

The BurstCube Gamma-Ray Instrument: Hunting for the Largest Cosmic Explosions

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ABSTRACT

The joint detection of gravitational waves (GWs) and their electromagnetic counterparts offers critical insight into the extreme physics of binary neutron star and neutron star-black hole mergers. BurstCube was a 6U (10 x 20 x 30 cm) astrophysics CubeSat built in-house at NASA's Goddard Space Flight Center to enhance the search for GW counterparts by increasing coverage of the transient gamma-ray sky. Operating in Low Earth Orbit in 2024, the spacecraft was sensitive to the 50 keV – 1 MeV energy range and searched for short gamma-ray bursts (sGRBs) using four cesium-iodide crystal scintillators coupled to arrays of silicon photomultipliers. As the first CubeSat to utilize NASA's Tracking and Data Relay Satellite System (TDRSS), BurstCube was also capable of autonomously transmitting science alerts to the ground for rapid, multi-wavelength follow-up by other astronomical observatories, though this feature was not ultimately enabled in flight. Here, we present a high-level overview of BurstCube's science instrument, including its science goals, on-orbit operations, results, closeout, and lessons learned for future gamma-ray small satellite payloads.

INTRODUCTION

Binary neutron star (BNS) or neutron star-black hole (NSBH) mergers can produce both gravitational waves (GWs) and short gamma-ray bursts (sGRBs), which last less than 2-3s in duration but are among the most powerful and violent explosions in the universe. Detecting coincident GW-sGRB signals beyond those of the 2017 BNS merger event would provide crucial insight into the most extreme cosmic objects, phenomena, and processes, including into jet emission, merger progenitors, black hole formation, element formation, and cosmology.¹

The BurstCube mission (**Fig. 1**) aimed to enhance coverage of the transient gamma-ray sky as part of a new era of multi-messenger astronomy, supplementing existing space-based gamma-ray observatories such as *Fermi* and *Swift* to improve the probability of detecting a GRB in a coincident GW-GRB event. Built in-house at NASA Goddard Space Flight Center (GSFC), BurstCube was a 6U CubeSat observatory with a view of the full unocculted sky (i.e., 360° view where unobstructed by Earth) and sensitive to 50 keV – 1 MeV. The spacecraft's primary science goal was to detect sGRBs (at an estimated rate of ~20/year) in addition to other transient high-energy phenomena. BurstCube also had the capability to rapidly send science alerts via NASA's Tracking and Data Relay Satellite System (TDRSS) for preliminary source localization and characterization, which would then be immediately disseminated to the global astronomical community via the General Coordinates Network (GCN) for multi-wavelength follow-up.

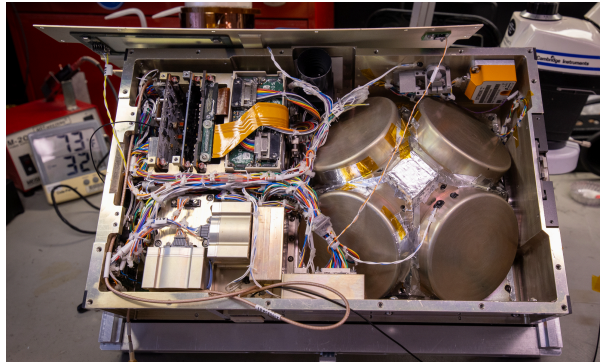


Figure 1: BurstCube with Assembled Bus Components (Left) and Science Instrument (Right).
Credit: NASA/Jeanette Kazmierczak²

Science Instrument Payload

The BurstCube science instrument was approximately 4U (10 x 20 x 20 cm) and consisted of four cylindrical 1U (10 x 10 x 10 cm) detectors) assembled in a 45° square pyramid as shown in **Figs. 1-2**. BurstCube's

detector performance was comparable to that on larger instruments, with a single BurstCube detector having ~70% effective area of a single sodium-iodide detector on *Fermi*'s Gamma-ray Burst Monitor (GBM) instrument at 100 keV.³ A GRB's relative brightness in photon rates as seen across the different detectors allowed one to approximate the location of the transient phenomenon, which drove the science need for spacecraft attitude control/knowledge; in contrast, CubeSats with only 1-2 detectors cannot localize transients.

Each BurstCube detector head (**Fig. 2**) contained a thallium-doped cesium-iodide (CsI(Tl)) scintillator crystal coupled to an array of 116 low-power, low-mass silicon photomultipliers (SiPMs) biased to ~54 V. The visible scintillation light produced by a gamma-ray photon interacting with a detector's CsI crystal was read out by the detector's SiPMs as electrical signals; these amplified signals were summed by the detector's Instrument Detector Analog Board (IDAB) to produce one analog output signal per detector head.³ A single IDAB "hit" indicated a single photon interaction, with the signal amplitude proportional to photon energy. At the base of the instrument, the four detectors were connected to a central Instrument Digital Processing Unit (IDPU) that routed power to the heads, digitized IDAB signals, and communicated with the spacecraft flight computer.

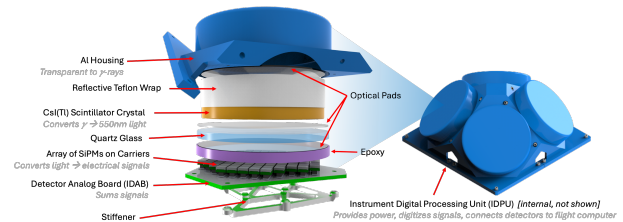


Figure 2: Exploded View of the BurstCube Science Instrument for a Single Detector Head⁴

FLIGHT OPERATIONS

On Dec. 13-14, 2023, BurstCube and another GSFC 6U CubeSat, SNoOPI (SigNals of Opportunity P-band Investigation), were delivered to Nanoracks / Voyager Space in Houston, TX for integration with the CubeSat Double-Wide Deployer System, during which the delivery teams performed final performance checkouts and battery charging. On Mar. 21, 2024, the integrated spacecraft/deployer system launched to the International Space Station (ISS) as a SpaceX Commercial Resupply Services (CRS)-30 rideshare aboard a Falcon 9 rocket. BurstCube deployed from the ISS (**Fig. 3**) into Low Earth Orbit on Apr. 18, 2024, powering on shortly afterwards for the start of spacecraft commissioning.

Through the duration of the mission, the spacecraft beamed health and safety data every 1-2h to ground via TDRSS; in addition, the team's flight operators worked with NASA's Wallops Flight Facility to support a minimum of two direct-to-Earth spacecraft passes per day, during which the flight team sent commands, uploaded flight software patches, monitored spacecraft health, downloaded new data files, and erased previously downloaded files still onboard the spacecraft. Unfortunately, the mission encountered a variety of attitude-related hardware anomalies that delayed and prolonged instrument commissioning (nominally planned to last 1-2 weeks), including commercial-off-the-shelf (COTS) reaction wheel issues as well as improper deployment (via a COTS panel release mechanism) of one solar array wing that covered the star tracker. The end of the mission was hastened by a non-optimal spacecraft attitude as well as intense solar activity, both of which contributed to high drag and faster atmosphere re-entry.



Figure 3: BurstCube (Left) and SNoOPI (Right) Deploy from the ISS, with ISS Solar Arrays in the Foreground.

Credit: NASA/Matthew Dominick⁵

Despite this, the instrument commissioning itself began smoothly starting May 16, 2024 (59th spacecraft pass), with no anomalies observed; the instrument detectors and coarse science data (Continuous Binned Data – CBD) were enabled on May 23 and May 30, respectively. High-resolution science data (Time-Tagged Events – TTE) were briefly collected and verified from May 30-June 2 and then again June 28-29, but only permanently enabled after Aug. 13 due to data management concerns amidst the mentioned spacecraft anomalies.

The instrument's science trigger algorithm for detecting GRBs and producing rapid preliminary science data (Alert Trigger Data – ATD) was enabled starting Aug. 6, with several iterations of parameter adjustments (timescale, threshold significance, energy bands) to

refine the trigger rate; during this time, science alerts through TDRSS were disabled to prevent TDRSS overuse and interference with spacecraft health beaconing. Due to the brevity of the mission and the delay with trigger enabling, all of BurstCube's triggers were likely due to background radiation – e.g., from the South Atlantic Anomaly (SAA) or polar horns – and not astrophysical in nature. While the team had thoroughly tested the capability to upload command sequences for the spacecraft to autonomously disable and re-enable triggering when entering and exiting the SAA, this feature was not executed on orbit due to BurstCube's rapid end of life.

A month before the end of the mission, the team relaxed various Science Mode operating limits such as the minimum battery voltage threshold to allow for longer instrument operation, and spacecraft commands were likewise altered to enable the instrument to stay on when known issues tripped the software fault detection and correction system. On Sep. 14, 2024, BurstCube's end of mission was officially declared five months after deployment as the spacecraft altitude decayed towards 200 km, attitude control grew increasingly difficult, and communications became spotty.

RESULTS

Analysis of science instrument on-orbit performance is currently underway, but the overall instrument behavior and performance in flight were as expected from on-ground testing. No housekeeping errors or flags were tripped, and the instrument appeared in good health throughout the mission. A reaction wheel anomaly caused the execution of a very specific combination of commands that put the instrument into an untested “intermediate” state, but the team resolved this via updates to the command sequence logic. In contrast, the team was prepared for the need to tweak on-orbit trigger settings as part of nominal commissioning, with real-time science alert beaconing being the last step if the instrument had had more on-time in flight.

The BurstCube team is currently completing the first round of science analyses and working to make the science data publicly available via NASA's High-Energy Astrophysics Science Archive Research Center (HEASARC) archive. The mission's data analysis pipeline is likewise publicly available in the form of the *bc-tools* software package, which builds on the Medium-Energy Gamma-ray Astronomy library (MEGA11b) and *Fermi*'s Gamma-ray Data Tools (GDT). The *bc-tools* package is an open-source Python library that processes BurstCube data files and generates science products that can be used for analyses, and the software can be easily adapted to other gamma-ray CubeSats.⁶

Source localization was dependent on the relative photon rates across detectors and the photon attenuation from surrounding components, which was quantified via multiple on-ground instrument calibrations performed with gamma radiation sources fixed at various angles relative to the spacecraft coordinate system. Due to issues with spacecraft attitude knowledge, however, attitude information had to be reconstructed for proper localization. The team additionally used data from other missions to assist with timing uncertainties.

The BurstCube team developed a proof-of-concept on-ground source classification algorithm, which was tested against *Fermi* trigger data that included GRBs, solar flares, particle events, and soft gamma repeaters (SGRs). The team also employed a Bayesian block time-series analysis to identify time periods during which the detector count rates were statistically above background, then searched through source catalogs of other gamma-ray instruments for possibly coincident triggers.⁶ In the latter manner, the team discovered various detected candidate events that included a GRB and a solar flare.

Detection of GRB 240629A

Upon analysis of downloaded coarse science data (CBD), the team retroactively discovered a likely detection of GRB 240629A⁷, which was a long GRB that occurred on June 29, 2024 and also seen by *Fermi*-GBM and the Space-based multi-band astronomical Variable Objects Monitor (SVOM). BurstCube's trigger feature was not yet enabled at the time of the GRB, hence the spacecraft did not produce any alert data.

LESSONS LEARNED & CONCLUSION

BurstCube set many milestones in its flight: it is the first CubeSat to communicate via TDRSS, used on many larger missions such as *Fermi*; the first CubeSat built in-house with GSFC's Astrophysics Division; and one of the first astrophysics missions to fly SiPMs, an alternative to the large photomultiplier tubes used on older missions. BurstCube additionally fostered many partnerships at GSFC and various universities, providing invaluable experience across the full mission lifecycle to scientists and engineers at all career levels. Looking forward, BurstCube contributes spaceflight heritage to StarBurst, a gamma-ray Pioneer-class mission led by NASA Marshall Space Flight Center with a launch readiness of ~2026, as well as to other high-energy detectors in development that employ SiPMs (e.g., heliophysics mission concepts to be proposed as part of NASA's Artemis Program).

From BurstCube's development and flight, it is clear that SmallSats can accomplish a great deal of cutting-edge science and technology demonstrations despite their miniature size; however, they are still full space missions

that cannot be underestimated, especially as the level of effort on many subsystems does not scale proportionally with mission size. A spacecraft's integration and test (I&T) and flight operations teams should have significant knowledge overlap and inter-team involvement during the I&T phase; in addition, while difficult to achieve on a small team (all hands on deck), it may be useful to have a designated POC during flight operations who is responsible for pass planning and personnel management but not directly performing said pass activities. Finally, the team found the TDRSS health beacons and automatic daily spacecraft reboots (which allowed for the testing of software patches as well as recovery from bad spacecraft states) to be incredibly helpful during commissioning and anomaly troubleshooting.

Acknowledgments

The BurstCube mission was funded under NASA's AstroPhysics Research & Analysis (APRA) program.

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