“Black Box” Beacon for Mission Success, Insurance, and Debris Mitigation

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ABSTRACT
The recent demonstration of the Globalstar network for robust satellite links (Anywhere & Anytime with 24/7 global coverage) permits new ways for improving mission success, improving failure analysis, and accurately tracking orbital debris of inactive satellites. To date, the Globalstar link has a 100% success rate in orbit with 14 of 14 orbital flights since 2014 verified. The proposed “Black Box” solution for satellites allows for a small and autonomous low-data rate link with key diagnostic information. Even if the subject satellite is partially or completely dead with the small Black Box the attitude, voltages, currents, GPS, temperatures, and camera data can be downloaded in near real-time for critical corrective action and for understanding a failure path. The proposed Black Box comes in three sizes with respective capabilities and options: A miniature “Patch” for side wall mounting (10 x 8.5 X 1.5 cm), a PC104 board for internal “Stack” mount, and a larger “Barnacle” Box for larger satellites. The Black Box can be qualified for short, medium and long lifetimes. Most of the Black Box subsystems are at TRL=9 with orbit performance.

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”, about the size of a smartphone, 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 Figure 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 beacon 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.

Figure 1: Side Mounted “Patch” Black Box Model (10 x 8.5 X 1.5 cm). Top surface shows three antennas for TX, RX, & GPS, 5 solar cells, and a 64-pixel grid array.
BLACK BOX SYSTEM DIAGRAM

The Basic Black Box System diagram is shown in Figure 2. The EyeStar radio product (dashed box) is shown with the additional Black Box systems. Power is generated from five solar cells for low-rate beacon transmissions and higher rates if the external spacecraft power is available or extra battery. The Grid IR array is 8 by 8 pixels and is used as a Horizon sensor and/or a crude imager to verify deployments and/or view earth/sun. Other options for the 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. Insurance underwriters and safety directors have much less risk and ability to assign failure with detailed Black Box assessment data. Educators also benefit greatly when students receive continuous satellite status data hours before the satellite makes first contact with a ground station, or still receive reduced data for an otherwise dead-link satellite.

Figure 3: Thin “Patch” Black Box located within 1U on the side of a 3U CubeSat.
MECHANICAL CONFIGURATIONS

Figure 3 shows the thin Patch configuration that was designed to 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 custom packaging. Figure 4 shows the 1) Thin Patch Black Box for side mounting, 2) Black Box PC104 for internal Stack mounting, and 3) “Barnacle” Black Box for larger Satellites. Figure 5 Shows a detailed mechanical assembly drawing of the Patch Black Box system.

Figure 4a: Thin Patch Black Box for Side Mounting
Figure 4b: PC104 Black Box for Internal Stack Mounting
Figure 4c: “Barnacle” Black Box for larger Satellites: Solar Array and Antennas not shown

Figure 5: Sidewall Patch Black Box Assembly diagram
A summary Table 1 is included to compare the main features of the three standard Black Box configurations.

**THINSAT HERITAGE FOR BLACK BOX**

The TSAT and GEARRS 1 and 2 Sats pioneered the CubeSat – NSL/Globalstar communication network for global and real-time (low latency) visibility of satellites with no required CubeSat ground stations $^1,^2$. With mass production and the miniaturization of electronics and mechanisms very low cost and powerful ThinSats can be manufactured (Figure 6). The ThinSat is ideal for STEM learning, Research applications, and exploring the new region from 100 to 350 km for climate, ionospheric and DOD discovery with little worry for orbital debris problems because of short lifetimes ($<$ 1 month)$^3$.

![ThinSat components](image)

**Figure 6**: 60 ThinSats are manifested for launch in fall 2018. Each ThinSat Mothership is very 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 7075 frames. One CSD canister launches 21 ThinSats at a time.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Patch Black Box</th>
<th>PC104 Black Box</th>
<th>Barnacle Black Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size L x W x H</td>
<td>cm</td>
<td>10 x 8.3 x 1.45</td>
<td>9.6 x 9.0 x 2.1</td>
<td>13 x 13.8 x 4.4</td>
</tr>
<tr>
<td>Mass</td>
<td>g</td>
<td>125</td>
<td>125</td>
<td>990</td>
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<td>Battery Voltage</td>
<td>V</td>
<td>3.7</td>
<td>3.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>A-hrs</td>
<td>2.2</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Solar Area</td>
<td>cm^2</td>
<td>42.75</td>
<td>N/A</td>
<td>102.6</td>
</tr>
<tr>
<td>Simplex Beacon</td>
<td>Bytes/s</td>
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<td>1</td>
<td>8</td>
</tr>
<tr>
<td>IMU, Mag./Accel/ Gyro</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>6 Analog Inputs</td>
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<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Voltage &amp; Temp</td>
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<td>Yes</td>
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<tr>
<td>Inhibits</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Options**

| Lifespan                    |       | 1,2,5          | 1,2,5,10,20     | 1,2,5,10,20       |
| Receiver                    | RF On/Off | RF On/Off     | RF On/Off      | Commands          |
| IR Horizon Sensor           | 8 by 8 Grid | 8 by 8 Grid | 8 by 8 Grid | 8 by 8 Grid |
| Dose - Particle radiation   | KeV   | >40           | >40            | >40              |
| Camera                      | Pixels | N/A           | N/A            | 128x96           |
| e- Plasma Probe, Density    | e-/cm^3 | 100-10^7     | 100-10^7       | 100-10^7         |
GLOBALSTAR 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\(^1\,^2\). 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 like 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.

![Figure 7: Globalstar constellation of satellites for Global coverage and real-time 24/7 visibility.](image)

In Figure 7 the Globalstar constellation is shown giving 24/7 connectivity to many 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

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 gateways, 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.

DATA OPERATIONS

The NSL ground station technology (Figure 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.

![Figure 8: Overall Communications Architecture.](image)

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 15 seconds.

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Figure 9 Web Console Simplex Telemetry Display.

For those who desire, the NSL web console (Figure 9) permits viewing, graphing, zooming, translation, and downloading Simplex telemetry data (commonly 18 or 36 Bytes per packet). 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 real time satellite position plotting on maps is also available using the web console.

GLOBALSTAR LINK PERFORMANCE

The Globalstar Simplex link beacon for the Black Box has performed well on fourteen professional EyeStar communication systems since 2014 with 100% reliability (14 for 14 mission success) with an associated ground segment. The low power EyeStar simplex communication systems have been tested between reentry at 110 km to over 750 km in altitude and have a TRL=9. Over 70 satellites with EyeStar simplex units are manifested for 2018. Some other advantages of the EyeStar simplex radios and the Black Box include: no new ground station required, simple fixed 25 mm square patch antenna, it operates well on a tumbling satellite, and a typical data latency through the communications network to the internet of several seconds.

In Figure 10, Simplex raw data packets received shows the unweighted but still very uniform coverage. Note some of the weaker coverage areas over the Pacific Ocean. Detail coverage of the Simplex unit is discussed in reference 2.

In Figure 11 is an 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 11) 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 10: Simplex Coverage maps show good global coverage. Red dots show packet transmission.

Figure 11: Black Box Particle Detector option: Dose Coverage option for Black Box
BLACK BOX EXAMPLE OF EYESTAR RADIO

Figure 12 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 as usually in the case for redundancy to the flight battery/array if the main processor or other systems fail). In Figure 12 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 master powering up the EyeStar radio and little data was available for understating the failure. However, at marker 2 the NSL console lit up again with simplex packets restored. More failure analysis could now be accomplished along with more valuable data. The Globalstar ground station was always active after the satellite was thought dead and no Globalstar data cost 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.

**SUMMARY:**

Globalstar Simplex units have been fully demonstrated in space and have the potential as a game changer using a low cost, small, and independent Black Box link if adopted for new satellites. This low power and independent Black Box link ensures mission success, minimizes orbital debris collision with more accurate tracking predictions (JSpOC) from GPS, and greatly improves failure analysis visibility for correcting future designs and assigning insurance risk (Actuarial Considerations) for improved subsystem assessments. ThinSats use common components for the Black Box and are similar in size. Sixty ThinSats are planned for orbital launch this year on an Orbital ATK ride and one Barnacle Black Box system is planned for launch this year as well3.

**ACKNOWLEDGMENTS**

We would like to thank Virginia Space (VS) and Twiggs Space Lab (TSL) for their funding and management of the 60 ThinSat satellites (very similar to a Black Box) manifested for launch and testing this year in a unique constellation. Also, NASA Space Grant and NSL internal funds helped with STEM student activities related to testing the ThinSats and Black Box Sub-Systems.

**REFERENCES**