ID, GPS Tracking, 24/7 Tag Link for CubeSats and Constellations: Flight Results

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ABSTRACT

The tiny 40-gram EyeStar-Tag processor, GPS, and radio link will ID its satellite with GPS and critical status data within a minute after turn-on. The autonomous low power EyeStar Tag GPS (20mW for 3D lock) is now at TRL-9 based on the successful release and operation of the Spaceflight Inc. ring on the 1/24/2021 rideshare launch. The orbit (530 km polar) was projected using GPS seven element arrays to generate, on the fly, the future ephemeris predictions while monitoring critical flight systems. The Tag continues to transmit over the Globalstar network of satellites and ground stations the GPS elements and status with low latency of seconds, even if the primary satellite fails or stops. Whether dead or alive, orbital elements and TLEs for debris tracking, attitude, and ID are available to the 18th Squadron. AFWERX’s SBIR investment helped fast track the Black Box and Tag systems. Key enablers and new architecture are flight referenced for 30 ThinSat constellation launched in February 2021 NG-15.

With the Globalstar constellation NSL 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 (110+ 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, commercial, and STEM 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 Telemetry Tracking and Command (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 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 altitude known. If the satellite reawakens after some long failure, the Black Box reports the new status, and the satellite may be reactivated. NSL customers have experienced this wake-up mode after a year on one of our Black Box/EyeStar communication processors after an unexpected two-month “dead” phase and wake. The “dead” satellite was reactivated.
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 Black Box System. The objective is to ID Satellites, provided critical 24/7 health and safety and lower conjunction areas (Fig. 2 & Fig. 3).

2.0 Black Box System DIAGRAMS

The basic Black Box System Diagram is shown in Fig. 4. 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 a Horizon Sensor. Other options for the Black Box include a) a high sensitivity, low bandwidth imager to snapshot internal or external mechanisms, b) encryption, c) additional mission specific sensors, d) various sizes and e) quality control testing levels.

Fig. 2. The ellipse represents collision cross-sections. Gray area represents intersection of two satellites without beacon GPS conjunction boxes.

Fig. 3. Example of three satellites. Sat B and C shows conjunction shrinking due to GPS Beacon Black Box. The ellipses represent collision cross-sections.

Fig. 1a. Flight Side Mounted “Patch” Black Box Model (10 x 8.3 x 0.85 cm, quarter, on left). Top surface shows two patch antennas for TX and RX, & one small GPS antenna, 4 solar cells, dose, and a 256-pixel grid IR. Fig.1b. EyeStar Tag picture on right (5.6 x 2.7 x 0.9) provides the EyeStar S3 and GPS 24/7 beacon.
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 0.222 MBytes per day or 17 bytes per 7 seconds. 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.

### 3.0 MECHANICAL CONFIGURATIONS

Figure 5 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 custom packaging. Figure 7 shows: a) EyeStar Tag the lowest SWaP-C of three units b) Thin Patch Black Box for side mounting, and c) Standard Black Box for larger satellites. Table 1 shows a further detail information of the Black Box systems.

![Fig. 4. System Block Diagram of general Black Box subsystems. The dashed-in boxes are the EyeStar radio.](image)

![Fig. 5 Comparison of Black Box systems Standard, Patch and EyeStar Tag on 6U CubeSat frame](image)

![Fig. 6. 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.](image)
The Black Box technology has evolved from the ThinSat production line which has embraced mass production and the miniaturization of electronics and mechanisms (Fig. 8). 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 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 AND EYESSTAR PARADIGM

A new paradigm was ushered in by TSAT, GARRS1, and GARRS2 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.

In Fig. 9, 10, and 11 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. 10) 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.
For those who desire, the NSL web console (Fig. 12) 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 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 100 commercial EyeStar communication systems since 2014 with 100% reliability (all mission success) with an associated ground segment.

The low-power EyeStar Simplex communication systems have been tested between 750 km in altitude to reentry at 110 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. 13 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. 13) are uniform over the entire earth with a weaker coverage area in the Pacific Ocean. The 53 deg. latitude cutoff is due to the Globalstar link.
6.0 BLACK BOX EXAMPLE OF EYESTAR RADIO

Figure 14 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.

7.0 SUMMARY OF CONVERTING GPS ORBITAL ELEMENTS TO TWO LINE ELEMENTS (TLE) AND EPHemeris

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.

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 15 & 16. 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 15 & 16 demonstrate the similarity of the velocity and position vectors between the original TLEs and our calculated TLEs at Epoch. Figures 15 & 16 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.

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:

\[
\mathbf{r} = \frac{GM_E}{r^2} + \frac{3e a^2 G M_E (-1 + 3 \cos^2 \theta)}{5r^4} - \gamma p(r) - \frac{1}{2} \gamma (\gamma - 1) \left( \frac{j^2}{r} + (r \dot{\phi} \sin \theta)^2 + (r \dot{\theta})^2 \right) - \frac{1}{2} (\dot{r} - r \dot{\phi}^2 \sin \theta - \dot{r} \theta^2)
\]

\[
\theta = \frac{6e a^2 GM_E \cos \theta \sin \theta}{5r^4} - \gamma p(r) - \frac{1}{2} \gamma (\gamma - 1) \left( \frac{j^2}{r} + (r \dot{\phi} \sin \theta)^2 + (r \dot{\theta})^2 \right) - \frac{1}{2} (\dot{r} \dot{\theta} - r \dot{\phi} \sin \theta \cos \theta)
\]

\[
\dot{\phi} = -\gamma p(r - R) r \dot{\phi} \sin \theta \sqrt{j^2 + (r \phi \sin \theta)^2 + (r \dot{\theta})^2} + r \dot{\phi} \sin \theta + 2r \dot{\phi} \sin \theta + 2r \dot{\theta} \dot{\phi} \cos \theta
\]

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 \( \gamma \).
which characterizes the drag on the satellite. The determination of \( \gamma \) is the majority of the effort to determine the orbit.

This drag term appears in the equations of motion as:

**Equation (4)**

\[
F_{\text{drag}} = -\gamma \rho (r - R_{\text{Earth}}) v \vec{v}
\]

Where \( \rho \) is an empirically determined altitude-dependent density function, \( \vec{v} \) is the velocity, and \( \gamma \) 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 \( \gamma \), 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)**

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

Plotting this in Fig. 17, 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 \( \gamma \) term) along the orbit. Finally, one can perform a \( \chi^2 \) fitting of the line to determine the scalar factor \( \gamma \). When performing this calculation for the GOCE 34602U satellite, one finds a value of

**Equation (6)**

\[
\gamma = 4.0916 \times 10^{-4} \frac{m^2}{kg}
\]

Visually, one can verify the adequate value of \( \gamma \) in Fig. 17.

**7.2 Flight Results of TagSat-1**

TagSat-1 was hosted on Spaceflight Sherpa-FX ring launched via SpaceX’s Transporter-1 on January 24, 2021.

Taking two data points from TagSat-1 as a test data set. These points are:

1. the insertion data (from January 24, 2021), and
2. the “six-satellite-lock” GPS data point that occurred on Feb. 9, 2021, about 16 days later.

For both data sets we have a time stamp, as well as a position and velocity in the ECEF (earth-centered, earth-fixed) coordinate system. After analyzes of data using AI Solutions FreeFlyer as follows:

1. team has propagated the satellite’s orbit forward in time from the insertion point to the GPS measurement, using the insertion data as our starting point.
2. We have propagated the satellite’s orbit backward in time from the GPS measurement to the insertion point, using the GPS data point on day 16 as our starting point.

The overall result is that evolving the orbit forward by 16 days from the insertion data point seems to give us a very accurate picture of the state of the satellite at the time when the GPS measurement is made. Evolving the orbit backward in time by 16 days from the GPS measurement seems to give us a less accurate picture of the state of the satellite at the time when the insertion measurement were made.

There are plots for latitude, longitude, altitude, \( v_x \), \( v_y \) and \( v_z \) at 16 days later, when the GPS measurement occurred. Figure 18, 19, 20 show results.

In these plots:

- red dots ==> FreeFlyer orbit, propagated forward from insertion data point
- black dots ==> FreeFlyer orbit, propagated backward from GPS data point (which was on day 16)
- solid lines ==> calculation, obtained by solving a differential equation in Mathematica, propagated forward (blue) or backward (green) from from the insertion point or GPS point, respectively

As you can see, the orbit propagated forward in time (red dots) is still very accurate after 16 days — the red dots line up quite well with the curve and with the black dots.
In review, the TagSat-1 flight was considered a mission success but requires further calibration regarding velocity. TagSat-2 manifested for June 25, 2021 and TagSat-3 manifested for December 1, 2021 will be used to further Black Box/EyeStar Tag optimization and commercialization.

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