Abstract #6126

"Black Box" RF Sat-Link for Space Debris, Mission Success and Risk Mitigation

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ABSTRACT

The 140-gram Black Box can ID its satellite with GPS within a few minutes after turn-on while in LEO orbit from pole to pole! The Black Box for small and large satellites can track damaged satellites or identify problems early, several hours before ground station contact. The Black Box is currently in SBIR Phase II and has been tested in orbit. It provides 24/7 real-time health and status visibility (latency in seconds), allowing for rapid response to sensor data and orbit pass preparations. The Black Box is a redundant downlink if a satellite is "lost" ensuring critical mission success and diagnostics for the duration of several years or orbit lifetime. Satellite debris can be accurately tracked with included GPS option to reduce collision probability by giving more detailed orbit certainty even if the primary satellite is disabled. From the Black Box orbital GPS parameters an accurate TLE can be produced for 18^{th} Squadron and for the payload team within minutes of orbit deployment. Advanced Manufacturing (AM mass produced) reduces cost in the Stamp version (ID and GPS) of the Black Box. The Black Box Stamp, Patch, and Standard subsystems are TRL 9 and in final beta testing in-orbit.

With the Globalstar constellation we now can monitor a satellite 24/7 anywhere in LEO orbits with data available anytime, without the need for expensive ground stations. With a 100% success in orbit using the NSL EyeStar processor and Globalstar comm systems (70+ radios in space with several tumbling) can contribute to the commercial, educational, and research small satellite market that is rapidly growing. The EyeStar radio is ideal for the next step to advance many NASA, DOD, and commercial satellites now that appropriate FCC, NTIA, and ITU licenses have all been approved.

The aircraft Black Box is well known and is essential for crash diagnostics after the fact, but in addition, the satellite Black Box and processor will operate in TT&C mode during the whole mission and will continue TT&C in orbit after a completed or failed mission. The Black Box transmits vital data, health and safety information, GPS, and summary data while in orbit at up to 8 Bytes/sec for 24/7 coverage. With its included solar arrays, the Black Box would operate for many years after the primary satellite fails so that essential data and tracking is continuous, and attitude known. If the satellite reawakens after some long failure, the Black Box reports the new status and the satellite may be reactivated. We have experienced this wake-up mode after a year on one of our Black Box communication processors after an unexpected two-month "dead" phase and wake. The "dead" satellite was reactivated.

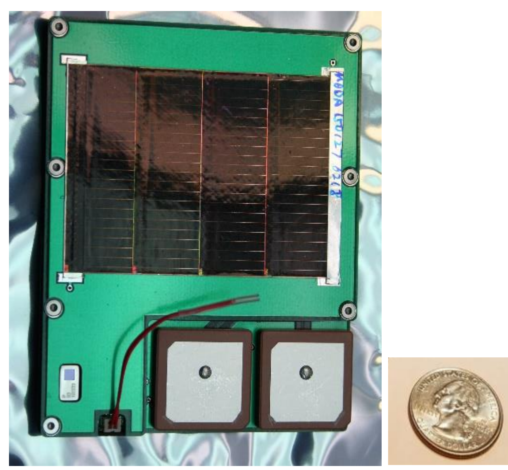


Fig. 1. Flight Side Mounted "Patch" Black Box Model (10 x 8.3 X 0.85 cm, quarter). Top surface shows two patch antennas for TX and RX, & one GPS antenna, 4 solar cells, dose, and a 256-pixel grid IR array.

1.0 INTRODUCTION

Small satellites, and especially CubeSats, are plagued with issues related to partial and complete failures, power-on issues (latency, anomalies and unknown attitude dynamics), TLE identification, orbital debris concerns, and marginal/expensive ground station links. A newly developed "Black Box" [1], about the size of a smart phone, is designed for external attachment (a barnacle) on any primary satellite and is itself an autonomous pico-FlatSat with its own hardened solar cells, battery, processor, IO, IMU, simplex radio/antenna, GPS, temp sensors, and diagnostic inputs from the primary spacecraft (see Fig. 1). Like an aircraft Black Box, it records all primary subsystems status at the time of a failure with attitude information, but in addition, it also includes a continuous Telemetry, Tracking and Command

(TT&C) ping of health and critical data 24/7 for near real-time global diagnostic coverage. Additional options to the Black Box are available: low-bandwidth camera, various sensors, encryption, extra battery, and various physical sizes.

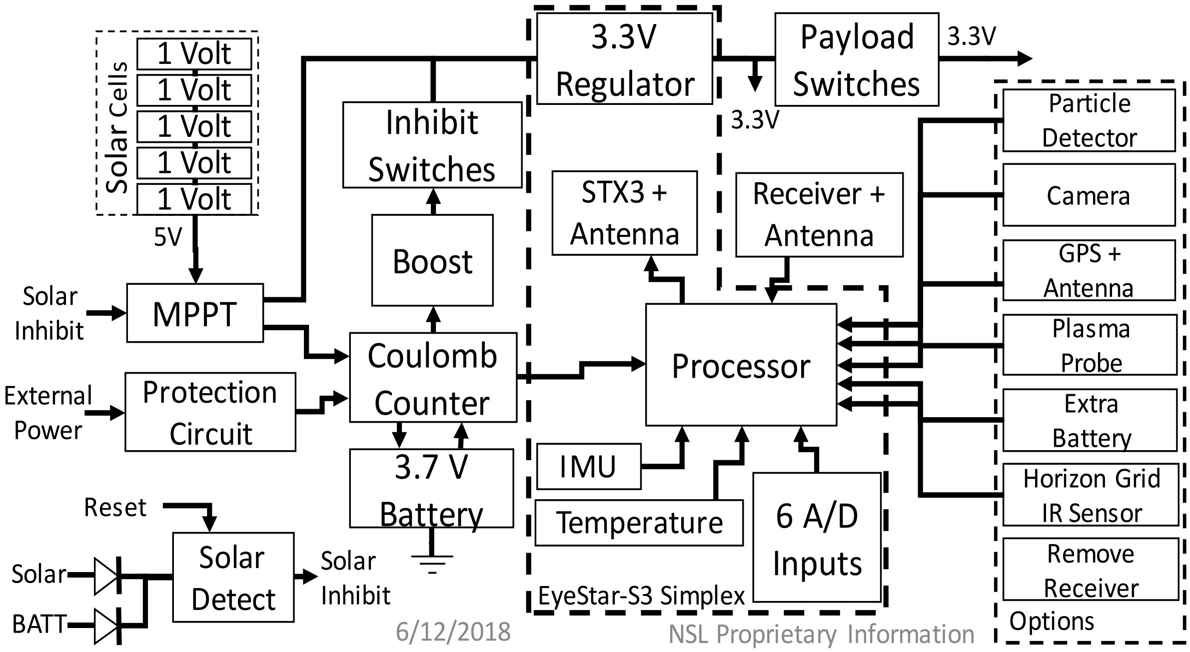


Fig. 2. System Block Diagram of general Black Box subsystems. The dashed-in boxes are the EyeStar radio.

2.0 BLACK BOX SYSTEM DIAGRAMS

The basic Black Box System Diagram is shown in Fig. 2. The EyeStar radio product (center dashed box) is shown with the additional Black Box option (right dashed box). Power is generated from four to five solar cells for low-rate TT&C transmissions and higher rates if external power is provided (spacecraft or extra battery.) One option is the Grid IR array, which is 8 by 8 pixels and is used as a Horizon Sensor and/or a crude imager to verify deployments and/or view earth limb/sun. Other options for the Black Box include a) a high sensitivity, low bandwidth imager (96 by 128 pixels) to snapshot internal or external mechanisms, b) encryption, c) additional mission specific sensors, d) various sizes and e) quality control testing levels. During normal operations, the Black Box can transmit mission critical data at 8 Bytes/sec using the Globalstar satellite network over the entire globe, with 24/7 coverage and a latency of seconds after the Black Box is activated.

Our experience indicates that critical mission success can be transmitted with the Black Box low-data rate channel, up to about 0.5 MBytes per day. If a primary satellite failure occurs, the Black Box goes into low power autonomous mode and sends back only vital information. Orbital debris issues are significantly reduced with accurate GPS position pings to narrow down the probability of collision cross section, even if the primary satellite dies, minimizing mitigation maneuvers. The Black Box lifetime may range from 1 to 15 years in duration based on cost/orbit requirements. The ability to determine space vehicle failure provides much needed clarity for insurance underwriters [2] to accurately determine end of life cause with Black Box assessment data. From an education perspective, the ability to understand the reason for satellite failures is invaluable, especially in risk-tolerant academic satellites.

Fig. 3. Thin "Patch" Black Box located on external surface of a 3U CubeSat (red). It requires 1U of surface area. GEARRS 3 is scheduled for launch 1st Q 2020.

3.0 MECHANICAL CONFIGURATIONS

Figure 4 shows the thin Patch configuration that was designed to externally fit onto the side of 1 to 6U CubeSat. It could also fit onto any larger satellite. The Black Box is available in three standard configurations in addition to

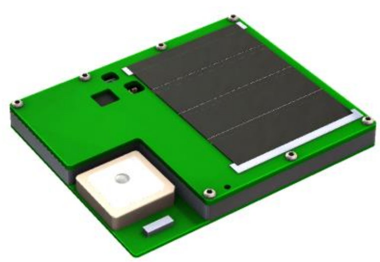


Fig. 4a. Thin Patch or Stamp Black Box for side mounting

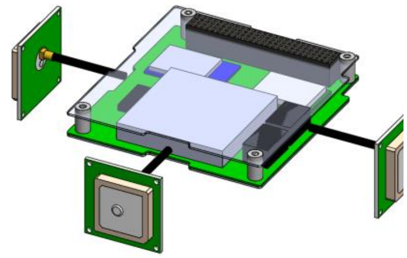


Fig. 4b. PC104 Black Box for internal stack mounting

Fig. 4c. "Standard" Black Box for larger satellites. TRL 9: flown on Spaceflight launch. Solar Array and Antennas not shown.

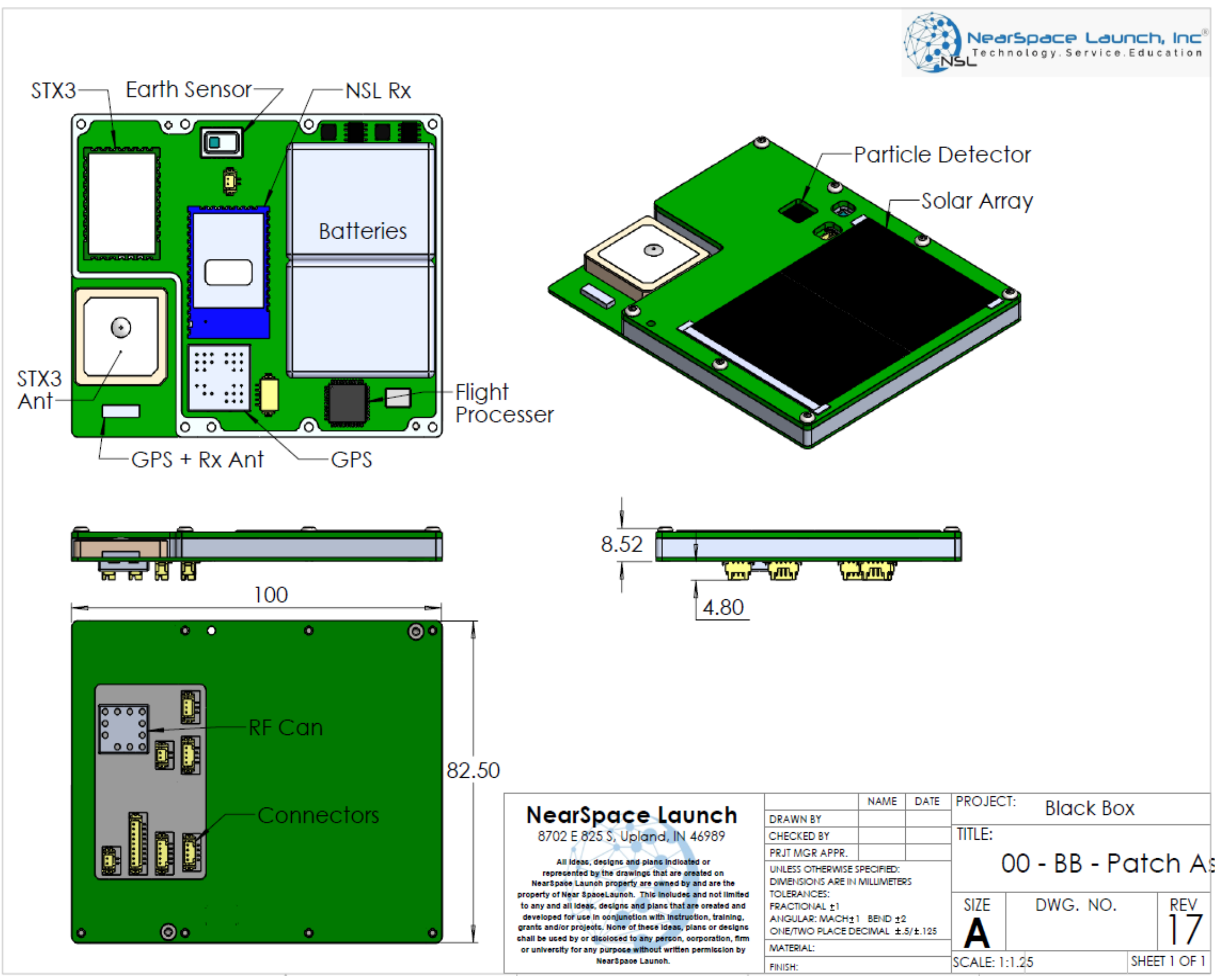


Fig. 5. Sidewall Patch Black Box Assembly diagram

custom packaging. Figure 4 shows: 1) Thin Patch or Stamp Black Box for side mounting, 2) Black Box PC104 for internal Stack mounting, and 3) Standard Black Box for larger satellites. Figure 5 shows a detailed mechanical assembly drawing of the Black Box Patch system.

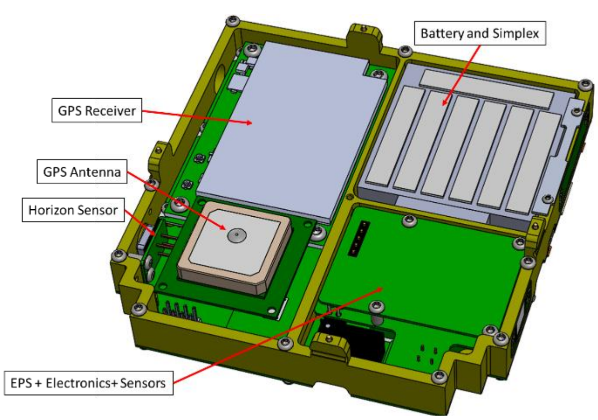
A summary Table 1 is included to compare the main features of the Stamp, Patch, and Standard Black Box.

Table 1. Comparison of Black Box Features

Parameter	Units	Stamp Black Box	Patch Black Box	Standard Black Box
Size L x W x H	cm	10 x 8.3 x 0.85	10 x 8.3 x 0.85	8.9 x 7.1 x 4.1
Mass	g	140	140	350
Battery Voltage	V	7.2	7.2	7.2
Battery Capacity	Ah	0.6	0.6	2
Solar Area	cm^2	45	45	>45
Simplex Beacon				
Max Data Rate Avg.	Bytes/s	1	8	8
IMU, Mag./Accel/ Gyro		Yes	Yes	Yes
6 Analog Inputs		Yes	Yes	Yes
Voltage & Temp		Yes	Yes	Yes
Inhibits		Yes	Yes	Yes
Options				
Lifespan/Shielding	years	1,2,5,10,20	1,2,5	1,2,5,10,20
Receiver		RF On/Off	RF On/Off	Optional
GPS		Internal or External	Internal or External	3rd Party (NovAtel)
IR Horizon Sensor		8 by 8 Grid	16 by 16 Grid	16 by 16 Grid
Dose - Particle radiation	KeV	>40	>40	>40
Camera	Pixels		128x96	N/A
e- Plasma Probe, Density	e-/cm3		100-10^{7}	100-10^{7}

4.0 THINSAT HERITAGE FOR BLACK BOX

The Black Box technology has evolved from the ThinSat production line which has embraced mass production and the miniaturization of electronics and mechanisms (Fig. 6). ThinSats have proven to be ideal for STEM learning, research applications, and exploring the new region from 100 to 350 km for climate, ionospheric and DoD discovery



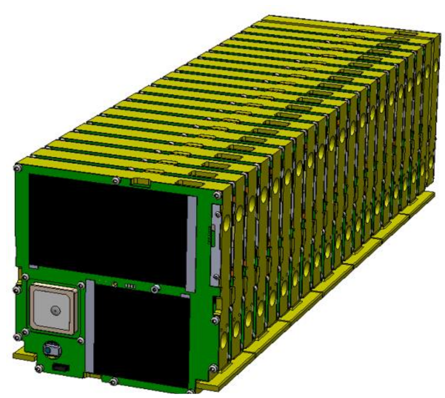


Fig. 6. Sixty ThinSats launched in Spring 2019 with full mission success. Each ThinSat Mothership is similar to the Black Box design and includes a thin patch PCB, 2.2 Ahr Battery, EPS, processor, GPS, antennas, Simplex radio, solar cells, sensors, and AL7075 frames. One CSD canister launches 21 ThinSats at a time.

while minimizing orbital debris problems because of short lifetimes (< 1 month.) [3,4] The Black Box is a natural maturation of the miniaturization of ThinSat technology.

5.0 GLOBALSTAR ENABLES THE NEW BLACK BOX PARADIGM

A new paradigm was ushered in by TSAT, GEARRS1, and GEARRS2 spacecraft which demonstrated the ability of terrestrial transceivers to operate in LEO using the existing Globalstar satellite phone network [1,4,5]. 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. Future systems using a communication model like the one employed on TSAT can have high reward as the opportunity for mission success increases. This is due to the nearly global coverage of spacecraft telemetry with low latency, and no mission specific ground infrastructure beyond a data server.

Fig. 7. Globalstar constellation of satellites for Global coverage and real-time 24/7 visibilitv.

In Fig. 7, the Globalstar constellation is shown. With its few seconds latency, the Globalstar network can enable a high degree of autonomy within satellite operations due to near real-time knowledge of satellite conditions. This can significantly reduce the risk of orbit operations with adaptability and optimization, and at much lower cost.

5.1 Globalstar Data Capacity

Globalstar has sufficient current network and system capacity. 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 gateway, nor are there anticipated to be any future capacity limitations due to the addition of CubeSats. The Globalstar system appears to have capacity to handle thousands of CubeSats transmitting thousands of packets per day.

5.2 Data Operations

The NSL ground station technology (Fig. 8) 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.

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 5 seconds.

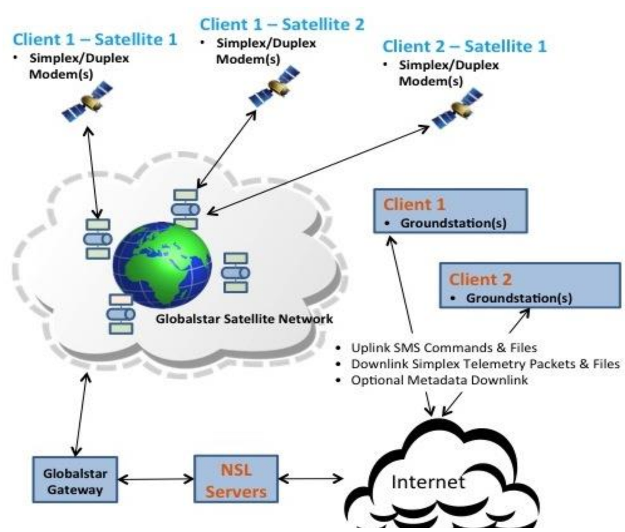


Fig. 8. Overall Communications Architecture.

For those who desire, the NSL web console (Fig. 9) permits viewing, graphing, zooming, translation, and downloading Simplex telemetry data (commonly 18 or 36 Bytes per packet). To display and download meaningful Simplex

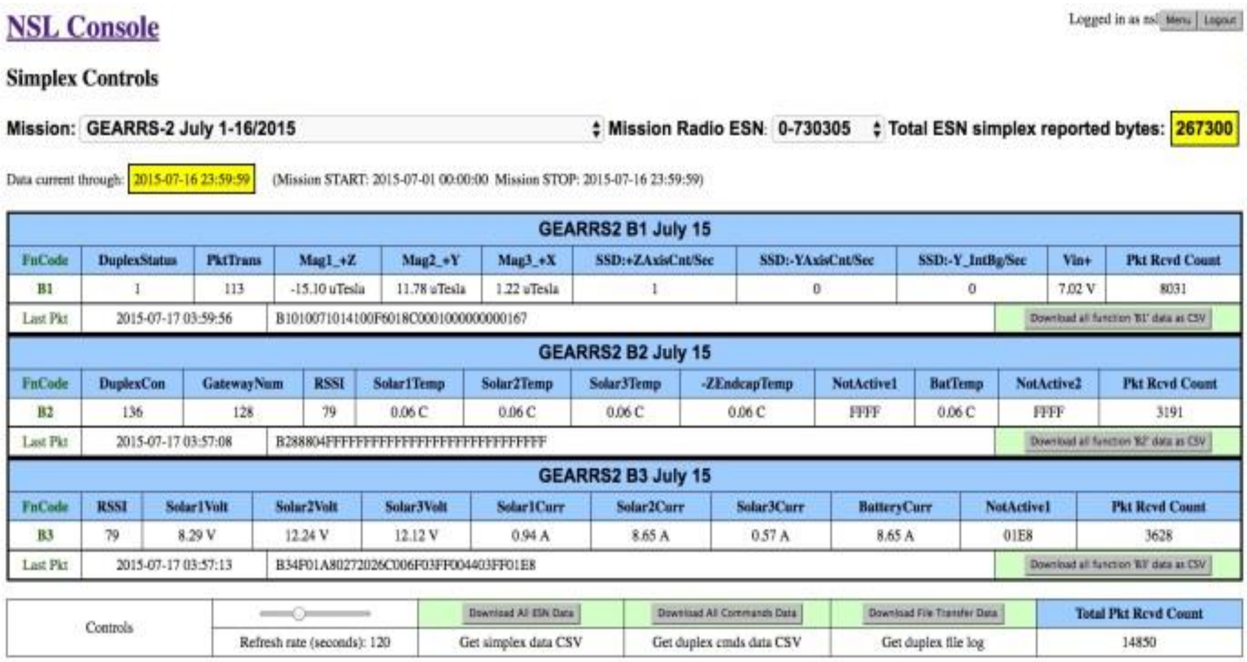


Fig. 9. Web Console Simplex Telemetry Display

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. Real-time tracking of balloon flight locations and real-time satellite position plotting on maps are also available using the web console.

5.3 Globalstar Link Performance

The Globalstar Simplex link beacon for the Black Box has performed well on 80 commercial EyeStar communication systems since 2014 with 100% reliability (all mission success) with an associated ground segment.

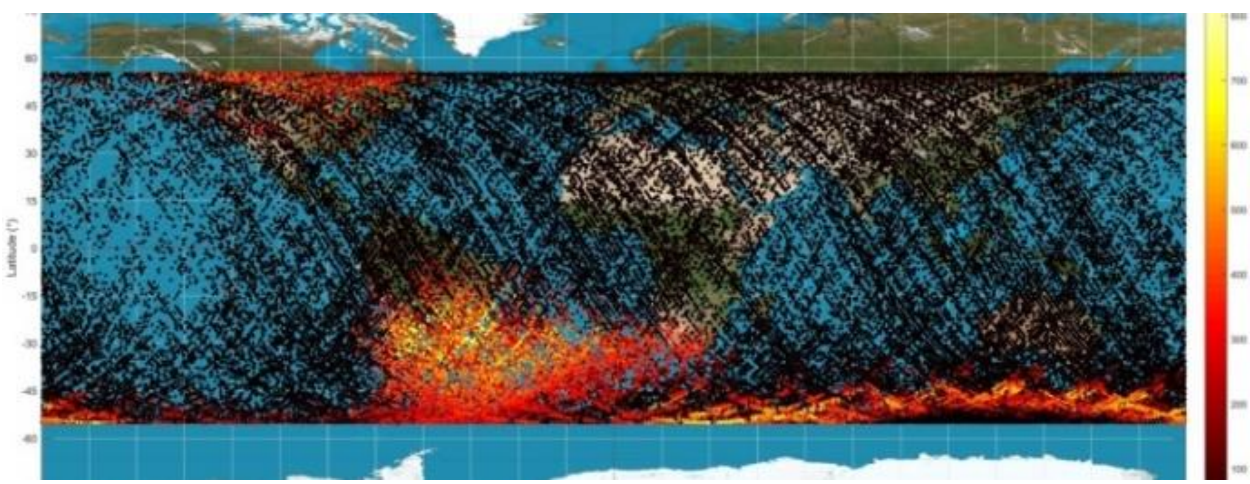


Fig. 10. GEARRS2 energetic particle data coverage map.

The low-power EyeStar Simplex communication systems have been tested between 750 km in altitude to reentry at110 km and have a TRL=9. Over 60 satellites with EyeStar Simplex units are manifested for 2020. Other advantages of the EyeStar Simplex radios and the Black Box include: no new ground station required, simple fixed 25 mm square patch antenna, operates through high degree tumble rates, and a typical data latency of several seconds from satellite to user.

In Fig. 10 is an example of STX-2 Simplex energetic particle data from several orbits of GEARRS2 [6]. 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. GEARRS2 Simplex coverage maps (Fig. 10) are uniform over the entire earth with a weaker coverage area in the Pacific Ocean. The 53 deg. latitude cutoff is due to the GEARRS2 Satellite inclination and not due to the Globalstar link.

6.0 BLACK BOX EXAMPLE OF EYESTAR RADIO

Figure 11 is an example of how the Black Box Simplex radio can help recover a "dead" satellite. For this case the EyeStar radio was not connected to its own battery or solar cells as in the Black Box (or alternatively to the flight battery/array if the main processor or other systems fail.) In Fig. 11 the satellite appeared to go "dead" for two months between the two vertical black lines and was abandoned. Little failure analysis could be accomplished without the primary space vehicle Command and Data Handling Unit (C&DH) powering up the EyeStar radio. However, at marker 2 the NSL console lit up again with Simplex packets restored. The Globalstar ground station was always active after the satellite was thought "dead" and no Globalstar data costs were incurred during this "dead" period. Once the satellite became "alive" again, the expensive primary ground station was activated and commands were again initiated with the satellite. More failure analysis could now be accomplished along with the continuing its mission.

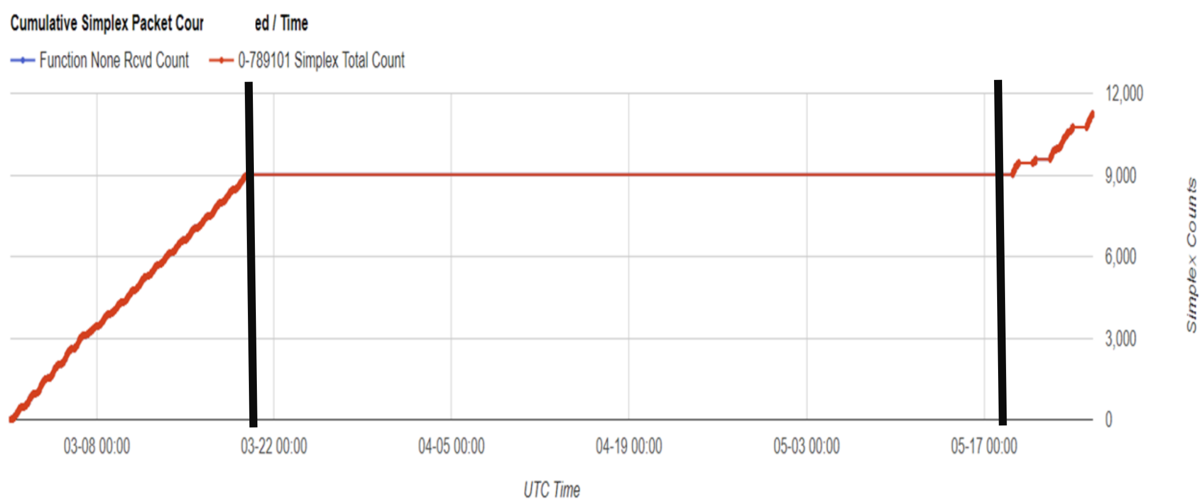


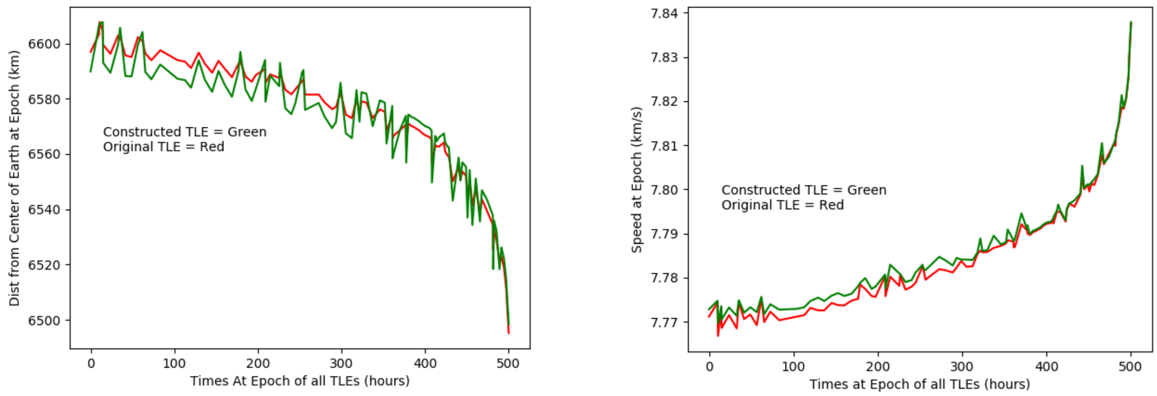
Fig. 11. Surprise turn-on of a "dead" satellite after a 2-month delay.

7.0 SUMMARY OF CONVERTING GPS ORBITAL ELEMENTS TO TWO LINE ELEMENTS (TLEs)

7.1 Orbital elements

The main objective of this section's analysis is to see how accurately and quickly one can map *in situ* GPS orbital elements and ID into TLEs for the 18th Squadron and payload team. Starting with the satellite GPS time, position and velocity vectors the TLE parameters are derived: Argument of Perigee, Eccentricity, Inclination, Right Ascension of Ascending Node, Mean Anomaly, and Mean Motion of a decaying LEO satellite. The implemented testing method uses a sample size of 101 TLEs from LEO satellite 'GOCE 34602U' [7]. Position and Velocity at time of epoch for each TLE were extracted using Skyfield's SGP4 [8] location predicting software. The LEO satellite 'GOCE 34602U' had an average altitude of 215 km and was known to be in freefall and de-orbiting in the 21 days during which the TLEs were extracted. The position and velocity vectors from the TLEs act as an artificial starting point (simulating real values transmitted from the satellite in orbit), and the goal was to generate orbital elements that match, within a certain degree of error, the respective orbital elements in the original TLE.

The results of three of the individual orbital elements – Mean Motion, Inclination and Right Ascension of Ascending Node – consistently have very small relative errors (typically of order 0.2 %, 0.04% and 0.06%, respectively), which means that the original TLE orbital values and the Skyfield-produced orbital values agree very closely. The Argument of Perigee, Eccentricity and Mean Anomaly values show significant relative error between the original values in the TLEs and those that are generated using Skyfield from the positions and velocities determined from the TLEs. These differences may be due to the small value of the eccentricity for the GOCE satellite. Furthermore, the errors in the Argument of Perigee and Mean Anomaly are highly correlated, as one might expect.



Figs. 12 & 13. Position and Speed at Epoch of original TLEs vs. Constructed TLEs

Despite the error in Perigee, Eccentricity and Mean Anomaly, the validity of the constructed TLE calculated from just position and velocity vectors and time is proven to be accurate, which is displayed in Figures 1 & 2. Skyfield has a method 'sat model propagator,' which takes in a time as a parameter and returns the predicted position and velocity vectors of the satellite at that time. Figures 12 & 13 demonstrate the similarity of the velocity and position vectors between the original TLEs and our calculated TLEs at Epoch. Figures 12 & 13 are proof that is it possible to make sophisticated orbital predictions using Skyfield software (which implements the SGP4 prediction algorithm) using just position and velocity vectors with the timestamp of when these values were recorded as a starting point.

7.2 TLE Decay Parameter Prediction in LEO

In predicting the orbit of a decaying satellite in LEO, the method currently used to predict the orbit from its TLE's does not properly account for orbital decay effects. Data from the satellite 'GOCE 34602U' was used during its drastic orbital decay period and the Skyfield Python library to propagate each TLE. In Fig. 13 one can quickly see the need for a better predictive method during this deorbit period.

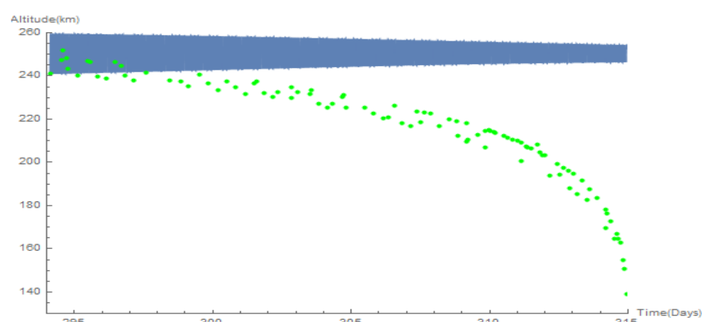


Fig. 13. Propagation of first TLE (Blue) and set of all altitudes from TLEs (Green) vs. time.

In previous work, the equations for motion were derived for a satellite in orbit around an oblate spheroid experiencing an altitude-dependent drag force. These equations take the form:

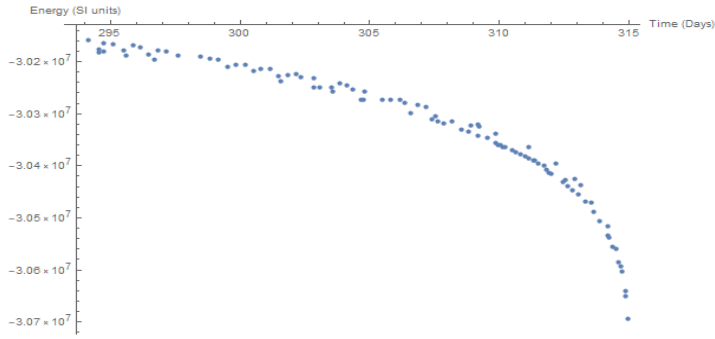


Fig. 14. Energy of satellite per unit mass vs. time.

Equation (1)

$$r: -\frac{GM_E}{r^2} + \frac{3\epsilon a^2 GM_E(-1+3\cos^2\theta)}{5r^4} - \gamma\rho(r-R)\dot{r}\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = \ddot{r} - r\dot{\phi}^2\sin^2\theta - r\dot{\theta}^2$$

Equation (2)

$$\theta: \frac{6\epsilon a^2 GM_E\cos\theta\sin\theta}{5r^4} - \gamma\rho(r-R)r\dot{\theta}\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = r\ddot{\theta} + 2\dot{r}\dot{\theta} - r\dot{\phi}\sin\theta\cos\theta$$

Equation (3)

$$\phi: -\gamma\rho(r-R)r\dot{\phi}\sin\theta\sqrt{\dot{r}^2 + (r\dot{\phi}\sin\theta)^2 + (r\dot{\theta})^2} = r\ddot{\phi}\sin\theta + 2\dot{r}\dot{\phi}\sin\theta + 2r\dot{\theta}\dot{\phi}\cos\theta$$

This is a set of coupled differential equations that comprise the primitive model of the satellite motion. This model incorporates a uniform density oblate spheroid gravitational model [9] for the earth as well as an altitude-dependent drag term. Given an initial condition, one can propagate the satellite forward by using a numerical differential equation solver. However, one must first determine the value of γ, which characterizes the drag on the satellite. The determination of γ is the majority of the effort to determine the orbit.

This drag term appears in the equations of motion as: **Equation (4)**

$$\boldsymbol{F_{drag} = -\gamma\rho(r - R_{Earth})v\vec{v}}$$

Where ρ is an empirically determined altitude-dependent density function, $\vec{v}$ is the velocity, and γ is a constant that is to be determined, which is proportional to the TLE BSTAR term [10]. With this and an initial condition, one can use a numerical ODE solver to propagate the position and velocity of the satellite forward in time. To calculate γ, one considers the energy per unit mass of the satellite in time. From each TLE, one can extract the altitude and velocity and calculate the energy of the orbit. **Equation (5)**

$$\boldsymbol{\frac{E}{m} = \frac{T+V}{m} = \frac{1}{2}v^2 - \frac{GM}{r} + \frac{2}{5}\frac{GMa^2\epsilon}{r^3}P_2(\cos\theta)}$$

Plotting this in Fig. 14, it is clear that E/m diminishes in time due to the drag.

In addition to this, one can also calculate the energy loss by performing a line integral of the drag force (without the γ term) along the orbit. Finally, one can perform a χ^2 fitting of the line to determine the scalar factor γ. When performing this calculation for the GOCE 34602U satellite, one finds a value of **Equation (6)**

$$\boldsymbol{\gamma = 4.0916 \times 10^{-4}\,\frac{m^2}{kg}}$$

Visually, one can verify the adequate value of γ in Fig. 15.

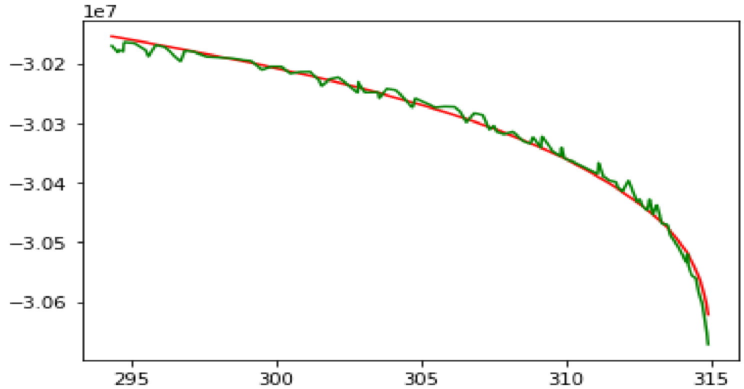


Fig. 15. Energy per unit mass from TLEs (green) and energy from drag (red) (SI Units) vs. time (Days).

8.0 ACKNOWLEDGMENTS

We would like to thank the AFWERX SBIR and AFRL KAFB Lab for their investment, enthusiasm, and many telecom meetings. We also thank many people in the 18th squadron for their help in specifying the TLE format for the catalog. Mr. Mike Miller was instrumental with the Black Box and ThinSat licensing requirements with FCC, NTIA, and Globalstar. As a partner, Globalstar engineers have been helpful in optimizing the EyeStar radios. We also thank Virginia Space (VS) and Twiggs Space Lab (TSL) for their funding and management of the 60 ThinSat satellite constellation (similar to a Black Box). Also, NASA Space Grant and NSL internal funds helped with STEM student activities related to testing the ThinSats and Black Box sub-systems.

REFERENCES

1. Voss, H., Dailey, J. and White, A. " 'Black Box' Beacon for Mission Success, Insurance, and Debris Mitigation," in Proceedings of the AIAA/USU Conference on Small Satellites`, SSC18-PII-11, Logan, UT, August 2018.
2. Gould, A. J. and Linden, O. M. "Estimating Satellite Insurance Liabilities," Available at www.casact.org/pubs/forum/00fforum/00ff047.pdf
3. Twiggs, R., Zucherman, A., Bujold, E., Counts, N., Colman, C. and Garcia, J. L. "The ThinSat Program: Flight Opportunities for Education, Research, and Industry, In this Proceedings of the AIAA/USU Conference on Small Satellites, SSC18-WKIX-05, Logan, UT, August 2018.
4. Voss, H., Dailey, J., Orvis, M., Voss, M., White, A., Shradler, B., Twiggs, R., Craft, M., Diamshidpour, A., Brandle, S., Kiers, K., Pugsley, J. and Bowser, I. "Architecture & Manufacture for 1/7U to 27U 60 ThinSat Constellations: Flight Results..," in Proceedings of the AIAA/USU Conference on Small Satellites, SSC19-S2-08SSC, Logan, UT, August 2019.
5. Voss, H., Dailey, J., Crowley, J., Bennet, B. and White, A., "TSAT Globalstar ELaNa-5 Extremely Low-Earth Orbit (ELEO) Satellite," in Proceedings of the AIAA/USU Conference on Small Satellites, SSC14-WK-6, Logan, UT, August 2015.
6. Voss, H., Dailey, J. and White, A. "Globalstar Link: From Reentry Altitude and Beyond," in Proceedings of the AIAA/USU Conference on Small Satellites, SSC16-WK-11, Logan, UT, August 2015.
7. Wikipedia contributors. "Gravity Field and Steady-State Ocean Circulation Explorer." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 27 Sep. 2019. Web. 18 Nov. 2019.
8. "Skyfield: Elegant Astronomy for Python," Available at https://rhodesmill.org/skyfield, accessed 18 November 2019.
9. Fitzpatrick, R. "Potential Outside a Uniform Spheroid," Available at http://farside.ph.utexas.edu/teaching/336k/Newtonhtml/node108.html, accessed 18 November 2019
10. Wikipedia contributors. "BSTAR." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 23 Apr. 2019. Web. 18 Nov. 2019.