186148
N94-28133
442476

THE GAMCIT GAMMA-RAY BURST DETECTOR

Benjamin J. McCall, John M. Grunsfeld, Srdjan D. Sobajic
Chinley Leonard Chang, David M. Krum
Albert Ratner, Jennifer E. Trittschuh
California Institute of Technology
Pasadena, California 91125
for the GAMCIT Team

ABSTRACT

The GAMCIT payload is a Get-Away-Special payload designed to search for high-energy gamma-ray bursts and any associated optical transients. This paper presents details on the design of the GAMCIT payload, in the areas of battery selection, power processing, electronics design, gamma-ray detection systems, and the optical imaging of the transients. The paper will discuss the progress of the construction, testing, and specific design details of the payload.

In addition, this paper will discuss the unique challenges involved in bringing this payload to completion, as the project has been designed, constructed, and managed entirely by undergraduate students. Our experience will certainly be valuable to other student groups interested in taking on a challenging project such as a Get-Away-Special payload.

SCIENTIFIC OBJECTIVES

The first report of gamma-ray bursts (GRBs) occurred in 1973 from earth orbiting satellites. GRBs are highly energetic events, that are characterized by a rapid increase in the observed gamma-ray flux, at energies from tens of keV to several MeV's. The decline of such events may be a simple exponential or quite complex non-linear decay. Three gamma-ray bursts observed by the BATSE detector on the Compton Gamma Ray Observatory are depicted in Figure 1.[1]

It soon became evident that gamma-ray bursts represent one of the most energetic and violent events in the observable universe. Ever since the first detection of these phenomena, many experiments, including the BATSE experiment, have been designed to monitor them, yet their origin is still one of the great enigmas of modern astrophysics. The BATSE observations have yielded important data on the possible origin of these events. By determining the coarse location of these bursts, BATSE researchers have observed an isotropic distribution of GRBs. Furthermore, from studies of the intensities of these bursts, researchers have deduced that the bursts are not distributed homogeneously, but have a definite boundary. [2] The distribution of a sample of gamma-ray bursts, observed by BATSE, and showing their isotropy, is shown, in Figure 2. These facts indicate that the bursts are either local to the solar system, distributed in a large halo around the Galaxy, or at cosmological distances.

One theory suggests that neutron stars in binary systems are the cause. In this scenario, a normal companion star transfers material into an extremely strong gravitational potential well near the neutron star. The energy gained by this matter is converted into gamma-rays near the surface of the neutron star producing a gamma-ray burst. Other models predict that comets, or other material is accreted by an isolated neutron star of black hole producing a GRB. An interesting prediction of these theories is that as the gamma-rays strike the atmosphere of the companion star, some of the gamma-ray energy may be converted to visible light. If these theories are correct, then a GRB may be accompanied by an optical transient. [3]

OVERALL SYSTEM DESIGN

GAMCIT uses two standard NaI(Tl) scintillation gamma-ray detectors, combined with a 35mm film camera and film sensitive to visible electromagnetic radiation. GAMCIT is the first experiment to search for gamma-ray bursts and their associated optical transients truly simultaneously. An intelligent micro-controller triggers the camera when a burst is detected by the scintillators. Two detectors are used to require a multiple coincidence between independent units, reducing the possibility of a non-gamma-ray burst triggering the payload. The time and location of the burst are determined by using an on-board Global Positioning System (GPS), which provides extremely accurate information. This information is needed to correlate the results of GAMCIT with other experiments, namely BATSE and the Pioneer Venus Orbiter. If we detect an optical flash we should be able to localize the source to within a radius of less than 10 arc minutes. To discriminate against solar flares and other anomalies, we incorporate a small silicon charged particle detector. Solar flares resemble gamma ray bursts, however, they are usually accompanied by a large flux of charged particles. The charged particle detector will detect such events and allow us to veto them.

STRUCTURAL DESIGN

The three major structural components of the GAMCIT experiment are the user lid, the main supporting structure, and the battery box. The GAS lid is the attachment interface between the can and the NASA mounting plate. Since we are using a Motorized Door Assembly (MDA), a major task was designing a space facing pressure vessel lid. The concerns that were dealt with during the design process were structural integrity, thermal insulation, and maximization of gamma-ray penetration. All structural components (not including fasteners) are 6061-T6 aluminum.

This was accomplished using a composite lid, composed of a thermally insulative inner core of Kevlar (manufactured by E. I. du Pont de Nemours & Co., Inc.) and high-density foam, and an exterior of aluminum which provides structural integrity and mounting. The regions above the scintillator crystals have the aluminum removed for greater gamma-ray penetration. The area above the camera lens is replaced by an optically transparent quartz window assembly. (See Figure 3.)

The main structure partitions the center region into three sections - two for gamma-ray detection and one for the optical camera and electrical system. The cross-section of this structure is a modified "Y." To avoid welding and maintain strength, this structural configuration is fabricated by taking three plates, bending them to the desired angles, and bolting them together back to back. Aluminum shelves are bolted normal to the partition surface to provide structural stability and allow the mounting of components. (See Figure 4.)

The main supporting structure bolts directly to the top of the battery box. The battery box consists of a top and bottom plate connected by aluminum bars. The bars act to both strengthen the box and to hold in or provide mounting for the battery cases. The individual battery packs consist of ten batteries (or, a few special packs of five) soldered and epoxied together. To allow for efficient replacement, each pack is then housed in a cage of two aluminum plates held together with metal spacers. The interior of the battery packs is coated with an electrically isolating gel to prevent premature discharging of batteries.

DETECTOR DESIGN

There are two major components of the detector system: the gamma-ray detector system and the optical transient detection system. The gamma-ray detector is comprised of two NaI(Tl) scintillator crystals, 16 cm in radius and spanning an angle of 115 degrees each. This provides GAMCIT with a gamma-ray viewing area of approximately 650 square centimeters. Each scintillator crystal is optically coupled to an 7.6 cm (3 inch) diameter eight-stage photo-multiplier tube (PMT) by the use of a light integration cone, the interior of which is coated with a highly reflective barium sulfate paint. (See Figure 5.) The PMTs collect the photons emitted by the crystals and convert them into an amplified electrical signal. This signal is then passed on to the electronics system.

The other major system is the optical camera system. The system is comprised of a professional 35mm film camera with a 250 exposure data back. The lens system is a standard 50mm f/1.2 lens available from the camera manufacturer. Since the image to be photographed is at infinity, and the depth of field is unimportant, the lens may be stopped down to the lowest setting (f/1.2). The focus ring, however, must be fixed so that vibrational stress does not cause the camera to de-focus. The data back holds 250 exposures, and each burst triggers the camera for five one-minute exposures, indicating that we will have sufficient film for 50 bursts. This is an over-estimate of the number of real bursts that are statistically expected, however, false triggerings may significantly increase this number.

The film used is standard 35mm Technical Pan film with a resolution of 320 lines per mm, sensitive to visible light. With an exposure of one minute at the 50mm f/1.2 setting we can expect to see up to seventh magnitude astronomical objects. Although the manufacturer suggests hypersensitizing the film prior to usage in astronomical applications, we find that such a task would be logistically daunting, and have found acceptable results without any such process.

ELECTRONICS DESIGN

At the heart of the electronics system lies a 16-bit CMOS, high-reliability, low-power micro-controller. The micro-controller is in charge of all instrument control, data handling and system maintenance functions. Figure 6 shows the block diagram for the payload.

The primary function of the micro-controller is to identify and record a gamma-ray burst. This is accomplished by having the output current from the PMT pass through the amplification and detection electronics.

The signal from the PMT will pass through a charge sense amplifier that will convert the current pulse into a voltage spike. This signal is then fed through two discriminators, a low level one that has a threshold level set to 15 KeV, and a high level one with a threshold set at 1000 KeV. Using the signals from the high and low level discriminators it is possible to determine whether an event (a burst) has actually occurred or if it is outside our mission specifications. This event signal passes through a series of 16 bit counters implemented in a field programmable gate logic array (FPGA). The counters determine the number of events that occur in a time bin. The time bins will correspond to durations of 50 microseconds, 100 microseconds, 1 millisecond, 10 milliseconds, 100 milliseconds, 1 second, 10 seconds, and 100 seconds. The outputs are multiplexed onto the data bus. The signal from the charge sense amplifier also passes through a pulse shaping amplifier. The pulse shaping amplifier lengthens the pulse creating a "flat top" for the analog-to-digital converter. The 8-bit A/D converter is activated by an event signal that is delayed by 500ns, so that the A/D converter digitizes the peak of the pulse shaping amplifier output. The A/D converter is set so that 0 KeV corresponds to chanel 0 and 1 MeV is channel 255.

A 5.5 sigma (where sigma is the standard deviation of the date in a given time bin) detection scheme is implemented in the software. A running average and sigma is kept over the last 17 time periods in each of the eight time bins. If in a given time bin a counter value exceeds the running average by more than 5.5 sigma, a burst is detected and the system will record the time and the A/D converter will be activated and will begin recording pulse heights. The charged particle detector output is monitored by the micro-controller and it serves as a veto in deciding to send the system to Burst Mode, (i.e. if we detect a charged particle simultaneously with a gamma-ray we will not enter Burst Mode).

In addition, the electronics system must communicate with the Global Positioning unit (GPS) to record the time and position of the Orbiter. This operation is performed every second. The data is buffered by Flash RAM and written to the hard disk drive through the IDE interface.

Camera operation is also controlled by the electronics system. When a burst is detected, and the system goes into Burst Mode, a relay is triggered that closes the shutter contacts on the camera body. The contact is kept closed for one minute, upon which it is opened and closed again immediately for the next exposure, until five exposures have been attempted. Furthermore, the electronics also has to monitor the level from a photodiode in the optical light path, so that the shutter can be closed (or not opened at all) in the event that the camera rotates into an extremely bright object, (e.g. the sun).

Finally, the electronics system is in charge of some elementary housekeeping. The electronics monitor the temperature, pressure, current and battery voltage sensors. The temperature and pressure sensors are polled by an A/D converter every minute, and are stored every five minutes. The current and battery voltage are monitored so that the micro-controller manager will send an interrupt if power begins to drop, allowing the system to save vital data.

POWER MANAGEMENT

One of the primary concerns of the GAMCIT Team was the power source selection, since all Get-Away-Special (GAS) payloads must be totally autonomous from the Space Shuttle Orbiter except for the crew activated relays. Thus, upon drawing up a power budget, it was our task to determine which type of power source was most appropriate to our application requirements. After a careful consideration of the products currently available on the market, and of those that fell within the NASA safety margins, we decided on standard commercially available alkaline D-size cells. The cells have a nominal voltage of 1.5 V with a rated capacity of 14.25 Amp-hours.

The major problem one encounters with alkaline cells is their less than ideal discharge characteristic. In general, such cells discharge linearly with time from their nominal voltage (1.5 V) to the rated cut-off voltage (0.8 V). In order to overcome this difficulty, we were forced to consider a DC-DC converter. The DC-DC converter we chose has an input voltage range from 7-35 VDC, and three output terminals: two at 12 VDC and 0.7 Amperes maximum current, and one terminal at 5.1 VDC and 5.0 Amperes maximum current.

The actual battery setup is configured as 27 packs of 10 batteries each, for a total of 270 batteries. Each pack of batteries provides 15 VDC nominally, discharging to the cut-off voltage of approximately 8 VDC. Each parallel leg of the total battery power supply is protected by a Schottky diode to prevent circulating currents which would lead to mission failure. In addition, the whole power supply is protected by a 6 Amp fuse, chosen in accordance with NASA regulations, on the ground leg.

The electronic system is fully powered through the DC-DC converter, except for a clock that is powered continuously and is supplied with its own power source, a small lithium watch type battery.

The two photo-multiplier tubes are powered by a -1500 VDC power supply. The voltage is reduced to the appropriate stage using a resistive voltage divider. The current is extremely low (< 1 microA) so that the resistive power dissipation can be kept low. The power supply will receive a +12 VDC signal from the DC-DC converter and will convert it to the -1500 VDC needed by the PMTs.

Finally, the optical camera system is powered by its own set of 6 alkaline D-cells. An adapter available directly through the camera manufacturer allows us to use 6 D-cells rather than 6 AA-size cells. The camera data back clock also has its own lithium watch type battery that will maintain the clock accurately for an extended period of time.

CONSTRUCTION AND TESTING

Currently GAMCIT is still in the early stages of construction. A prototype of the support structure has been constructed, and the battery box has been designed and one 10-battery pack has been built. The user lid has been designed but no construction has yet begun. The electrical system has been finalized and some prototyping has begun.

Most of the preliminary testing has been completed. We performed a battery test, the results of which were positive. The batteries lasted for a full day longer than anticipated. Another battery test will be attempted before the actual flight to ensure the validity of the first one. Two film tests were performed, which are yet to be carefully analyzed, but the results are positive as well. The primary concern is that because of the Orbiter's significantly higher velocity, we will not be able to see as deep as from earth. This effect occurs because the Orbiter's angular velocity is 16 times greater than the earth's, and the light that hits an area of 1 square millimeter on earth will spread over an area of 16 square millimeters in space. Effectively, the exposure is cut by a factor of 16.

One further test that needs to be done is the shake test on the PMT. A shake test involves mounting the PMT to a standard mounting plate, and actuating the plate via a motor operating at a certain frequency. The shake test will range from 20 Hz to 2000 Hz, increasing the magnitude of the oscillation from 20 Hz to 100 Hz, keeping it constant from 100 Hz to 1000 Hz, and decreasing the magnitude from 1000 Hz to 2000 Hz. A ruggedized model of the PMT is available from the manufacturer, however, it will not be known until after the test whether the ruggedized version will be needed. After the construction is complete we will run a full test on the entire experiment simulating the entire Orbiter flight, including Orbiter thermal and mechanical conditions, such as vibration, etc.

CHALLENGES

The GAMCIT project at Caltech has been driven entirely by undergraduate students since its beginning. GAMCIT is actually a spin-off of the Caltech Students for the Exploration and Development of Space (SEDS), a student group with over one hundred members (over 6% of the student body, graduate and undergraduate). The sponsorship of Caltech SEDS has been essential to the success of the project, in terms of drawing in interested students, facilitating support from Caltech's administration, and bringing in start-up funds from aerospace corporations.

While the sponsorship of a large student group is very beneficial, our experience has proven that projects such as ours cannot succeed without faculty and staff support. Dr. John M. Grunsfeld served as our first advisor for the GAMCIT project, and was instrumental in obtaining recognition and laboratory space for the project, as well as in the preliminary design work. After Dr. Grunsfeld left Caltech to become an astronaut candidate, the students of GAMCIT approached Dr. Maarten Schmidt of the astronomy department to serve as a faculty advisor. Dr. Schmidt's assistance has proven invaluable in securing financial support from Caltech and outside organizations to continue the project. It is also worth noting that securing course credit for work on the project has been very helpful in recruiting new members to the project team, and our thanks go to Dr. Joel Burdick of the mechanical engineering department at Caltech for assisting us in this respect.

However, the challenges involved in the GAMCIT project go far beyond those of politics. Because our "engineers" are all undergraduates, the project's participants have faced quite a learning curve in all areas of the science and engineering of the payload. While this makes for a much slower timetable than projects in industry might enjoy, it also serves to provide hands-on experience for undergraduates that is seldom available in standard university curricula.

As in any other workgroup, leadership, responsibility, and personal relations are critical issues to the success of a project such as ours. However, these problems are exacerbated by having an all-undergraduate working group - students are students first and space experimenters only in their "spare time." Offering course credit can serve as a limited incentive to "get things done," but ultimately the motivation must come from the students' own sense of involvement in the project, which is in turn dependent in large part on the leadership and group dynamics of the project.

In the end, most of the hard work on a project staffed by undergraduates must, unfortunately, be done during the school year. In the summer of 1993, GAMCIT was able to offer stipends to five students to work for ten weeks on the project (many thanks to Ms. Joanne Clarey of Corporate Relations and to Ms. Carolyn Merkel of the Summer Undergraduate Research Fellowship Board). While most of the design details were hammered out over the summer, much of the construction is left to the full project team this fall, and as before all students are sure to be pressed for time.

The challenges and pitfalls involved in a project such as ours, staffed entirely by students, are indeed distinct from those faced in similar projects in industry or the military. While the pitfalls are many, the rewards of a student-run project are even more plentiful. We welcome correspondence from present, past, or potential student groups who are interested in Getaway Special projects.

CONCLUSIONS

The GAMCIT experiment has been a rewarding experience for all involved in its design and construction. GAMCIT also provides an almost guaranteed return, because any gamma-ray data collected can be correlated with similar observatories currently on ULYSSES, the Pioneer Venus Orbiter and the Compton Gamma Ray Observatory. A single optical transient correlated with a gamma-ray burst would provide a stringent constraint on burst theories.

REFERENCES

1. Fishman, G.J., Meegan, C.A., Wilson, R.B., Paciesas, W.S., Pendleton, G.N., The BATSE Experiment on the Compton Gamma Ray Observatory: Status and Some Early Results, NASA Conference Publication 3137, 1992, pp. 26-34.

2. Meegan, C.A., Fishman, G.J., Wilson, R.B., Paciesasm W.S., Pendleton, G.N., Hornack, J.M., Brock, M.N., and Kouveliotou, C., Spatial Distribution of Gamma-ray Bursts Observed by BATSE, Nature, 1992, vol. 355, pp. 143-145.

3. Surka, D.M, Grunsfeld, J.M., Warneke, B.A.: GAMCIT - A Gamma-Ray Burst Detector. Shuttle Small Payloads Symposium NASA CP-3171, 1992. (Paper 15 of this compilation.)

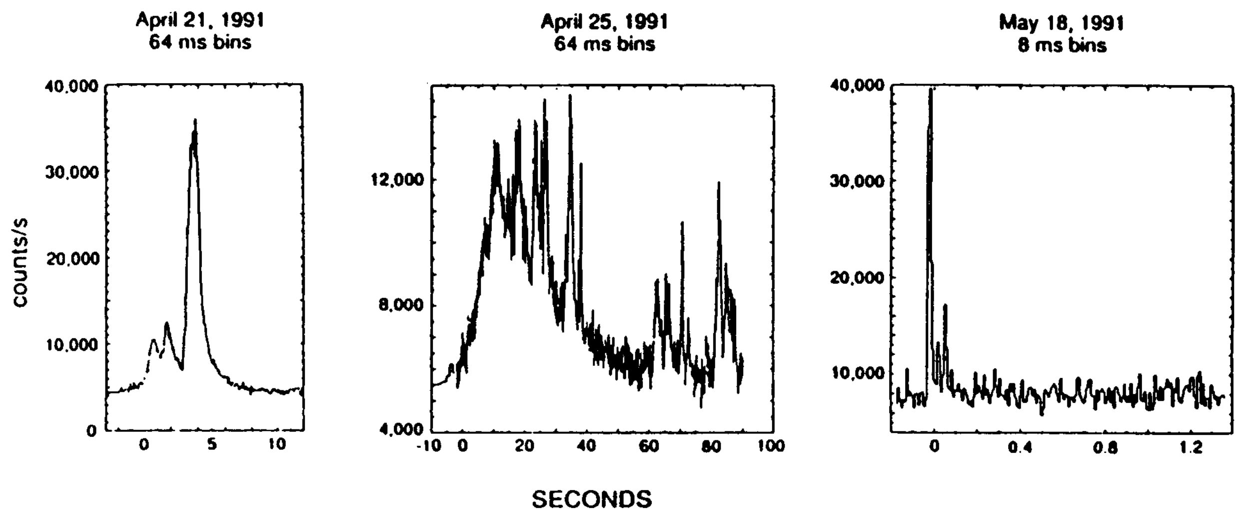

FIGURE 1. A sample of gamma-ray bursts as observed by the BATSE instrument on the Compton Gamma Ray Observatory (reproduced from [1]). These burst profiles show the wide variety of structure and varying time durations of gamma-ray bursts, from milliseconds to 100s of seconds. The energies of the gamma-rays in these plots range from 60 keV to 300 keV.

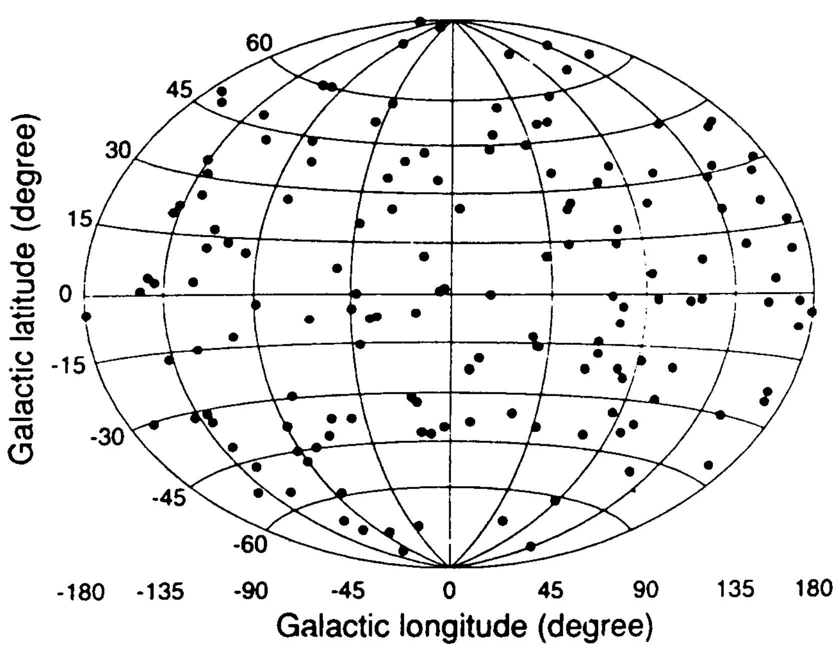

FIGURE 2. The angular location of gamma-ray bursts in Galactic coordinates as observed by the BATSE instrument on the Compton Gamma Ray Observatory (reproduced from [2]). The observed distribution shows no significant deviation from isotropy. In particular no enhancement along the Galactic plane (latitude=0) is seen, as would be expected if the sources of gamma-ray bursts had the same distribution as the stars in the Galaxy.

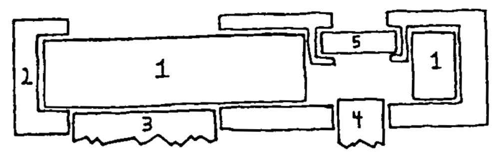

FIGURE 3. A cross section of the user lid. 1. Kevlar and foam insulation. 2. Mounting brackets. 3. Scintillator Crystal. 4. Camera Lens. 5. Quartz Window.

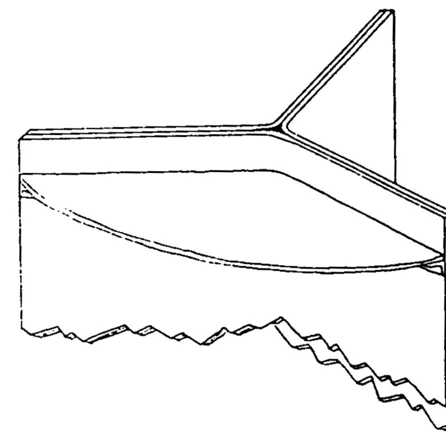

FIGURE 4. A cut-away view of the "Y" shaped supporting structure, with one shelf in place.

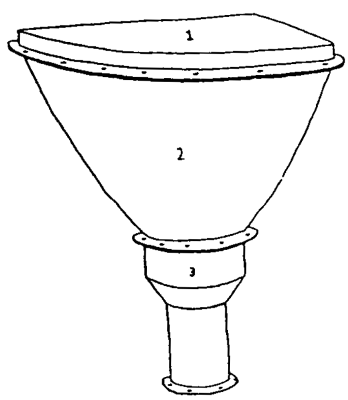

FIGURE 5. The gamma-ray detector assembly. 1. Scintillator Crystal. 2. Light Integration Cone. 3. Photo-Multiplier Tube.

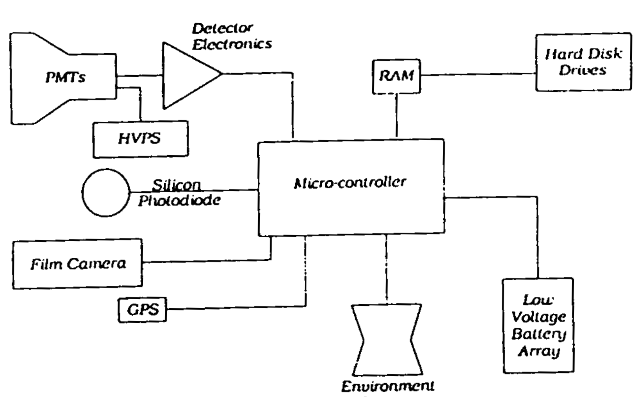

FIGURE 6. Block diagram of the Caltech GAMCIT experiment.