**BurstCube Data Caveats**

**July 22,2025**

BurstCube was deployed from the ISS on April 18, 2024, and reentered the Earth's atmosphere on September 16, 2024. Its 5 months of operations included spacecraft and instrument commissioning but faced unexpected challenges due to hardware failures or poor performance in the solar array, GPS, attitude determination and control system (ADCS), and expected noise in the low-energy channels of the instrument. This led to difficulties in determining the orientation of the spacecraft and instrument, and uncertainties in the absolute timing of the data. A detailed description of the on-orbit challenges is in Perkins et al. (2025), and the caveats associated with the data are described below.

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1. **Attitude Information**

   Due to onboard hardware issues with ADCS, spacecraft attitude information is not available in most of the public archive. Limited intervals of attitude information for candidate transients have been manually reconstructed with ADCS telemetry when the spacecraft was in Sunlight and had good data. These datasets have attitude files in the HEASARC archive and are described in Myers et al. (2025).

   The BurstCube instrument response functions are in a reference frame relative to the spacecraft coordinates. When attitude information is available, these can be used to determine localizations in sky coordinates. When attitude information is not available, it is not possible to reconstruct the position of a source on the sky.

2. **Orbit Files**

   Orbit files were reconstructed from publicly available Two-line Element (TLE) files for BurstCube (NORAD Catalog ID 59562). They span the full duration of the on-orbit lifetime, even if the archive data does not span that full range because the instrument only operated for a subset of that time. Due to uncertainties in Timing (see Caveat #11), there may be unknown offsets between MET time in the data files (CBD/HK/TTE) and the orbit files. The uncertainties in those offsets are characterized by the TIME_ERROR columns in the data files. Orbit file time is more accurate and independent of the spacecraft or instrument clocks.

3. **Unphysical Detector Counts**

   There were intervals during on-orbit operations where the BurstCube instrument was on, but not in a fully operational state with all switches enabled. Some of this was due to commissioning activities and other times due to issues with fault detection and correction processes. When the instrument was in this off-nominal state, there was data produced, but with unphysical detector counts in HK and CBD set to either 0 or extremely high values. These intervals have been captured in the GTIs, and are filtered out in the cleaned files.
   There are also intervals with anomalous rates varying over thousands of seconds with scatter between low and high values. The physical origin of this behavior is undetermined, and they are not filtered in the GTIs.

4. **TTE Intervals**
   Operational challenges during commissioning delayed nominal instrument operations including the generation of TTE. Towards the end of the mission, TTE data and triggering were enabled. Triggering was being tuned, but no onboard astronomical triggers were detected, and therefore no associated TTE was downlinked. However, a small set of 34 100-second duration TTE files were downlinked for commissioning and instrument validation. Those files are available in the archive in the corresponding daily datasets.

5. **TTE Data**
   TTE times for day 15 August 2025 do not align properly with the TTE collection window established by the data timeline. While the goal is to have the root cause identified and resolved in a future reprocessing, please bear in mind that times for the collected data may be subject to a non-zero offset in addition to listed time corrections.

## 6. BurstCube Instrument Timeline

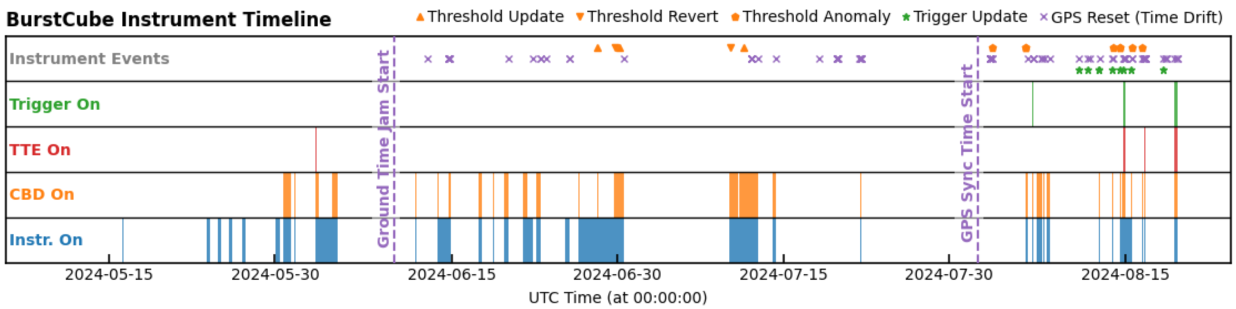


*Figure 1: BurstCube Instrument Timeline denoting important instrument events including when the instrument was on, when enabling data types, updating thresholds and triggering. The detailed timeline of events is available in a time sequence of events.*

Due to BurstCube spacecraft anomalies and emergencies, and lower than anticipated downlink rates, BurstCube was not able to consistently recover all instrument and spacecraft data. As such, it is not possible to recreate an as-flown mission timeline given the lack of data. The timeline we present is the best possible reconstruction given the data successfully downlinked.

Spacecraft electrical power system (EPS) Packets and Instrument Housekeeping packets are primarily used to regenerate the mission timeline. The mission timeline was reconstructed with different packet types with different arrival cadences and times. Typically, spacecraft housekeeping data, used to reconstruct instrument on/off status arrives at a lower cadence than the instrument housekeeping data that was used to reconstruct CBD, TTE, and Trigger status.

Therefore, the written mission timeline may have events that appear out of order by several seconds when several events from different data packet types occur at nearly the same time.

For example, the written timeline table may show that the instrument has been turned off before the CBD science packet generation stops due to additional instrument housekeeping packets arriving between the two spacecraft packets that capture the instrument state.

Packet cadences also change several times throughout the mission to better match available data downlink rates.

## 7. Instrument Detector Threshold Adjustments

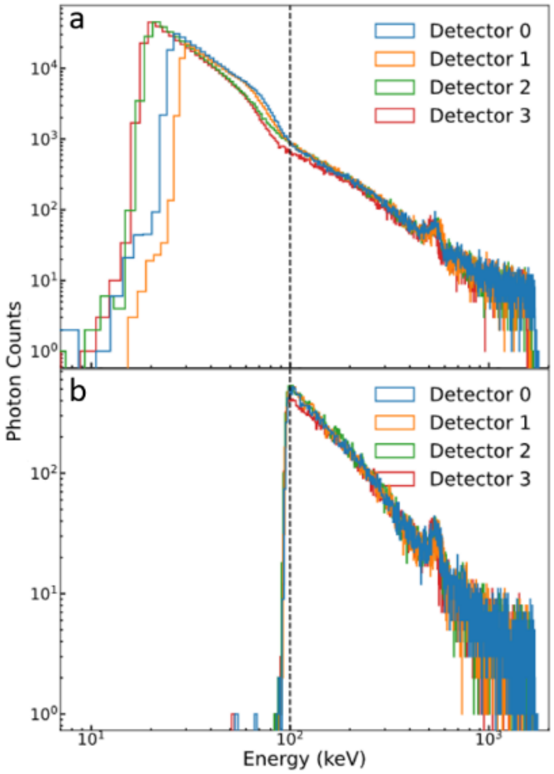


*Figure 2: instrument energy spectra before (a) and after (b) threshold update.*

| Detector Head | Default Threshold (keV) | Updated Threshold (keV) |
|---|---|---|
| **Detector 0** | 26.93 | 100.12 |
| **Detector 1** | 30.33 | 99.73 |
| **Detector 2** | 21.40 | 99.41 |
| **Detector 3** | 20.30 | 99.45 |

*Table 1: Detector energy thresholds before and after adjustment.*

Early in on-orbit operations, the instrument demonstrated a non-Poissonnian noise component. It was determined that by increasing each of the four instrument detector head's energy thresholds to ~100 keV, that this noisy component could be suppressed (Fig 2).

This threshold correction was tested several times in a temporary fashion before making the change permanent. This resulted in several days of operation where the instrument would have "**Updated"** thresholds (Fig 2b) before "**Reverting**" back to (Fig 2a). The energy thresholds are before and after adjustment are listed in Tab 1.

### 7.1 Anomalous Instrument Thresholds

Towards the end of the mission there are several anomalous mission times where for handfuls of seconds the instrument thresholds were not set properly (Fig 1, orange pentagons). It is not certain that the BurstCube instrument was collecting CBD data at these times, but photon count rates located in the fast-housekeeping data should be considered error-prone. Duration of these anomalous windows in order is 20.224s (first 3 markers), 43.52s (3 markers), and finally 7.424s (last two markers).

### 7.2 Trigger Module: Trigger Significance Thresholds

While not fully utilized during the BurstCube mission, the on-board rate threshold trigger module was successfully operated and tested. The design was to trigger onboard on rate increases in at least two detectors above the threshold in the trigger energy band, generate Alert Trigger Data (ATD), and relay the ATD files to the ground via TDRS, and distribute alerts via GCN within 15 minutes of the trigger. In testing of the trigger, the instrument repeatedly triggered every 10 minutes – the required minimum wait time between subsequent trigger. The BurstCube team tuned the trigger energy groups, timescales, and threshold to optimize triggering on astronomical events. Trigger tuning was never completed before the end of the mission.

**Trigger Energy Groups**

The BurstCube on-board trigger module evaluated potential triggers over two energy groups:

- EGROUP0 covered binned energy channels from 2 through 5 (equivalent to energies ~70 keV through 360 keV
- EGROUP1 covered binned energy channels from 3 through 14 (equivalent to energies ~125 keV through 1800 keV)

When updating threshold settings away from the default settings (A) the start channel for both EGROUP0 and EGROUP 1 where increased to 3 and 4 respectively (~125 keV and ~200 keV) to account for the increased instrument noise at low energies

**Trigger timescales**

BurstCube's trigger timescales were not modified over the course of the mission. BurstCube was set to trigger on the following eight timescales (in ms) [64, 128, 192, 256, 384, 512, 768, 1024]. Each EGROUP possessed its own independent significance thresholds for each timescale.

**Trigger Thresholds**

Three trigger module settings were attempted while BurstCube was on orbit:

- Threshold Setting A - Default significance thresholds: Both energy groups and all trigger timescales were active, with 5.3$\sigma$ for the shortest timescale and 4.5$\sigma$ for all others.
- Threshold Setting B - Best significance thresholds: Broadest energy group disabled, 8$\sigma$ for smallest timescale, 6$\sigma$ for next smallest, 5$\sigma$ for all other timescales.
- Threshold Setting C - Only briefly enabled, it had the timescale significances of Threshold Setting B but both energy groups were enabled.

Threshold setting changes specifically are called out by letter change in BurstCube mission timeline. Changes to trigger module significance threshold settings can be seen in the BurstCube Timeline (Fig 1) as green stars.

While BurstCube did not successfully trigger on any astrophysical event, the limit testing of the triggering algorithm can inform future missions utilizing rate triggers (e.g. Starburst). Note that BurstCube did detect astronomical transients in offline analyses (see Myers et al. 2025).

## 8 CBD Time Drifts

Whenever a pause occurred in the pulse-per-second (PPS) signal from the BurstCube spacecraft to the instrument, the instrument clock would improperly operate. The sub-second clock would not reset at a 1s cadence and instead roll-over at ~ 2.24s value, while the seconds clock would cease counting. This would cause moments of odd time behavior where the instrument clock would jump forward and backward for several seconds until a new PPS signal was established (Fig 3, left). Afterwards, normal clock functionality would resume.

These CBD time drifts are denoted as GPS Resets in the BurstCube Timeline (Fig 1.), as well as the full mission timeline, where the magnitude of the CBD time drift is also noted. These CBD time drifts do not alter relative CBD packet time outside of the short duration around the GPS resets.

Each CBD time drift however can accrue up to several seconds of absolute time shifts, and each re-occurring event can add additional absolute time drift. These absolute time drifts are reset on the synchronizing of the instrument clock with the spacecraft clock that occurs on spacecraft reboot, or when time is resynchronized between the instrument and spacecraft. The absolute time drift during each 25-hour or less reboot window is represented by an additive absolute time error. Note that the spacecraft conducted planned reboots every 25 hours to clear registers and reset configurations. Especially later in the mission, there were also irregular reboots.

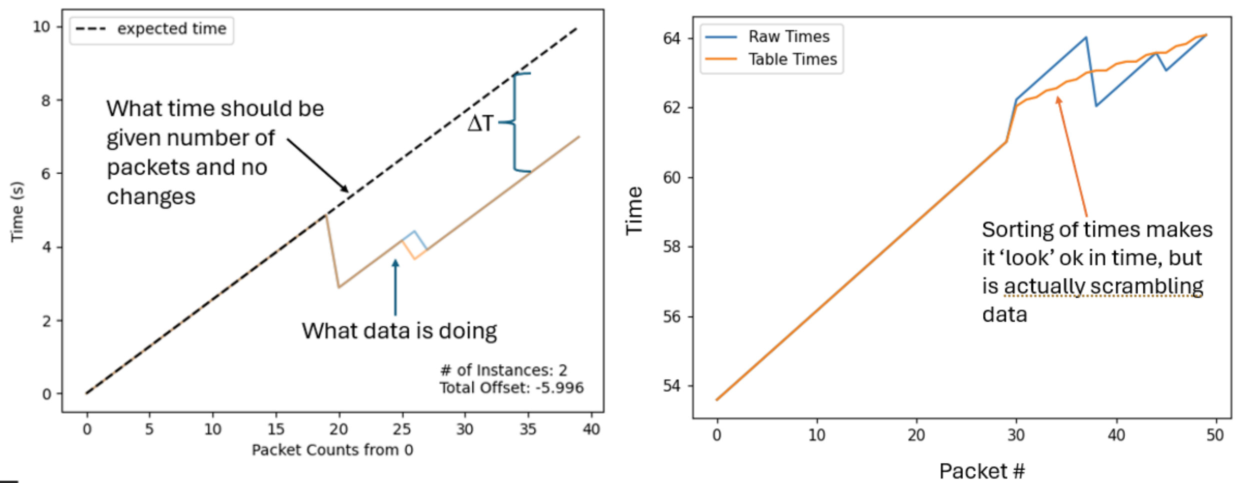


*Figure 3: Example of CBD Data blending caused by GPS switch reset.*

## 9 CBD Data Blending (Packet Cadences <0.256s)

Another unfortunate outcome of the CBD time offset is that CBD packets now overlap in time. When the pipeline rectifies the CBD data it appears as that over the affected time, CBD packet cadence has increased dramatically, but in reality, it is mixing CBD data from different time periods (Fig 3, right). Whenever CBD data is obtained with packet cadences <0.256, it should be treated with *extreme* caution. These CBD data are filtered out in the archive clean files.

## 10 CBD Bad Time Intervals

There are two types of CBD data omitted from the provided Good Time Interval (GTI) windows outside of times the instrument is in the SAA. This is when the CBD data is recorded with non-physical values representing zero counts across all detectors, or extremely high counts that could not be physical.

The periods of time where CBD packets contain zero photon counts was determined to be a software error, when shutting off the instrument. Instrument hardware power switches would be turned completely off but the on-board software flags indicating that the software should generate CBD packets were not always cleared correctly. This would result in the software continuing to generate CBD packets despite no input from the instrument itself.

During shorter periods of time, CBD packets would contain count rates that were both incredibly high and constrained to fixed-length windows of time (multiples of 30s intervals, typically 60s or 90s but in a single case as high as 690s). Root cause of this issue was not identified from on-board spacecraft messages or from the output of instrument housekeeping, but could potentially be tied to some spacecraft function that operated for a short time and introduced noise.

## 11 Time Corrections

To make the data usable for science analyses, the BurstCube pipeline corrected time in all public data products. The original as recorded time on the spacecraft/instrument (converted to MET) is listed as ORIGINAL_TIME, with the best estimate of corrected absolute time as TIME, and TIME_SYST_ERROR as the uncertainty in the correction.

Throughout the duration of the BurstCube mission, the BurstCube spacecraft's GPS did not reliably provide valid GPS positions and time. For the majority of the mission, the GPS was not utilized to set the spacecraft or instrument times due to a concern about the reliability of the time synchronization. While it was eventually determined that GPS time locks occurred frequently enough that allowing the GPS to automatically set the spacecraft time was acceptable, the frequency (at best a ~handful of times within a 25-hour spacecraft reboot window) was still infrequent enough that ground-based time-reconstruction was necessary.

### Reconstruction Methodology

Due to spacecraft packet cadences and sparsifying of stored spacecraft data packets due to data downlink volume concerns, receiving GPS packets with good validity was rare (typically less than 1 per 25 hours, or the length of a full BurstCube reboot window). However, the BurstCube flight software (FSW) would update the GPS time field within its data packets only when a valid lock was achieved. A GPS time field update within the packetized data enabled bounding a known absolute time between two spacecraft times (the packet preceding and after time GPS time field update).

Assuming that the spacecraft clock is reasonably accurate and does not drift meaningfully over the order of ~25 hours, additional GPS time field updates allow the relationship between absolute time and spacecraft time to be further bounded. Each new set of GPS times and pair of spacecraft packet times can further constrain the error bars on known absolute time (Fig 4). This methodology cannot operate across reboot boundaries, as all on-board clocks are stopped and an indeterminant amount of time passes before they are restarted, requiring a reevaluation of the relationship between GPS time and spacecraft time.

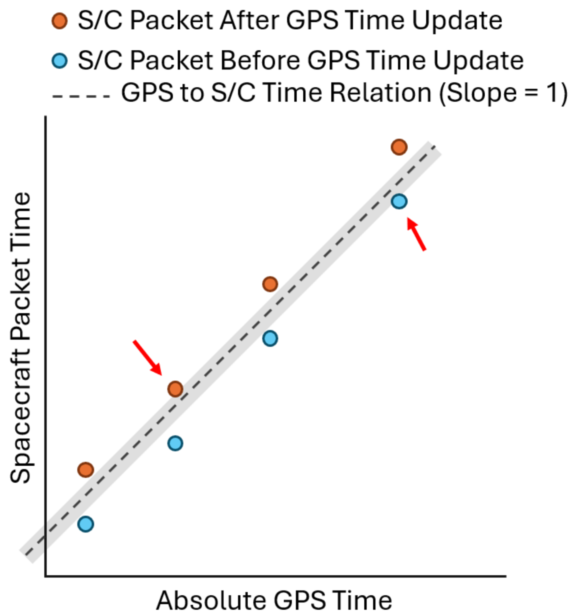


*Figure 4: Diagram depicting how ground-based time reconstruction is bounded by spacecraft packet times and multiple GPS time updates. The red arrows show the limiting points that bound the error (grey shaded region) around the true absolute time (black line).*

The BurstCube instrument clock operates independently from the BurstCube spacecraft clock. It is synchronized to the BurstCube clock when BurstCube reboots, but only later in the mission was modified to also update when the spacecraft clock is updated (whether via a command from the ground or through automatic GPS sync). Therefore, an independent time correction is necessary for the instrument clock.

Occasionally, BurstCube would reboot multiple times per day, or a GPS lock would not occur and update the GPS time field for over 25 hours. In these windows time could not be directly reconstructed.

Early in the mission lifetime, an error occurred that caused the BurstCube clock to skip forward the duration of time that had passed since BurstCube last rebooted. While this was typically ~25 hours (Fig 5), it was not always the case. Due to data gaps and high reboot frequency (and thus unknown lengths of time-jumps further obfuscating satellite on-time) early in the mission, not all data from this time period could be reconstructed.

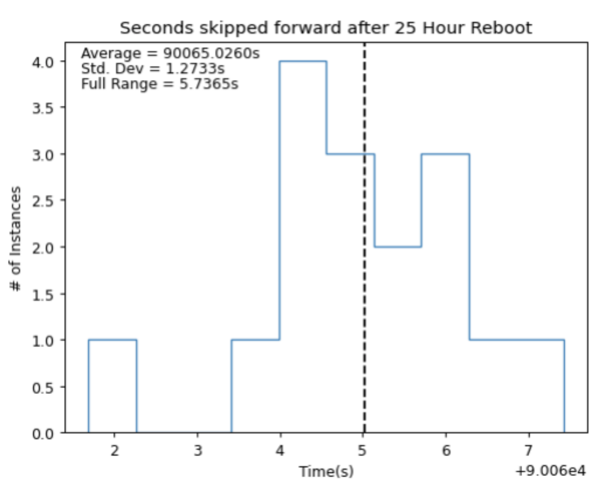


*Figure 5: Early in the BurstCube mission, a software error caused the spacecraft time to jump forward the duration of time the spacecraft experienced since the prior reboot. The variance of this time update is shown in this plot.*

After the above spacecraft time issue was corrected, the average clock drift time on spacecraft reboot was determined through comparing the time correction offset between adjacent reboot windows (Fig 6). On average, each spacecraft reboot would incur 24 +/- 4.4 seconds of clock drift. This value allowed us to reconstruct most time correction windows, albeit with larger absolute error. Additionally, using this methodology put bounds on the absolute time accuracy when jamming spacecraft time from the ground (Fig 7a). On average, resetting the spacecraft time from the ground yielded a 38.4 +/- 2.4 second offset. Note that 37 second of this are from the unaccounted-for leap second difference between UTC and TAI time epochs (as of 1 January 2017).

After on-board GPS syncing was enabled, an offset from absolute time persisted on the spacecraft (Fig 7b) albeit at a much smaller magnitude (1.5 +/- 1.0 seconds). This may be explained by the fact that when GPS synchronizes to the spacecraft clock, the FSW would only ever update the second's counter. As the GPS PPS was unreliable or likely not running at all, this means that the sub-seconds of the GPS time and the spacecraft clock are never synchronized, leading to potentially 1-2 seconds of clock drift depending on the timing of the synchronization.

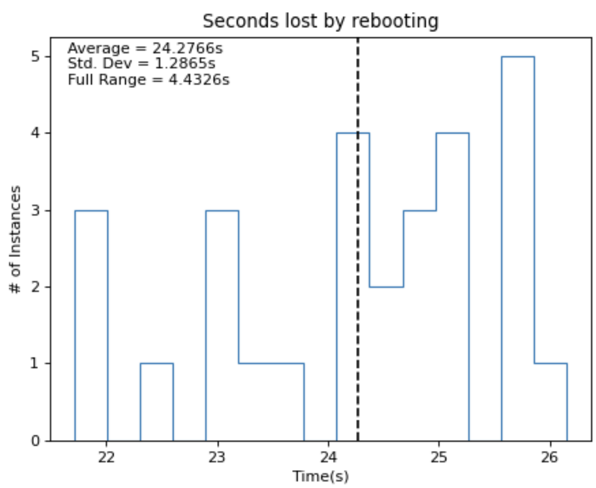


*Figure 6: The BurstCube spacecraft saved TAI time to memory on reboot, but every reboot stopped the clock from counting for an undetermined time. Time corrections include a best-attempt to reconstruct the duration of this down-time on orbit.*

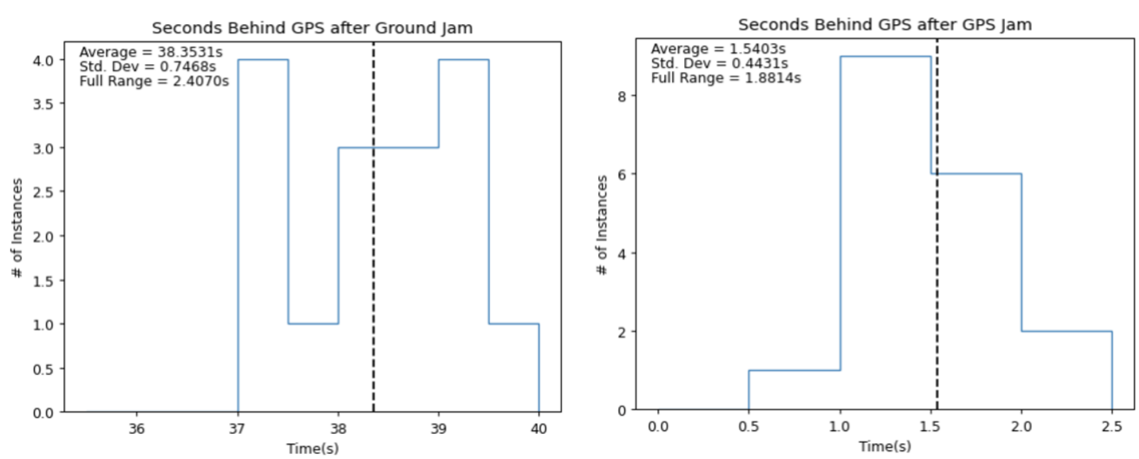


*Figure 7: During the BurstCube mission, both jamming time to the spacecraft from the ground and later automating the process with the on-board GPS unit was used. However, both methods still possessed a consistent offset from true*

*GPS time. The additional ~37s of offset introduced by jamming time from the ground is an inadvertent omission of the leap second difference between time in UTC and TAI time (37s as of 1 January 2017).*

## Acronym List

ADCS – Attitude Determination and Control System
ATD – Alert Trigger Data
CBD – Continuous Binned Data
EGROUP – Energy Group
EPS – Electrical Power System
FSW – Flight Software
GCN – General Coordinates Network
GPS – Global Positioning System
GTI – Good Time Interval
HK - Housekeeping
ISS – International Space Station
MET – Mission Elapsed Time
PPS – Pulse Per Second
S/C – Spacecraft
SAA – South Atlantic Anomaly
TAI - International Atomic Time
TDRS – Tracking Data Relay Satellite
TLE – Two Line Element
TTE – Time Tagged Event
UTC - Coordinated Universal Time