA sets up the BPSTCS ground system components (antennas, receivers, bit syncs, key generators, switch matrices, transmitters, etc) to collect the downlink and generate the uplink signals required. During the pass, StreamLINK generates the uplink bit stream for commanding and collects the downlink data. The SGCS uses control scripts to monitor telemetry, command the vehicle and send out anomaly alerts if necessary. For the

STPSat-1 mission, the main script waits for AOS, ensures the uplink and downlink are set up properly, and then begins normal pass operations. This includes scheduling the flight transmitter on-time, running a critical health check, uploading payload and engineering commands, and downloading stored data. The critical health check monitors a large set of telemetry that effectively characterizes the overall health of the spacecraft. Alerts are generated for out of limit points and in certain cases, autonomous recovery operations are triggered. Following the critical health check, command uploads are sent to the vehicle. Each command is sent individually and verified as received prior to sending the next command. If a given command file cannot be fully uploaded in one pass it is carried over to the following passes. While commands are uploaded, stored state of health and payload data is received. For each received data type, the SGCS monitors data quality and sequence numbers and requests retransmission of missing data to ensure the payload engineers receive all science data. Finally, after LOS, the SGCS processes the state of health and payload data, generates plots, and sends out emails to all interested parties regarding the pass status. Data products are then transferred via FTP from the SGCS to NRL within 15 minutes. This pass Concept of Operations allows for all interested parties to monitor as much or as little of each pass as desired. All data is received on the ground without requiring a person in the loop, thus significantly reducing the recurring costs.

On-orbit anomalies: Dealing with on-orbit anomalies without operators in the loop to make anomaly assessments and send commands is arguably the most difficult challenge. First, the anomalies from the first year of operations, and even further back, from integration and test (I&T), were characterized and evaluated, based on severity, likelihood of occurring, and standardization of a response. The two anomalies that are most likely to occur elicited a standard response. They were a GPS receiver anomaly and a processor anomaly. Both anomalies are due to radiation effects that were likely to increase in frequency the longer the mission exceeded its design life. In both cases, a specific telemetry state identifies the anomaly and was easily incorporated into the critical health check. The response to each anomaly is the execution of a sub-script that examines additional telemetry to identify the proper command uploads, and autonomously fixes the problem. In addition to well characterized and rather benign anomalies like these, there are anomalies that have a standard response but are severe enough that a review by an engineer is required. Furthermore, new anomalies that require individual analysis cannot be ruled out. In these cases, the SGCS script sends emails and text messages to the proper engineering group and continues to downlink data to gather information on the anomaly. Spacecraft safehold is the best example of an anomaly that has a generally standard response but requires an engineering review. STPSat-1 has a power positive tumble safehold state that is triggered by an under voltage, however, there are many possible causes for the under voltage condition. After the engineering team is alerted by the SGCS, telemetry review and analysis determines if it is safe to begin recovery from safehold, and if so, the automated recovery process is initiated and the vehicle can return to normal operations in a matter of hours. This minimizes the cost of conducting a safehold recovery procedure while ensuring a detailed understanding of the anomaly cause and that it is ready to return to normal ops.

The last piece of the anomaly resolution concept for the STPSat-1 mission is the recognition and acceptance by all parties that anomaly response times are generally longer compared to operations concepts that use a fully staffed 24/7 ground station and a global ground station network. The trade-off in this case is the drastically reduced operations cost which over the course of a mission may easily outweigh slightly increased payload downtime. In STPSat-1's case, the alternative was the satellite end-of-life and thus no data at all.

3. SHIMMER AND CITRIS RESULTS MADE POSSIBLE BY THE MISSION EXTENSION

The greatly reduced operations cost allowed the extension of the STPSat-1 mission which contributed significantly to the science accomplished by its two payloads. For this mission, the increased time on orbit facilitated scientific results that were not possible to achieve with only the nominal mission. The following sections summarize those results.

3.1.SHIMMER extended mission results

The main science objective of the extended SHIMMER mission is the measurement of mid-latitude mesospheric clouds at latitudes up to 58° north and 58° south, which are the most poleward latitudes that are sampled by SHIMMER in the boreal and austral summer, respectively. These clouds are extensions of the more persistent Polar Mesopsheric Cloud (PMC) layer, which forms each summer. Between about 50°-60° latitude PMCs can be observed by the naked eye from the ground during twilight when the lower atmosphere is dark and the upper atmosphere is still sunlit. They are thus known more popularly as noctilucent clouds (NLC). At even lower latitudes (equatorward of 50°), their occurrence is considered by some as a novelty [4] and even as a harbinger of long-term change [6]. Indeed the mid-latitude region is precisely where the societal and scientific interest was galvanized by reports in the last decade of increases in cloud occurrence and brightness. In response to this interest, NASA selected the Aeronomy of Ice in the Mesosphere (AIM) small explorer which was launched in April of 2007 and is devoted to the study of PMCs [7]. Initial results from AIM reveal spectacular images of PMCs with intricate patterns that suggest heretofore unexplored dynamics in the mesopause region. However, there are two important limitations to AIM's coverage of mesospheric clouds that are addressed by SHIMMER.

One major strength of SHIMMER relative to AIM, is its ability to measure the dimmer clouds that form at non-polar latitudes (40°-60°). The only AIM instrument which observes at these latitudes is the Cloud Imaging and Particle Size (CIPS) imager, which because it views clouds in the nadir, not the limb like SHIMMER, is not very sensitive to the dimmer clouds occurring in this latitude region.

The second strength of SHIMMER is its ability to measure the diurnal variations in mesospheric clouds. The importance of diurnal variations in mesospheric clouds was not fully appreciated when AIM was proposed in 2001 but evidence is now clear that local time variations are important in governing the distribution of PMCs [8] and their extension to mid-latitudes [9]. AIM, and all other NASA and NOAA mesospheric cloud sounders before it (SBUV, SME, SNOE), are in sun-synchronous orbits. This means that observations are made at a single local time at mid-latitudes, preventing a description of cloud properties over the diurnal cycle. SHIMMER is not in a sun-synchronous orbit and the low latitude inclination of SHIMMER means that at the "top" of the orbit (observation locations at ~58° latitude), SHIMMER records many images of the atmosphere and samples a wide range of local times. These local times precess about 0.5 hrs/day so that SHIMMER can easily observe the entire diurnal cycle over one mesospheric cloud season. Figure 3 summarizes the dense coverage obtained by SHIMMER between 40° and 58° N.

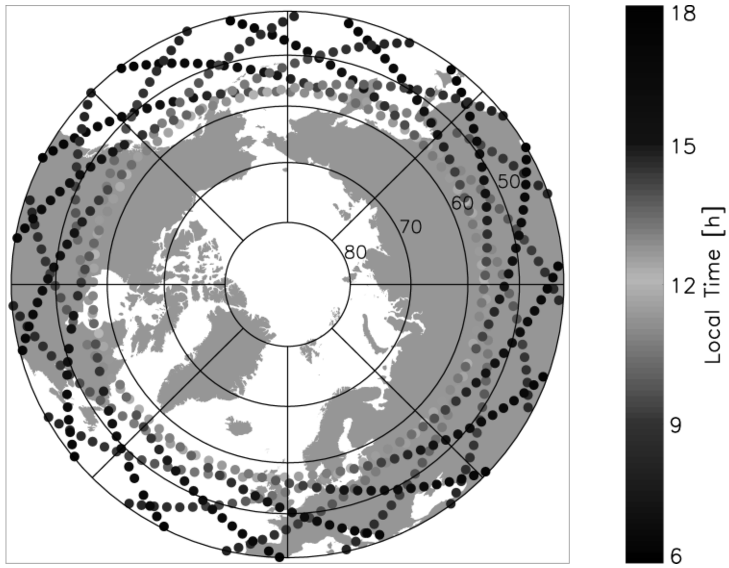

Figure 3: SHIMMER measurement locations for July 16, 2007. The map extends from the north pole to 40°N and a limb image is indicated by a colored circle, where only every other measurement is plotted for clarity. The local times of the measurements precess by about thirty minutes from one day to the next [9].

The extension of the SHIMMER data to more than two years provided the local time variation of mid-latitude PMCs in both hemispheres for at least two seasons [10]. The second northern season was particularly insightful, since the PMC local time variation was radically different than in the previous season, which has never been observed before and which has an immediate impact on the interpretation of historical PMC data. Future investigations using SHIMMER data are expected to advance our understanding of processes in the middle atmosphere and can also be valuable as tests of new high altitude extensions of operational weather forecast systems [11]. In addition to the PMC measurements, the extension of the SHIMMER OH measurements, also resolved in local time, are expected to facilitate new studies of the middle atmospheric photochemistry and dynamics [3].

3.2. CITRIS and Complementary Measurements for C/NOFS

After successfully, completing its first-year Space Weather proof-of-concept mission, the CITRIS receiver on STPSat-1, was used to complement the C/NOFS (Communication /Navigations Outages Forecasting System) mission. C/NOFS carries one of NRL's CERTO (Coherent Electromagnetic Radio Tomography) beacon transmitters, the signals of which can be received by CITRIS yielding TEC (Total Electron Content) and scintillation measurements in VHF, UHF and L-band [12]. Irregularity structures, e.g., Spread-F, in the equatorial ionosphere are well known for causing some of the most serious communications and navigation effects, especially in the form of radio scintillations. Predicting when communication and navigation outages might occur from scintillations is a critical area of research for both DOD and NASA. CITRIS measures both the causative irregularities via TEC and their effect as scintillations.

The STPSat-1 with CITRIS is in an almost circular orbit near 555 km altitude with a 35° inclination. C/NOFS was launched (April 2008) in an elliptical orbit of ~400 km x 850 km at 13° inclination about one year after the CITRIS launch (March 2007). The orbital periods of the two satellites are relatively close, so that the CERTO beacon stays in view of the CITRIS receiver for several days at a time. Figure 4 illustrates the measurement configuration. When the satellites are in range the reception path (white line) sweeps out the entire equatorial region in a few orbits, providing much needed information on TEC and scintillations that are out of track for the C/NOFS satellite. An important development from the first year of the STPSat-1 mission is described by Bernhardt et al. [13] and is a new satellite-to-satellite (CERTO-to-CITRIS) measurement capability whereby it is possible to retrieve absolute TEC via a geometric analysis. Finally, when C/NOFS is not in view, CITRIS makes measurements from the global network of French DORIS beacons and from other satellites in low earth orbit (e.g. ROCSAT3/COSMIC, DMSP/F15, RADCAL, GFO, etc.). Because of the approximately 95 minute orbital periods, CITRIS will always make measurements at the same longitude as C/NOFS within 48 min.

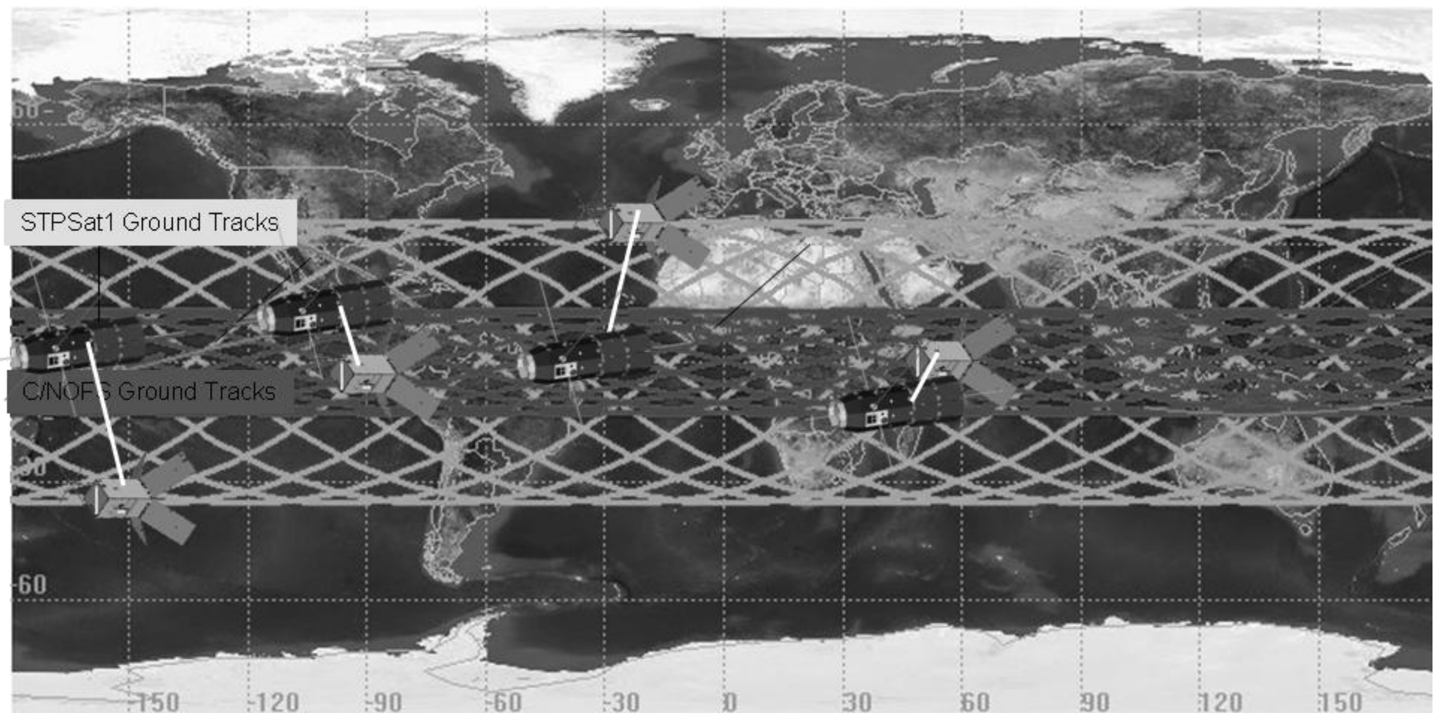

Figure 4: The Orbital Tracks of STPSat-1 and C/NOFS.

4. LESSONS LEARNED AND RECOMMENDATIONS

As of this writing, STPSat-1 continues to operate despite the continuing, radiation-induced degradation of its systems. We anticipate processor resets to continue to rise in frequency (1 in the first year, 4 in the second). However, the automated recovery process discussed above largely mitigates that concern. The spacecraft continues to produce valuable science data and provides a model for maximizing the value of low-cost missions and ensuring responsible cost efficiency of their operations. This also leads to the question of whether ground station automation, after the initial launch and early orbit operations, can be used to reduce the cost of future satellite missions. Based on the success of the STPSat-1 mission extension, the answer is definitely "yes" for missions that can accept the moderately increased risk of anomaly downtime. Given the often limited funding, the significant cost reduction offered by this operations approach warrants that it be considered for future mission planning.

Furthermore, for missions like STPSat-1, completely separate ground systems are generally developed for (1) the integration and test phase and (2) the flight phase of the mission. One of the reasons StreamLINK was so easily adapted to operate STPSat-1 was that it was the I&T ground system when the spacecraft was being built. Mission costs could be reduced even more by utilizing the same ground system for both I&T and flight and not duplicating development costs. This also enables the spacecraft engineers to develop and test automation scripts in a controlled environment on the ground prior to launch to ensure reliability and repeatability of the operational activities. While it is understood that operations personnel and engineering support must be actively engaged in early orbit checkout and initial operations, it seems reasonable that most missions could transition to automated operations 2-3 months after launch, potentially saving the government or commercial customer millions of dollars depending on the lifetime of the mission.

Finally, to meet the demanding schedule constraints of the mission, the entire development cycle from concept to on-orbit commanding was accomplished in less than six weeks. There is currently a strong desire in the small satellite industry for Operationally Responsive Space (ORS) missions to reduce the time from concept development to having an operational satellite on orbit that fully meets the customer's requirements. The hardware, software, and techniques that were used in support of the STPSat-1 mission extension demonstrate the ability to field a small, inexpensive ground station, fully integrated and tested in a minimal amount of time. This capability could be useful and cost effective for future ORS missions.

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Doug Firestone received his B.S. in Aerospace Engineering from Virginia Tech and a M.S. in Aerospace Engineering from the University of Colorado, Boulder. While attending Virginia Tech, he completed internships with Orbital Sciences, working on several different satellite programs as well as the Pegasus launch vehicle. After graduating, Doug worked for HTSI as part of an engineering support staff for operational spacecraft. He then moved on to AeroAstro where he supported the STPSat-1 mission as the lead integration and test engineer. Following the launch of STPSat-1 Doug went to work for Tiger Innovations in Reston,VA where he currently works.

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Dr. Carl L. Siefring has been working as research physicist in the NRL Plasma Physics Division since 1987 and is the Project Scientist for the CITRIS instrument. Dr. Siefring received his B.S. in Electrical Engineering from the University of Maryland (1980) and Ph.D. in Electrical Engineering specializing in Electro-Physics from Cornell University (1987). Dr. Siefring has been involved in over 20 sounding rocket experiments and 11 satellite missions since 1981. He has developed numerous instruments for measuring the ionospheric space plasma environment, including electric field and plasma wave receivers, Langmuir probes, and HF and VHF beacons and receivers. He has also been involved with ground-based remote sensing of the ionosphere using optical and radio techniques.