Utilizing Fractionated Space Mission Design and Small Satellites for a Next Generation Gamma Ray Burst Observatory

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Abstract

Since the discovery of Gamma Ray Bursts (GRBs) by the Vela satellite, the field of GRB astronomy has been rapidly evolving in order to explain the most catastrophic event in the universe. Missions over the last two decades have pinpointed GRBs as extragalactic sources as well as shed insight on their nature. NASA's recent Swift mission provides a platform for multiwavelength analysis of GRBs and their afterglow as well as transmitting GRB position data to other observatories. A future mission can compliment Swift's array of multiwavelength instrumentation as well as providing more rapid, accurate GRB position data. A fractionated, small satellite mission can utilize the scale of small satellites to rapidly slew to a GRB target and then use stereoscopic observation and short baselines to further pinpoint the GRB position. A fractionated mission design places various scientific instrumentation as the primary payload on each individual satellite, providing robust performance and a greater field of view by decentralization. Additionally, future space interferometry missions will employ formation flying and fractionated design. A fractionated, small satellite mission will provide a cost effective proof of concept and valuable data to the scientific community.

1 Introduction

The past two decades have seen a tremendous surge of on-orbit Gamma Ray Burst (GRB) observatories. Well over ten space science and space exploration missions hosted GRB detecting instruments to observe and later localize GRBs in the sky. However, with little exception, these spacecraft consisted of large spacecraft with other missions which may interfere with GRB observation. Recently several notable missions, Swift and Integral, have made great contributions with their observations of GRBs at high redshifts and their quick localization of GRBs. Despite this progress, dependence on a single, large monolithic spacecraft has limited the opportunity to observe many GRBs. Earth limb constraints, errors modes, and lack of an all-sky field of view hamper these missions' ability to quickly locate and observe

An alternative approach would consist of using a

formation of four small satellites with distributed observing, communication, and computing capabilities. This approach would bypass many issues hindering recent missions. A very wide formation would overcome earth limb constraints and allow an all-sky field of view, and by using several satellites, observation-killing error modes would be unlikely. Moreover control moment gyroscopes (CMGs) can be utilized in attitude control to quickly slew to detected GRBs to more quickly provide observation and precise localization.

2 Background

In the early 1960s, the United States was concerned about the Soviet Unions advances in nuclear weapons and ballistic missile technology. Fortunately, this fear was mutual and both sides agreed to ban all nuclear testing in space through the Partial Nuclear Test Ban Treaty of 1963. Following the agreement, the American Vela satellite was deployed in haste to monitor Soviet compliance. The Vela satellites were not met

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with radiation from Soviet nuclear testing but inexplicable blips coming from outer space In a paper published in 1973, Dr. Ray Klebesadel explained the concept of a GRBs which were serendipitously discovered by Vela.

Shortly thereafter, GRBs were confirmed as powerful, extragalactic sources and became the subject of detailed study due to the insight they may shed into cosmology, particle physics, and gravitational physics.

2.1 Gamma Ray Bursts

GRBs are the most powerful events in the universe; their short life, ranging from fractions of a second to about a minute, blots out the entire galaxies where they are located. Due to their vast amounts of energy, brief nature, and vast distances (generally $Z \sim 2.0$), it is difficult to capture data to confirm existing GRB models. On the other hand, these models need to be tested due to broad assumptions required to sate three different fields of physics relevant in modeling a GRB: astrophysics, general relativity, and particle physics.

There are two types of GRBs: long and short. Short GRBs are believed to be created by the collapse of a neutron star binary system; they last from milliseconds to seconds long. They occur as smaller redshifts and are less beamed, with a greater spread in their collimated jets as compared to long GRBs. Long GRBs are modeled by the Collapsar theory, or the implosion of a star of $M \geq 30 M_{\odot}$ into a black hole; these bursts last upwards of a minute and occur at greater redshifts when larger, Population III stars existed. For both models, internal shocks within the stellar media provide the energy to create prompt GRB emission. Each GRB produces a very distinct light curve, which is traditionally binned in events/time bin. With accurate timing information, events can be time logged as well.

Following a GRB, afterglow emission resulting from secondary shocks in the plasma outflow from the burst emits radiation in all but -ray electromagnetic regimes. For all but a few GRBs, afterglow is the only studied emission from GRBs. Its spectrum provides valuable information on GRB outflow and particle interactions within the collimated jets.

2.2 Recent GRB Observation Missions

The requirements for modern GRB are two-fold. Satellites must first detect GRBs and localize their

position; next, they must transmit the localized coordinates to other observatories for subsequent observation of the GRB prompt emission and its afterglow. Additionally, specialized spacecraft may follow up with additional instrumentation for its own observation. In the case of Swift, the spacecraft follows up with observation in X-rays, UV, and optical regimes.

Over the past decade numerous missions have sought to detect GRBs, though only recent missions have been designed expressly for that purpose. Following the Vela satellites, the Compton Gamma Ray Observatory (CGRO)[1]; launched in 1991 and deorbited in 2000, was the next satellite mission which had instrumentation to detect GRBs. The Burst And Transient Source Experiment (BATSE) [2], an instrument on-board CGRO, consisted of eight panels of NaI scintillator to detect X-rays in the $\sim 10 keV$ range. While BATSE was able to produce a skymap of GRBs over the period of its mission, its large size and lack of precise GRB detectors precluded its ability to produce consistent, quick, and accurate GRB localizations.

Several other missions existed in parallel with CGRO such as the Italian BeppoSax[3] and the High Energy Transient Explorer (HETE-II)[4]. These missions, as well as several deep space missions which were fitted with GRB detecting instruments, formed the second incarnation of the Interplanetary Network (IPN)[5][6], which used timing and location information from all observing satellites to localize GRBs using multilateralation. Due to the time distances between spacecraft, IPN localization calculations were done well after the GRB; additionally, uncertainty in spacecraft positioning resulted in systematic errors.

Recently, there have been two outstanding missions: NASA's Swift [7] and ESA's Integral [8]. Both have been able to localize GRBs to arcminutes and observe weak GRBs at high redshifts; however, they are still limited by their large size and lack of field of view. Swift's use of a large Cadmium Zinc Telluride (CZT) array with a coded mask aperture, a large structure which partially 'shades' the CCD array from GRB radiation. This method provides precise pointing data as shown in Figure 1, provides a 2sr field of view, providing only a 15% view of the entire sky[7].

Fortunately, instrumentation for GRB detection is relatively small, making small satellites a prime candidate for GRB observation. To this end, several recent GRB missions have been flown with small satellites: HETE-II and Agile[9]. Both hosted a variety of instrumentation and were able to localize GRBs within 10'. Moreover, Tsubame [10], currently in

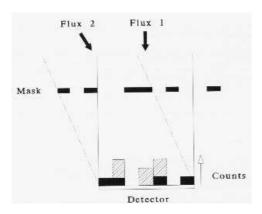


Figure 1: A coded mask aperture functions by occulting incoming flux, producing a projection of the mask onto the CCD medium. The shift and strength of each projection corresponds to a different angle of incidence[11]

development by Tokyo Institute of Technology, is a nanosatellite that uses control moment gyroscopes (CMGs) for rapid slewing.

2.3 Fractionation

In contrast to traditional, monolithic satellite design, fractionated satellite design distributes on-orbit tasks over several spacecraft to create a decentralized method of accomplishing mission tasks. The F6 Program, as laid out by DARPA [12], consists of several different technology enablers indicative of fractionated spaceflight: networking, wireless communication, power beaming, distributed payload operations, cluster operations, and distributed computing. While the F6 criterion may not be relevant in its entirety to space science missions, fractionation in a limited form will certainly improve mission performance.

Distributing the payload requirements can yield numerous advantages to improve observation and provide more robust handling of typical space science error modes[13]. Distributed primary payloads will allow for far greater effective area for detecting a burst, increasing incident flux, thus decreasing the time it takes to detect a GRB. By distributing the payload over long baselines, timing information can collected to furthering improve data accuracy by enabling triangulation. Moreover, multiple observations from different instrumentation greatly improve accuracy. Next, by distributing multiwavelength payload over multiple satellites, each satellite can observe GRBs and their afterglows in its own energy regime without interacting with other payloads and their re-

quirements. Additionally, fractionation will allow for smaller satellites which can slew much faster to provide observation of prompt afterglow emission. Finally, typical error modes, such as earth limb constraint and faulty or uncalibrated instrumentation can be entirely avoided.

Networking, distributed communications, and distributed processing would allow crosslinking to optimize the formation's GRB localization in real time using multiple observations and IPN methods made possible by GPS timing and position data. Moreover, a larger formation would create a larger footprint on earth which can enable direct downlinking of coordinates to the Gamma Ray Burst Coordination Network (GCN) [14] without routing through TDRSS.

2.4 Scientific and Technical Opportunity

The current focus for GRB observation missions is to use a small field of view to observe a small number of GRBs to an accuracy of several arcminutes. This is in contrast to the methodology behind CGRO, which was to have a near all-sky field of view $(4\pi sr)$ with accuracies on the order of degrees. Scientifically, the next generation GRB mission should provide an allsky field of view and arcminute accuracies. Using a monolithic spacecraft design approach, such a satellite would be a Large Space Telescope (LST) scale endeavor, similar to Hubble, which may have to lie out of earth orbit. But by utilizing a fractionated spacecraft approach, multiple spacecraft would provide an all-sky field of view with each one having a small field of view instrument to provide arcminute accuracies. By implimenting CMGs, slew times can be dramatically cut down, enabling more timely observation of prompt and afterglow emission. Interestingly, this mission may be done at a cost of less than or equal Swift, the current vanguard GRB observing mission.

Additionally, over the next several decades several next generation, LST observatories have been designed to utilize multiple spacecraft in clustered flight [15]. A small satellite mission with multiple spacecraft in clustered flight would provide a relatively inexpensive proof of concept to these more advanced missions. Technical experience and a historical precedent would not only facilitate mission design and operations, but also funding opportunities and political support.

3 Mission Objectives and Requirements

Given the scientific and technical opportunities, there are two different objectives for a fractionated, small satellite observatory:

- 1. To provide rapid detection, localization, and observation of GRBs while transmitting localization data to other observatories; and,
- To utilize several small satellites in a fractionated manner as a demonstration of viability of this mission architecture for future space science missions.

To meet these mission objectives, a series of requirements must be met:

- The mission and satellite design must utilize distributed payload, computation, and communication in observing GRBs;
- 2. The mission and satellite design must allow for an appropriately long baseline to use triangulation as a method of localization;
- 3. The mission and satellite design must provide an all-sky field of view with the ability to localize GRBs to an error box of $\sim 10'$;
- 4. The mission and satellite design must allow for a mission lifespan of 5 years;
- The mission and satellite design must incorporate instrumentation for multiwavelength observation;
- 6. The satellite design must allow for quick slews $(\sim 60^{\circ}/10s)$ and precise pointing $(\sim 1')$; and,
- The satellite design must incorporate communication with TDRSS and preexisting GCN infrastructure.

4 Mission Design Drivers

To best fulfill the mission requirements, several design elements need to be determined. The primary design element is the size of the formation, both in terms of the of number of spacecraft and the type of formation. Generally, angular resolution of a source improves as a function of the number of satellites: $\theta \propto \frac{\theta_0}{\sqrt{N}}$, but a trade off is necessary to limit the cost of the spacecraft and develop a formation structure which will maximize the spacecraft baselines.

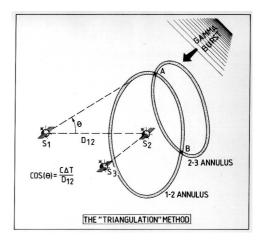


Figure 2: Triangulation of Gamma Ray Bursts as done by the Inter Planetary Network.[16]

To provide triangulation which can limit GRB localization to a small error box, three observing satellites with long baselines are required. If only two satellites are performing baseline localization, they can only produce an error annulus for potential GRB localization; adding another satellite will provide another error annulus. The intersection of the annuli create two error boxes, as shown in Figure 2, one of which can be discounted based on detector localization. The addition of another observing satellite will provide a total of four different triangulations, which over-determines the location of a burst. A χ^2 analysis can then be used to constrain the baseline localization to an even smaller error ellipse [17]. To provide redundancy in the event of error modes, to create an extra degree of freedom in further mission design, and to minimize total mission cost, it is optimal to choose four satellites.

To optimize the baseline localization accuracy, the four satellites should be placed in a square formation around the earth as detailed in Figure 3. The only stipulation with this decision would be that the satellites would not be free to network directly with the satellite opposite from them, but must communicate via a relay provided by the other satellites in the formation. While this does slow down communication and limit the fractionation mission, the baselines provided by this formation far outweigh the mitigating factors. Next, line of sight can only be establish at altitudes greater than 3,000km, which would avoid communicating through the atmosphere. However, to avoid the radiation-adverse environment of the Inner Van Allen Belt, a higher altitude would need to be chosen.

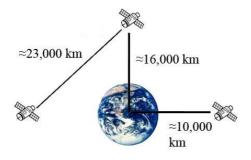




Figure 3: Approximate orbit for a four satellite Gamma Ray Burst observatory providing an all-sky field of view.

5 Preliminary Mission and Satellite Design

5.1 Overview

Each satellite will be capable of independent, autonomous operation, requiring that it have all standard subsystems. This uniformity reduces development and material costs; moreover, testing and calibration can be cross-checked between satellites, enabling robust development and mission handling. The only varying parameter on each satellite will be the primary scientific payload which provides followup observation of prompt and afterglow emission. The primary payload and its supporting structure can be up to about 60kg in mass and consume about 50Wof power; these limits would easily allow for a CCD detector with a capable observing area and field of view. The following subsections demonstrate a satellite hosting a primary instrument of a 10° field of view coded mask aperture CZT detector; this detector is comparable to the Burst Alert Telescope (BAT) onboard Swift. Other scientific instrumentation would consist of five NaI scintillating detectors and two 1D wide-field X-Ray detectors that would detect and locate the GRB.

Such a satellite will mass approximately 500kg and consume 515W in observing mode. The mass budget is located below in Table 1, while the power budgets are located in Table 3 and Table 4 in the power subsection.

Table 1: Demonstrative Satellite Mass Budget

Subsystem	mass (kg)	Mass Fraction
Communications	26	0.05
Power	74	0.15
ADC	46	0.09
Propulsion Structure	50	0.10
CDH	22	0.05
Payload	170	0.35
Structure	98	0.20

The following subsections will discuss the subsystems in detail and their relation to the mission objectives.

5.2 Orbit and Propulsion

To maximize the baseline between satellites and to easily work within the mass, power, and link budget constraints of a small satellite, the orbit altitude for the formation would be 10,000km as depicted in Figure 3. This creates a baseline of about 23,000km between each satellite. Due to the nature of the instrumentation and the isotropic distribution of GRBs in the sky, the orbit inclination can be optimized based on the radiation exposure at various inclinations; however, a low-inclination orbit will benefit from additional GPS signal availability.

Because information of each satellite's relative coordinates and pointing is far more vital to the mission than precise stationkeeping, the stationkeeping budget is minimal. A general Δv requirement of $\sim 20\frac{m}{s}$ per year can be met with either monopropellent hydrazine or cold gas. For my the power and mass modeling, hydrazine was chosen due to its higher I_{sp} .

Two options are available for orbit insertion; either a direct launch to MEO or a transfer from LEO. In the first option, all four satellites can be launched on the same vehicle to the orbit altitude; maneuvers can be made using on-board propulsion to move satellites into a different orbit until there is a window to return to formation at the design altitude. The second option would launch all four satellites on the same vehicle into a LEO orbit; at that point, satellites would take turns using a solid-kick stage until all of them are in formation at design altitude.

For mass and power estimates, the latter option is chosen as it would more rapidly place the satellites in their correct position in the formation. This option would required approximately 250kg of solid rocket booster with a structural mass of 40kg for an insertion into a similar inclination, circular orbit at 10,000km from 1,000km. Hydrazine for five years of

stationkeeping will mass about 20kg and its support mass will be about 10 kg.

5.3 Attitude Determination and Control

Due to the rapid nature of GRBs, rapid slewing and accurate pointing are essential to meeting the mission requirements. In addition to the attitude control, precise pointing and position information are required to determine the burst location and forward the coordinates to other observatories through the GCN

Due to the mass requirement, the options for attitude control are limited. The pointing and mass requirement limit the list of viable options to CMGs. CMGs have proven to be effective solutions for ADC on spacecraft with sizes ranging from nanosatellites [18][19] to space stations. The current TSUBAME mission, under development by Tokyo Institute of Technology, utilizes four CMGs for 90° slews in 10sfor a 50kg-class satellite [19][10]. Fortunately, CMGs can be effectively scaled to meet the requirements of this mission. In order to slew 60° in about 10s, a torque of 32Nm can be produced by four CMGs. The CMG system would mass about 45kq while using 50W of power during spin up and roughly 5 W during maneuvering. To counteract CMG singularities, where the angular momentum vectors of the CMGs point such that no torque can be produced in specific directions [18], magnetorquers or hydrazine can be employed to complete maneuvers.

Using multiple instruments can be used to aid in attitude pointing determination. Primarily, gyroscopes, sun, and earth sensors can utilized to determine pointing to high precision and accuracy to meet the mission's pointing requirement. Additionally, the primary scientific payload should be able to determine pointing with known celestial objects, such as the Crab Pulsar Wind Nebula or other high energy sources to about an arcminute.

5.3.1 GPS

For many years, GPS has been an effective tool for terrestrial and space navigation in low earth orbits; though it has seen little testing at other MEO altitudes and above constellation[20]. At an orbit of 10,000km, a approximation can ensure that coverage is provided. The full-width half-max (FWHM) of the GPS signal is roughly 9°[20] while the earth subtends about 13.5° . A low-inclination, circular orbit ($i \lesssim 5^{\circ}$) should provide multiple satellite coverage as the equatorial regions would generally be covered

within the GPS FWHM. To provide further coverage, GPS signals may be received from GPS satellites on the other side of the earth.

For instance, it is possible that errors may range to $\sim 10km$, the long baselines with a light distance of 76.7ms make the GPS error of $\Delta t \simeq 3.33 \times 10^{-5}s$ as compared to typical detector errors of about $\Delta t \sim 10.\times 10^{-6}s$. Even these detector errors are subject to uncertainties in the GRB prompt emission light-curve, about 10% of the burst's length, which can range from milliseconds to minutes. Despite the altitude and separation of the formation's satellites, GPS errors are already equal to or superseded by other standard errors. The impact of this uncertainty on baseline triangulation for GRB localization will be discussed in the Section 5.6.1.

5.4 Communications and Command and Data Handling

The communications subsystem is vital to meeting the many mission requirements. The satellites must be able to share all local pointing and timing information with other satellites in the formation in real time in order to provide effective use of rapid baseline localization techniques and multiple observations which places a high demand on both the communication and command and data handling (CDH). Data relay is accomplished through direct crosslinking. In completing the science mission, the formation must be able to relay GRB coordinates to the GCN typically with direct downlink and alternatively via TDRSS. Lastly, mission control and telemetry information can be accomplished with a direct downlink to the ground station(s) or, again, via TDRSS. Table 2 provides a summary of the data on all communications links in the mission. All bands which carry position, pointing, and timing information have a bandwidth of at least 100kbps, enough bandwidth to broadcast millisecond samples of the information vital to GRB localization. The crosslink within the formation has a bandwidth of 500 kbps in order to exchange light curve information from its 5 NaI detectors, 2 wide-field X-ray detectors, and primary instrumentation in addition to all other data required for localization.

In order to process position data, communications, telemetry, and detector information 11 processors are required. The total includes 7 processors for the scientific instrumentation, 1 for ADC, 3 for communications, and 1 for telemetry. Over the course of the mission, data storage may become an issue, with GRB runs lasting upwards of minutes with sampling

Table 2: Mission	Communications Data Summary
antion Crosslink	TDRSS Crosslink Downlink I

	Formation Crossink	IDRSS Crossink	Downlink 1	Downlink II
Distance (km)	23,0000	25,000	10,000	10,000
Frequency (GHz)	0.100	2.000	2.000	1.000
Data Rate (bps)	500,000	100,000	100,000	40,000
Output Power (W)	15	20	15	13
Tx Gain (dB)	2	8	10	3
Rx Gain (dB)	2	15	20	15
SNR	5.8	6.19	8.36	5.74

at microsecond intervals. While integration times for the instrumentation needs to be optimized for the flux and detector area sizes, a $1\mu s$ sampling rate provides a liberal estimate for data storage requirement. NaI detectors would require about 8 bits/channel, with at least one channel/detector. For a 150s run, about 750MB would be required for data storage from only the NaI detectors, with about 1GB of data required including only the two X-Ray camera. The primary instrument data storage requirement will vary between different payloads, but a 100s run with a 16,000 pixel CCD will consume 1.5GBof data storage. To sufficiently record data for simultaneous processing, future downloading and the possibility of extended observation of multiple GRB targets, each satellite should have 10GB of radiationhardened memory.

5.5 Power

To power each satellite, solar panels will be used in conjunction with NiMH batteries while in eclipse. Approximately $1.6m^2$ of triple-junction solar panels will provide beginning of life (BOL) power of 584W, eventually degrading to the operational 515W over the course of 5 years. NiMH packs will degrade to the same power over 5 years as well.

There are two modes of satellite operation: standby and observation. In standby mode, the primary scientific instrumentation and all communications except the telemetry band of each satellite are not used. Power consumption in this mode is approximately 350W. While in observation mode, all subsystems of the satellite may be in use and power consumption will be at a maximum. Power consumption in this mode, assuming direct downlink and downlink via TDRSS is approximately 515W.

The standby and observation power budgets are outlined by Table 3 and Table 4, respectively.

Table 3: Demonstrative Satellite Power Budget: Standby Mode

Subsystem	Power (W)	Power Fraction
Communications	89.	0.25
Power	123.	0.35
ADC	53.	0.15
Propulsion	0.	0.00
CDH	40.	0.11
Payload	49.	0.14

Table 4: Demonstrative Satellite Power Budget: Observation Mode

Subsystem	Power (W)	Power Fraction
Communications	159.	0.31
Power	123.	0.24
ADC	53.	0.10
Propulsion	50.	0.10
CDH	55.	0.11
Payload	74.	0.14
Remaining Power	1.	0

5.6 Scientific Instrumentation

5.6.1 Overview

Each satellite will host three types of scientific instrumentation used for the observation of GRB prompt and afterglow emission. Two detecting and localizing instruments will provide an approximate location for the GRB which will serve as the slew target for the satellite and its primary observing instrument. These two instruments, the NaI scintillating detectors and the wide field X-ray cameras, provide accuracies of approximately 10' and $5^{\circ}-10^{\circ}$, respectively. As mentioned earlier, the primary instrumentation may vary between each satellite and will be used for follow-up observation and attitude determination.

Time differences of the summed light curves of each satellite, made possible by long baselines, supplement the accuracies of the detection and localization instruments in forwarding localization to the primary instrumentation. Once each satellite confirms detection of a GRB through change and duration of flux, light curve information can be compared to provide directional information using IPN methods. This is made possible by time-tagging events instead of using time bins for data collection, meaning that each detected event will be stored in data with time-tags.

While analytical methods exist for IPN methods [21], calculations and simulations for a four-satellite system is beyond this scope of this study. Rather, approximations for a one-dimensional, on-axis two-satellite system can be extended. Using a 23,000km baseline, the optimal two-satellite baseline localization provides a 68% containment radius of 44' for a 10ms burst. Assuming the satellites possess a primary instrument with 10° field of view, baseline methods yield useful results for GRBs up to 0.1s in duration. The addition of satellites would not necessarily decrease the containment radius, but would enable useful baseline measurements from GRBs not on the plane of the formation.

Data can be further improved by corroborating observation between all satellites. With astronomic observations, observational accuracy increases with the number of telescopes: $\theta \propto \frac{\theta_0}{\sqrt{N}}$, where N, is the number of telescopes. This is due to the union of multiple overlapping containment regions, which produce a smaller containment region for the same probability of the source's existance. This phenomenon is demonstrated abstractly in Figure 4.

5.6.2 Sodium Iodide (NaI) Scintillating Detectors

NaI detectors have been used for decades to detect radiation in numerous scientific and medical instruments. After passing a thin collimator, incident radiation fluoresces photons by ionizing atoms in the NaI grid. In order to boost scintillating performance, the grid is dopped with Thallium. The fluoresced photos are gathered through a photomultiplier tube, creating a pulse with intensity information, as depicted in Figure 5.

NaI detectors have flown in numerous GRB detection missions and they include numerous advantages and disadvantages. They are relatively light weight, with a specific gravity of 3.67, inexpensive, have a near omnidirectional field of view, and have a very modest power requirement for the photomultiplier tube, roughly 5W. Moreover, their high energy threshold ranges from 10-100keV [22]provides reasonable protection against false positives from radiation trapped in the Van Allen Belt; this threshold

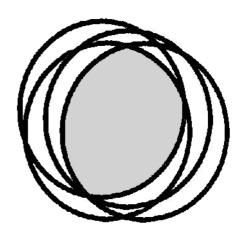


Figure 4: By overlapping the containment regions as observed by each telescope, a smaller region and better accuracy can be derived from a system of telescopes. In this figure, four overlapping containment regions, as depicted by black circles, produce a smaller one, as depicted by the gray area.

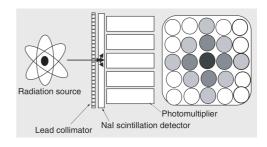


Figure 5: Diagram of an NaI detector.[25]

can be raised by increasing the collimator thickness.

Despite their advantages, NaI detectors provide very limited directional information and require large areas for detecting weak and highly redshifted GRBs. The location of a GRB can be derived by looking at the intensity of the light curve as detected by the individual detectors on a satellite; an algorithm such as CGRO's 'Locburst' can produce localizations as accurate as several degrees, but typically a little more [23]. Also, uniformity of the detectors poses yet another difficulty. Small variations in each NaI panel and photomultiplier can provide different scintillating responses and efficiencies; fortunately, laboratory testing can calibrate the detectors to have similar responses to radioactive sources.

Each satellite will have five NaI panels, each with an area of $0.28m^2$, for a total area of $1.38m^2$. This

is comparable to CGRO's BATSE[24], which utilized eight NaI panels with area $0.20m^2$ for a total area of $1.50m^2$. By analogy, the angular resolutions will typically fall within $5^{\circ}-10^{\circ}$, with some GRBs having smaller error boxes. Using cumulative observation from four satellites, the angular resolution can be as low as 2.5° with only the NaI detectors.

Despite the rather high angular resolution, the very large collecting areas will be capable of detecting small changes in flux. Once the NaI detectors trigger, they can provide the satellite and the formation approximate locations for follow up observation with the primary instrument.

5.6.3 Wide Field X-Ray Detectors

Small wide wield X-ray detectors have been flown on a number of GRB observatory missions, the most notable two being Agile and HETE-II. These are codedmask aperture detectors which occult some of the incident flux to determine the GRB position as illustrated in Figure 1. These instruments have many advantages with respect to their size, which is why have been chosen to fly on board the Agile and HETE-II small satellites. These detectors require very modest power and mass, about about 10kg and 10 - 20W, respectively. They provide a fairly large field of view at 1.8sr for SuperAGILE (Agile's wide field X-ray detector)[26] and 1.6sr for HETE-II's WXM [27]; despite this large field of view, they provide very good localizations with angular resolutions about 5' - 10'. With four satellite observation, resolution can be reduced to 1.25' - 2.5'.

The shortcoming of these detectors is their detecting abilities. Despite a rather low energy threshold around 40keV, a one dimensional coded mask aperture may occult the flux from weak GRBs. While this shading may function well in eliminating radiation from the Van Allen Belts, it does impede observation. Additionally, an error mode or occulting of one of the detectors in the 1D pair will provide only one-dimensional coordinates, or a band in the sky which contains the GRB source. To compensate for its shortcomings, it is paired with the NaI detectors, which provide a very good sensitivity and low accuracy.

5.6.4 Primary Instrument

One of the benefits of fractionated mission design is the ability to distribute a primary payload to each individual satellite, allowing it to be designed and operated without interference from other valuable instrumentation. By utilizing four satellites, four different

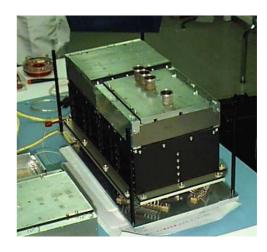


Figure 6: HETE-II's Wide Field X-ray Monitor (WXM). Each detector of HETE-II's two WXMs is able to measure position in one direction using a 1D coded mask aperture. Two detectors provide a coordinate which, when confirmed, can be relayed to the GCN.[28]

primary payloads can be placed on each spacecraft for concurrent multiwavelength observation. The primary instrument functions to provide extended observation of GRB afterglow and more precise localization of the GRB. The primary payload is designed as a 'black box' that can be readily integrated into the spacecraft. While geometries, data requirements, and other factors of these detectors may vary, they are allotted about 60kg in mass and consume about 50W of power. The determination of the particular instruments is left for further study, though several possibilities are presented in this study as examples.

The basic requirement for any primary instrument on this mission is that it can utilize a coarse localization from the NaI detectors and baseline methods to determine the source location to a few arcminutes. At that point, each satellite will slew the primary instrument to the approximate location of the burst. Thus, each instrument will only need to provide a small field of view, roughly 10° to allow for the worst NaI localizations. The benefit of a small field of view is that it requires a smaller instrument to achieve the same angular resolution, thereby reducing the mass and power requirements as well as cost.

For this study, a coded-mask aperture CCD array with a 10° field of view was selected. This instrument would serve to give a very accurate localization of the GRB in the 15-150keV range, much like Swift's BAT. Other X-ray instruments could operate in high energy regimes by additional shielding. X-ray

polarimeter, such as one being designed for Tsubame, use a scintillating medium and observe the polarization of photos from GRBs[29], shedding light into the physical mechanisms of a GRB. Optical and UV cameras can also be used, though due to their larger wavelength, optics for these regimes, particularly optical, will require massive detectors. Nevertheless, observations from optical to hard X-ray can be provided on satellites in this formation. Moreover, utilizing multiple observations can produce localizations on the order of ten arcseconds.

6 Sortie Overview

What distinguishes this GRB mission from others is the distinct way it utilizes fractionated mission design to detect and observe GRBs. Because there are four satellites which may or may not observe the GRB, each sortie may slightly differ. The sorties will consist of several stages: detection, communication, and sustained observation.

When in standby mode, each satellite will target its primary instrumentation in different directions in order to ensure at least one satellite will be pointing near the location of the burst.

In the detection stage, a burst is detected and a locally-available localization is derived using its differential light curve from the NaI detectors and a position from the wide field X-ray camera. At this point, the satellite begins autonomously slewing toward the burst target.

In the communication phase, satellites will share timing and light curve data to provide a localization based on baseline timing and overlapping containment radii. Throughout the communication phase, each satellite will reform its local GRB localization using this data and continue slewing to new coordinates. Coordinates derived in this phase can be forwarded to the GCN via direct downlink or TDRSS. Due to power consumption and signal latency, downlinking via TDRSS would not be preferred. If none of the four satellites can establish a downlink to the GCN site, coordinates will be carried through TDRSS.

In the sustained observation phase, the primary instrument begins its observation of the source. At this point, the primary instrument can determine the final coordinates for arcsecond-order localization, depending on the duration of burst and the observational wavelength regime of the instrument. The primary instrument will continue to observe the GRB afterglow emission and downlink observational data following the termination of the sortie. The entire sor-

tie may last as long as 10 minutes, but the first two stages should take about 10 seconds following the detection of the burst.

7 Cost

The cost of the mission is difficult to approximate in a preliminary study, though basic estimates can be made using the HETE-2 mission as an example. The HETE-2 satellite cost \$8.4 million and \$15. million to launch[30]. Both HETE-2 and this mission benefit from using instrumentation that has already been used extensively, eliminating many development costs for making the instrumentation. Considering the larger size of these satellites and additional instrumentation, each satellite may cost from \$30 to \$100 million, making the cost of the formation roughly \$120 to \$400 million, not including a launch vehicle. This compares to the cost of Swift, which was about \$250 million.

8 Further Study

Further study is required to verify the assumptions in this report and to provide a strong analytical basis for further development.

Most of the required work regards the ability to time events with high precision and provide accurate baselines, both required GPS timing. Thus, research needs to determine the viability of GPS for a low inclination orbit of about 10,000km for GPS coverage and for errors. Stemming from these GPS errors, are those associated with the IPN methods used to derive localizations from baseline timing. Considering the IPN relies on baselines orders of magnitude longer, work needs to be done to show how these methods scale with four satellites in earth orbit.

Also lacking is the selection of the primary instrumentation for each individual satellite. Its selection is based on the needs of the astrophysics community and not within the scope of this study. However, final satellite design cannot be completed without a specific payload. Once each payload is selected, appropriate cost estimates can be made for each individual satellite and for the entire mission.

An additional aspect of future study is the determination of how the computing responsibility will be divided between satellites. While each satellite may operate individually, additional implimentation of distributed requirements may increase observational efficiency.

Finally, an interesting derivation of this mission that is worth research is a standard bus which can tag along larger spacecraft on interplanetary missions. By relying on the exploration spacecraft for communications, the smaller GRB observing satellite can provide very useful data to the IPN at much further baselines. Although such a mission would not accomplish the mission requirements as laid out in this paper, it may provide additional observation outside of earth orbit.

9 Conclusion

Current GRB space missions have provided very valuable information for understanding the nature of the universe's most clamatic events. However, the field of view of their detecting instrumentation limits their view to only a fraction of the sky. Additionally, each satellite is limited by its spot in orbit, limiting observations by the earth's limb. Moreover, error modes delay dispatchs to the GCN enabling additional observations. To improve the field of view and maintain current accuracy by using current mission architectures would inevitably require a very large and expensive spacecraft.

Utilizing a formation of fractionated small satellites provides several distinct advantages over current mission architectures for a future GRB on-orbit observatory. First, this mission would provide redundant, all-sky $(4\pi sr)$ coverage, over six times greater than the current NASA Swift mission, enabling it to view all GRBs in the sky. Second, the formation can relay coordinates to the GCN with times comparable, if not faster, than the current GRB missions. Third, it can provide rapid multiwavelength observation for both both prompt and afterglow GRB emission. Fourth, it provides far more reliable and robust mission performance by using several similar satellites, all while providing data at comparable accuracies to current missions. Fifth, such a mission may cost less than the current vangard missions. Lastly, it provides confidence in flying future formation flying satellite missions.

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