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CONSTRUCTION OF THE GAMCIT GAMMA-RAY BURST DETECTOR

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GAMCIT is a Space Shuttle 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.

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 Space Shuttle 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 a 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].

GET-AWAY SPECIALS

NASA's Get-Away Special (GAS) program allows organizations to fly small, self-contained payloads of their own design aboard the Space Shuttle. Caltech SEDS has reserved three GAS containers for this purpose, each with a 200 lb. payload capacity. The containers, 19.75 inches in diameter and 28.25 inches high, come equipped with an electronic interface, permitting astronaut control during flight. They may also be equipped with an optical window or motorized door assembly to enable direct observations of space.

OVERALL SYSTEM DESIGN

GAMCIT uses two standard NaI(Tl) scintillation gamma-ray detectors and two solid-state avalanche photodiode (APD) X-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 gamma-ray 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, especially BATSE. If an optical flash is detected, post-flight analysis 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, a small silicon charged particle detector is incorporated. 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 the payload 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 a Motorized Door Assembly (MDA), which exposes the experiment directly to space, is being used, the design of a space facing pressure vessel lid was an important task. The concerns that were considered during the design process included structural integrity, thermal insulation, and maximization of gamma-ray penetration.

These concerns were met by using a lid composed of Invar steel (36% Nickel). The regions above the scintillator crystals have the steel completely removed for greater gamma-ray penetration. The area above the camera lens is replaced by an optically transparent quartz window assembly.

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.

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 three major components of the detector system: the gamma-ray detector system, the X-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. 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 X-ray detector system consists simply of two small (1 cm square) avalanche photodiodes, mounted on top of the GAS canister.

The final 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 the payload will have sufficient film for 50 bursts. This is greater than the number of real bursts that are statistically expected, however, false triggerings may cause more exposures to be taken than a statistical analysis might expect.

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, the camera is expected to see up to seventh magnitude astronomical objects. Although the manufacturer suggests hypersensitizing the film prior to usage in astronomical applications, such a task would be logistically daunting, and acceptable results have been obtained without any such process.

Figure 3 (left side) shows a perspective view of the payload with all components integrated.

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 3 (right side) 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 the 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 μs, 100 μs, 1 ms, 10 ms, 100 ms, 1 s, 10 s, and 100 s. The outputs are multiplexed onto the data bus.

A 5.5 σ (where σ is the standard deviation of the data in a given time bin) detection scheme is implemented in the software. A running average and σ are 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. At this point, data from the APDs will also be recorded for ground-based analysis. 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 the payload detects a charged particle simultaneously with a gamma-ray it will not enter Burst Mode).

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, a careful analysis of available battery technologies and their ability to meet payload requirements was necessary. After a careful consideration of the products currently available on the market, and of those that fell within the NASA safety margins, standard commercially available alkaline D-size cells were selected. The cells have a nominal voltage of 1.5 V with a rated capacity of 14.25 Amp-hours. A DC-DC converter is necessary to ensure a steady output voltage. High voltage power supplies are also included to power the two photo-multiplier tubes and the two avalanche photodiodes.

The batteries are 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. Also, the whole power supply is protected by a 6 Amp fuse, chosen in accordance with NASA regulations, on the ground leg.

CONSTRUCTION AND TIMETABLE

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.

GAMCIT is likely to be manifested for launch on the Space Shuttle Endeavour flight on January 12, 1995. This flight is a 16-day, all space-viewing, low-inclination flight, which is ideal for the experiment. An added advantage is that this flight will be the first flight of the project's advisor, Dr. John M. Grunsfeld, formerly of Caltech (see below). In order to meet this launch date, the payload must be ready to deliver to NASA by September. The students working on the project plan to complete most of the construction by June and spend the summer testing the payload and integrating and debugging the electronics.

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. 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, experience has shown that projects such as this cannot succeed without faculty and staff support. Dr. John M. Grunsfeld served as the 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, 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 should be noted that securing course credit for work on the project has been very helpful in recruiting new members to the project team.

However, the challenges involved in the GAMCIT project go far beyond those of politics. Because the project's "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 this. 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.

The challenges and pitfalls involved in a project such as this, 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. The author welcomes 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 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., and 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.)

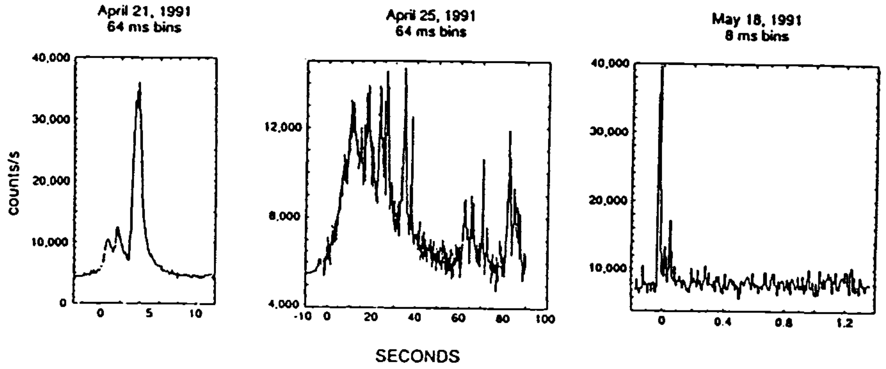

Figure 1: Three bursts detected by BATSE (reproduced from [1]), showing the wide variety of structure and varying time durations of gamma-ray bursts, from milliseconds to hundreds of seconds. The energies of gamma-rays in these plots range from 60 keV to 300 keV.

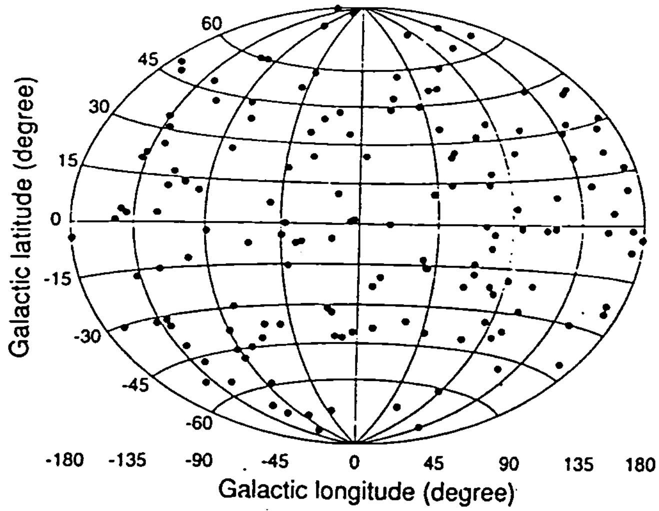

Figure 2: Angular location of gamma-ray bursts in Galactic coordinates as observed by BATSE (reproduced from [2]). This distribution shows no significant deviation from isotropy. In particular, no enhancement along the Galactic plane (latitude=0) is seen, as would be expected if the sources of gamma-ray bursts had the same distribution as the stars in the Galaxy.

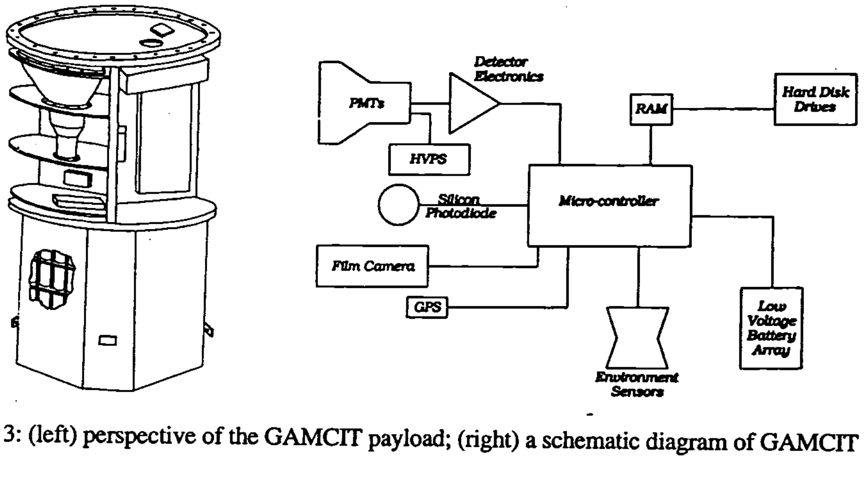

Figure 3: (left) perspective of the GAMCIT payload; (right) a schematic diagram of GAMCIT