BurstCube: A CubeSat for Gravitational Wave Counterparts

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ABSTRACT

BurstCube aims to expand sky coverage in order to detect, localize, and rapidly disseminate information about gamma-ray bursts (GRBs). BurstCube is a '6U' CubeSat with an instrument comprised of 4 Cesium Iodide (CsI) scintillators coupled to arrays of Silicon photo-multipliers (SiPMs) and will be sensitive to gamma-rays between 50 keV and 1 MeV. BurstCube will assist current observatories, such as *Swift* and *Fermi*, in the detection of GRBs as well as provide astronomical context to gravitational wave (GW) events detected by LIGO, Virgo, and KAGRA. BurstCube is currently in its development phase with a launch readiness date in early 2022.

Keywords: gamma-ray bursts, cubesat, smallsat, gravitational waves, scintillators, silicon photo-multipliers

1. INTRODUCTION

The first joint detection of GWs by the Laser Interferometer GW Observatory (LIGO) of GW170817 and the short GRB (sGRB) GRB170817A by the Gamma-ray Burst Monitor (GBM) on-board the *Fermi* Gamma-ray Space Telescope[1] confirmed that the progenitors of sGRBs are Neutron Star-Neutron Star (NS-NS) collisions.[2] Since that discovery, other NS-NS events have been detected by the GW observatories[3] but no further coincident events have been seen. Additionally, LIGO, Virgo and KAGRA are commissioning major upgrades.[4] The

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simultaneous discovery of GW and electromagnetic signatures requires dedicated and coordinated observations by large communities of both ground and space-based observatories. Existing sensitive GRB observatories cover only $\sim 70\%$ of the sky at any one time, and any increase in sky coverage by additional facilities increases both the likelihood of coincident detection, and the number of sGRBs that can be correlated with both strong and sub-threshold GW signals.

BurstCube is a small CubeSat in the integration phase with the aim to detect and characterize sGRBs that are counterparts of GW sources. BurstCube is a '6U' CubeSat (each 'U' is approximately 10 cm x 10 cm x 10 cm so that a '6U' is approximately 10 cm x 20 cm x 30 cm) with a '4U' instrument package. The instrument consists of four CsI scintillators read out by arrays of SiPMs. It will detect photons from approximately 50 keV to 1 MeV and roughly localize gamma-ray transients on the sky, rapidly sending alerts to the ground which will enable follow-up at other wavelengths and at greater sensitivity. The BurstCube project began in the Fall of 2017 and has a projected launch readiness date of early 2022. Instrument integration and spacecraft integration is underway as of the Fall of 2020.

2. SCIENCE OBJECTIVES

The primary science objective is to detect and characterize sGRBs that are the counterparts of GW sources. The joint detection of NS-NS GW events provides insight into fundamental physics, cosmology, jet physics, GRB emission mechanisms, element formation, the neutron star equation of state, and black hole formation.

Table 1. BurstCube Level 1 Requirements. Note that this is not the expected performance of the mission and as-expected performance is known to be exceed these requirements. Final on-orbit performance metrics will be provided in a future publication.

Requirement ID	Requirement
MR1-001	BurstCube shall have a trigger sensitivity of < 1.7 ph cm^{-2} s^{-1} (50-300 keV, 1 sec).
MR1-002	BurstCube shall have an energy range $<=$ 50 keV to $>$ 1MeV
MR1-003	BurstCube shall localize 90% of bursts to 30 degree radius (90% confidence) within 60 degrees of instrument zenith for GRBs brighter than 10 ph cm^{-2} s^{-1} (50-300 keV)
MR1-004	BurstCube shall have a field of view $>$ 6 sr
MR1-005	BurstCube shall time tag events to $<$ 1 msec
MR1-006	BurstCube shall rapidly deliver trigger data (>100 kbits/trigger) to the astrophysical community within 15 minutes for 90% of triggers.
MR1-007	The mission shall deliver continuous data ($>$ 120 Mbits/day) to the astrophysical community within 24 hours for 90% of the data.

BurstCube will monitor the variable gamma-ray sky, complementing existing facilities to provide additional sky coverage for rare and unusual transients in the era of multi-messenger astronomy. It will provide autonomous detection, localization, and dissemination of new events to the world-wide astrophysics community within minutes of detection. Finally, BurstCube will fully characterize the broad gamma-ray spectral and temporal evolution of transient events. The BurstCube Level 1 requirements are provided in Table 1.

Secondarily, BurstCube will monitor the sky for rate and unusual transient gamma-ray events. With no additional hardware or requirements, BurstCube will also be sensitive to all GRBs such as long duration hypernovae, and supernova (associated, high-redshift, and nearby sub-luminous), transient galactic sources such as magnetar flares and accreting binaries, and local sources such as solar flares and terrestrial gamma-ray flashes.

3. BURSTCUBE INSTRUMENT

Each BurstCube detector fits in a '1U' space (10 cm x 10 cm x 10 cm) and consists of an approximately 90 cm diameter by 19 mm thick CsI crystal housed in an aluminium can. The detailed mechanical design is based on

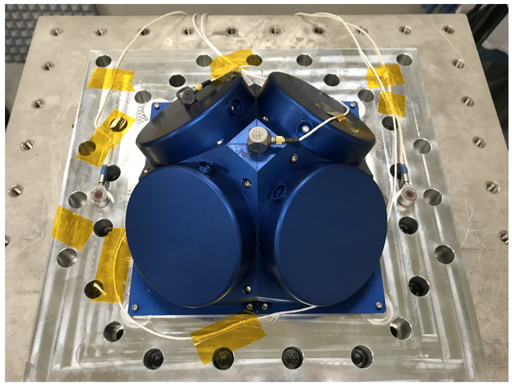


Figure 1. The BurstCube instrument is comprised of four single quarter detectors (SQD). A prototype SQD was subjected to vibration and thermal vacuum tests to validate the design. Shown here is the prototype SQD (on the top left) attached to a vibration table with three mass models used to simulate the mass of the full instrument. The prototype SQD included the full mechanical stack (crystal and SiPMs) along with the front end electronics. The full instrument is '4U' in size (approximately 20cm x 20cm x 10xm).

the *Fermi*-GBM. Optical pads are used to mechanically couple the crystal to a quartz window and the quartz window to arrays of SiPMs. These pads provide optical coupling and mechanical buffering. The mechanical housing holds each detector at an approximately 45 degree angle to zenith allowing for all-sky coverage and localization. Four detectors are mounted together to form the instrument; localizing gamma-ray sources by comparing relative rates in each detector (see Figure 1). Section 3.2 details the predicted localization accuracy and sensitivity.

Gamma-rays pass through the aluminum housing into the CsI crystal and produce scintillation light. This light is collected by an array of 116 SiPMs (Hamamatsu 13360-6050) which convert it into an electrical signal. The SiPMs are mounted on carrier boards (two SiPMs per board) and these carriers are mounted to an instrument detector analog board (IDAB) which combine signals from 19-20 SiPMs. Each of these groups is individually amplified then summed to provide a single analog output signal per detector. The four IDAB boards are connected to an instrument digital processing unit (IDPU) that provides power to the IDABs (line and bias) and continuously digitizes the signals. The IDPU interfaces with the command and data handling (C&DH) unit on the spacecraft. The IDPU determines peak times and amplitudes as well as measures the background signal and passes these individual events along to the C&DH.

Energy resolution measurements of the prototype detector shown in Figure 1 using a prototype IDAB and digitization with an oscilloscope (the flight measurements will utilize the IDPU) show that BurstCube will exceed the energy range requirements (Figure 2). Peaks as low as 26 keV (^{241}Am) and as high as 1.33 MeV (^{60}Co) are resolved. The energy resolution at 662 keV is $\sim$ 8.6% FWHM (the energy resolution over the full energy range is shown in Figure 2). The performance of SiPMs is known to be temperature dependent. The BurstCube instrument will adjust the SiPM bias voltage on orbit to compensate for changes in temperature over a pre-determined temperature range (-5C to 33C; well within the predicted temperature expected based on thermal modeling). Over this range the gain of the instrument will remain constant and tests in a temperature chamber show that the energy resolution at 662 keV remains 8.5% when the instrument is subjected to temperature changes within that range. The instrument will continue to operate if temperatures deviate from that range but will have degraded performance.

The instrument flight software resides as a core flight system (cFS) application[5] on the command and data handling (C&DH) processor and an FPGA application on the C&DH computer. The FPGA application process the incoming pulse heights from the IDPU by binning in energy and time channels. It passes these data (CBD, CTTE, and IDATA, see Table 2) to the cFS application. The cFS application passes data along to the spacecraft cFS applications and monitors the incoming data for significant rate increases; indicative of a GRB. When a rate increase is detected, it will package the information and alert the spacecraft software that a burst occurred so

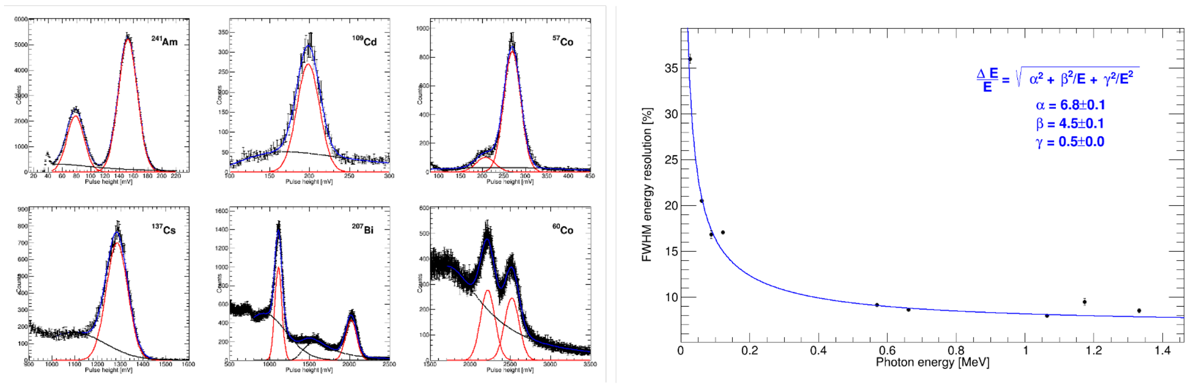


Figure 2. *Left:* The prototype BurstCube instrument can resolve radioactive lines from 26 keV to above 1.33 MeV. *Right:* The energy resolution at 662 keV is is $\sim 8.6\%$ FWHM and can be represented by the formula above over the full energy range. BurstCube is optimized to detect short GRBs and these measurements indicate the instrument will exceed requirements. The final flight energy range and resolution is expected to be slightly worse than those presented here due to the extra material that will surround the instrument once integrated into the spacecraft and the use of on-board pulse-height measurement instead of bench electronics.

that rapid communications to the ground can be initiated. The instrument flight software communicates to the IDPU via an SPI bus and processes instrument commands as well as housekeeping data from the instrument.

3.1 Prototype Environmental Testing

A prototype detector was subjected to NASA's general environmental verification standard[6] vibration and thermal vacuum (TVAC) testing to verify the design and reduce risk on the flight build. This included a single quarter detector including a full detector stack (crystal, housing, wrapping, and pads), a full SiPM array, and a prototype IDAB (the IDPU was not tested). Mass models of the other three detectors were used to simulate the full instrument during vibration testing (Figure 1). This effectively brings the instrument to technical readiness level 6. Further TVAC and vibration tests will be performed after spacecraft integration and test.

3.2 Software and Pipeline

The BurstCube software (simulations, science analysis, and data pipeline) are open source and freely available at `https://gitlab.com/burstcube` (some proprietary details including the full simulation mass model are not publicly available). The details of the software and pipeline are provided in Figure 4. The software is written in a cohesive Python library of analysis tools with a friendly API and no hard-coded values for ease of use by other CubeSats and SmallSats with similar instrument configurations.

bc-tools relies upon the gbm-data-tools[7] for several key functionalities including generating light curves, performing background fits, and producing and fitting spectra. The gbm-data-tools is a python library that can perform most of the tasks needed for a gamma-ray counting detector. It provides a well-documented, high-level API. BurstCube is utilizing this library and structuring it's data similar to *Fermi*-GBM for ease of compatibility. The BurstCube detector response is produced using detailed simulations performed using the MEGAlib toolkit.[8] Modeling of the BurstCube instrument is complete and modeling of the spacecraft components are underway (Figure 3).

The final pipeline will run on virtual servers at NASA Goddard Space Flight Center and will process the data as shown in Figure 4 generating data products as shown in Figure 5. Documentation is built automatically and deployment will be using Docker containers. Significant attention is being paid to the development of the ground software and pipeline due to the nature of the transient sources BurstCube is searching for. A goal of the project is to disseminate information to the scientific community as rapidly and as consistently as possible.

The BurstCube mission will provide several datasets to the astrophysical community (Table 2). BurstCube does not have the bandwidth to provide continuous time-tagged events like GBM provides and will provide binned

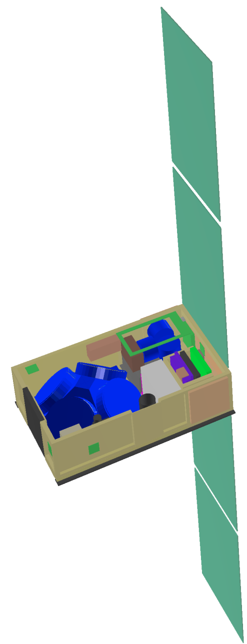


Figure 3. The detailed MEGALib instrument (the blue portion shown in the section of the spacecraft farthest from the solar panels) and space craft model allows for a robust simulation of the performance of BurstCube. The model shown here is based on the mechanical CAD drawing and includes a full instrument model and mass-substitutes of many spacecraft components. The model will be verified during calibration of the instrument.

data (BurstCube observes the full sky all the time when not in the south Atlantic anomaly (SAA) providing a continuous view of the transient gamma-ray sky). The continuous binned data (CBD) will be downlinked via an S-band connection to the Near Earth Network (NEN) at least once daily. When a burst is detected via the on-board software, alert trigger data (ATD) will be rapidly sent to the ground via the space network (SN). This brief dataset will include vital details about the burst. Trigger time-tagged events (T^3E) around interesting events (on-board triggers) will be sent to the ground via the Near Earth Network (NEN) at the next contact. BurstCube has enough onboard storage to save at least 24 hours of TTE data and can telemeter this to the ground at a user's request in case of an external trigger such as a GW detection or GRB detection from other instruments which occurred in BurstCube's field of view. The BurstCube team will provide an interface to the community to indicate a desire to get Requested Time Tagged Event (RTTE) data.

Response files will be distributed in HDF5 format in a single 2 dimensional matrix (photon energy vs energy channel) per detector and per pixel in a HEALPix grid. This will be easier for the end user since timing and matching will be done automatically. Additionally the full all-sky response will be included and used for localization as well. This allows for joint analyses (with, for example, GW data) over large areas in the sky. The ability to do a GBM-compatible analysis with RSP files and Xspec will always be supported.

Estimates of the performance of BurstCube are provided in Figure 6 based on the simulations described above. The effective area of a BurstCube detector is approximately 70% that of a *Fermi*-GBM NaI detector. The approximately disk shape of each BurstCube detector means that a gamma-ray source on axis will produce more hits than one off-axis (the effective area changes with incidience angle as shwon in Figure 6). This allows the localization of a gamma-ray source by comparing relative rates in each detector. bc-tools estimates the direction of a GRB using a Poisson likelihood method in a similar way as that done for *Fermi*-GBM (GBM uses a χ^2 method). Figure 7 shows the containment of a GRB detected by BrustCube at 10 σ over the whole sky.

4. BURSTCUBE SPACECRAFT AND MISSION

The BurstCube spacecraft is a custom '6U' design built at NASA Goddard Space Flight Center by the Engineering and Technology Directorate (ETD) and manged by NASA and Goddard's Small Satellite Project Office incor-

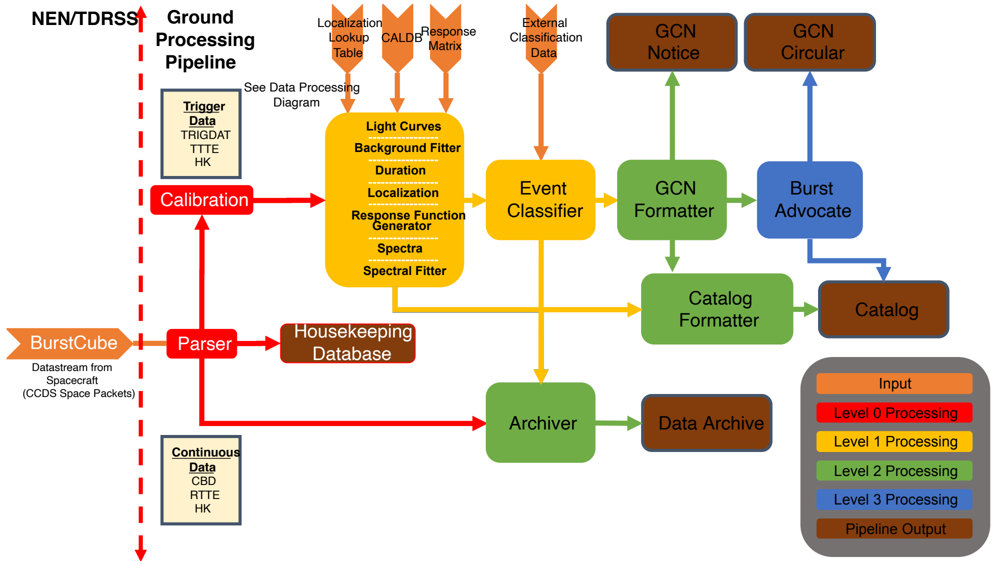


Figure 4. The BurstCube pipeline relies on several custom Python software packages as well as the gbm-data-tools. Due to the transient nature of GRBs, significant effort is being made to develop a robust and rapid data analysis pipeline. The different data levels are described in Figure 5. Additionally, the pipeline is being developed without hard-coded values so it can be adapted for use in other SmallSat and/or CubeSat missions in a straight-forward way.

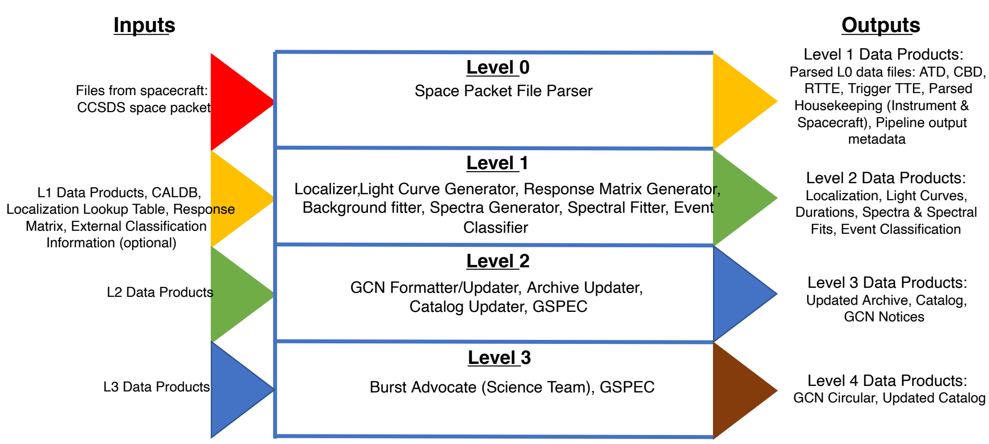
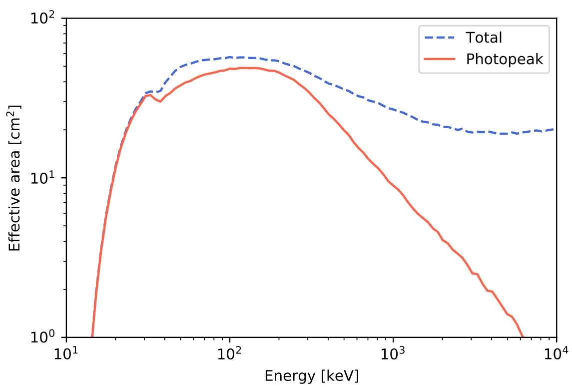


Figure 5. Almost all BurstCube data products will be released to the public as soon as they are processed. The pipeline is being developed to rapidly disseminate information.

porating many commercial off-the-shelf components (COTS). Several CubeSats are being developed at GSFC concurrently and many components are common between the buses, allowing for efficiencies in development as well as design reuse. It is assumed that Nanoracks[9] will integrate the spacecraft into the deployer and thus the mechanical design and overall system is developed with Nanoracks requirements in mind. All components show positive margins of safety at three sigma stresses and a Nanoracks vibration profile. A thermal model has been

Table 2. Several different data types will be produced by the BurstCube mission. Some of them (like the IDATA) will only be used onboard by the onboard software and storage. Users will be able to request RTTE data for interesting time periods for downlinking to the ground (such as around a known GW event).

Data Type	Description	Archive
Instrument Data (IDATA)	Time-tagged pulse heights	Onboard Only
Alert Trigger Data (ATD)	Dynamically temporally binned data around trigger from $-60 <$T0$<$ 60s, 16 energy channels	Trigger
Continuous Time Tagged Events (CTTE)	Individual time-tagged photons with 64 energy channels	Onboard Only
Trigger Time Tagged Events (T^3E)	TTE extracted in window around trigger from $-100 <$T0$<$ 300s (adjustable given bandwidth)	Trigger
Requested Time Tagged Events (RTTE)	TTE retrieved from buffer in window around external trigger	Daily
Continuous Binned Data (CBD)	Continous data (excluding SAA) with 0.2 s and 16 energy channel binning	Daily
Housekeeping	Both Instrument and Spacecraft housekeeping.	HK, Daily, Trigger



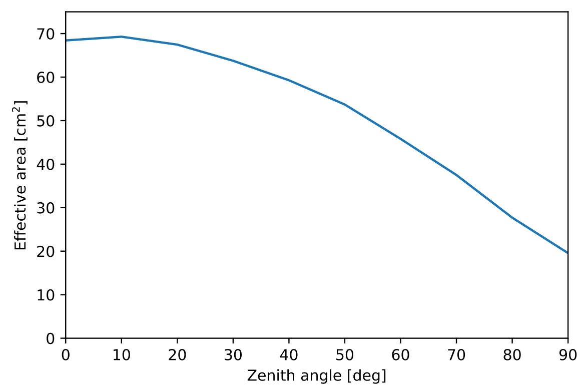


Figure 6. *Left:* The effective area of a single BurstCube detector is approximately 70% of a single *Fermi*-GBM detector at 100keV. *Right:* The effective area of a single BurstCube detector peaks on-axis and then drops as the source goes off-axis. This allows for the localization of gamma-ray transients via comparing relative rates in the four detectors. These plots were generated using the bc-tools and the MEGAlib model shown in Figure 3 excluding the spacecraft components which will modify the effective area curves.

developed and simulations show that all components are within limits. The structural and thermal design will be verified during environmental testing after the instrument is integrated into the spacecraft.

The attitude control system includes an Hyperion ST-200 star tracker, Sensonor STIM-300 inertial measurement units, a GOMSpace nanoSense Fine Sun Sensor, six Hamamatsu S5106 coarse sun sensors, a GOMSpace S5106 Magnetometer, an Hyperion GNSS200 GPS receiver,three CubeSapce CubeWheel 10 mNms reaction wheels and 3 custom built magnetorquers. This ACS implementation provides three-axis stability and allows BurstCube to exceed the requirements of 0.5 degree pointing accuracy and 0.1 pointing knowledge.

Power is supplied to the bus and instrument via an Ibeos 150W electrical power supply (EPS) and two 45 Whr Ibeos batteries. Two Blue Canyon Technologies Double Deployable solar panels generate power. A custom designed diode protection board interfaces the solar array wings with the EPS and converts the solar array voltage from 12V to 24V. Simulations of the orbit (assuming an ISS deployment) show that the batteries will at most experience 19.2% depth of discharge.

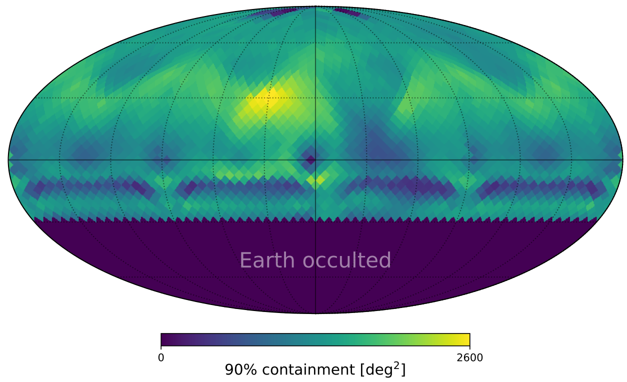


Figure 7. BurstCube localizes events on the sky using the relative rates in each detector, comparing this to simulations using a Poissonian Likelihood method. For most parts of the observable sky, the 90% containment is reasonable and can contribute to a GW localization. Note that the features are the pole are due to a known software bug.

A SpaceCube Mini-Z is used as the C&DH processing unit. This is a re-envisioned and upgraded version of the popular CSPv1 design collaboratively developed between NASA GSFC and NSF CHREC.[10] The Mini-Z includes a Xilinx Zynq-7020 system on a chip (SoC) with a Dual-Core ARM Cortex-A9 and an FPGA core with 85K logic cells. Storage includes 1GB DDR3 SDRAM and 4GB NAND flash. Several input-output options are available. The C&DH is connected to a custom designed special services card (SSC) via a backplane. The SSC provides the 4 TX and 4 RX LVDS interfaces to the BurstCube instrument as well as other necessary IO control for other components on the spacecraft.

Communications are provided via a software defined Vulcan NSR-SDR-S/S S-band radio. This radio includes a built in switch to support two Vulcan CSR-SDR-S/S omni-directional antennas. This radio is capable of communicating with NASA's Near Earth Network (NEN) at several Mbps (downlink) and approximately 50 Kbps uplink. Additionally, Vulcan has developed the ability to transmit to TDRSS-MA (downlink only) at about 1 Kbps enabling the rapid information transfer to the ground needed to disemminate knowledge about gamma-ray transients to the science community. The radio transmits in both a high-power (needed for TDRSS communications) and low-power mode, allowing for efficient use of the radio. The Vulcan radio includes 64 Gbit of data storage capability which can be utilized by the C&DH for backup of critical data and for troubleshooting anomalies.

The flight software runs on the C&DH CPU utilizing NASA's core Flight Executive and core Flight Software (cFS). cFS allows significant reuse of software components (called apps) across GSFC's CubeSats. The core services as well as apps related to common hardware are being reused. New software is being written to interface with the instrument and process the science data. Several apps are being developed to find and correct faults.

The BurstCube mission has not been manifested for launch yet (this is expected in early 2021). Until the time of manifest, BurstCube's nominal deployment will be via the International Space Station at an altitude of 400 km and inclination of 51.6 degrees. As BurstCube is designed with GEVS standards for testing many other launches are available to use. BurstCube will orbit with the z-axis of the instrument pointed towards zenith with part of the orbit dedicated to battery charging when the solar panels will be pointed towards the sun at certain times of the year (low beta angles).

More details about the spacecraft design will be provided in a future publication.

5. BURSTCUBE STATUS

BurstCube has completed all critical design reviews (except for the ground segment which will occur in 2021) and is currently in the integration phase for both the instrument and spacecraft. The delivery of the instrument to the spacecraft is expected in 2021 with launch readiness in early 2022 (prior to COVID19, instrument delivery was Fall 2020 and launch readiness was Fall 2021).

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