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1. Executive Summary

GAMCIT (Gamma-ray Astrophysics Mission at the California Institute of Technology) is a student-designed and student-constructed experiment to monitor gamma-ray bursts that was carried onboard the Space Shuttle Endeavour on the STS-77 mission in May of 1996. The project was organized by Caltech's chapter of the Students for the Exploration and Development of Space (SEDS), an international organization of student space enthusiasts. The GAMCIT project is a unique one, even to Caltech. It is one of the few examples nationwide of a truly student-driven scientific research project. Every aspect of the project, from engineering design to purchasing to fabrication and testing, was performed or supervised by SEDS students. A loosely-organized Board of Advisors, including Caltech faculty and staff, JPL scientists and engineers, Caltech alumni, and even an astronaut, worked with the students along the way to provide assistance in scientific, technical, and logistical matters. However, the forty-some undergraduates involved were the ones who ultimately made the decisions and were responsible for the success or failure of the mission.

The payload performed normally in orbit (NASA's claim that the payload door closed during flight was later disproven) and successfully accumulated approximately 2 gigabytes of gamma ray data. Due to the combination of a software bug and an electronic glitch the temporal resolution of the data was reduced to about a few seconds. Due to excessive vibration during launch, the optical film camera failed to advance during flight. Despite these malfunctions, the experiment did perform well and yielded some interesting results. The environmental monitoring (sun sensor, temperature sensors, and pressure sensor) worked properly, shedding light on the in-flight conditions. The global positioning satellite (GPS) receiver performed much better than expected, providing timing information which allowed the gamma ray data to be precisely calibrated to universal time. A map of charged particle background was obtained which clearly shows the South Atlantic Anomaly. Finally, GAMCIT detected a gamma ray burst coincident with a detection by NASA's Compton Gamma Ray Observatory (CGRO).

While the experiment itself was only partially successful, the project as a whole was a complete success. The students who worked on GAMCIT benefited not only from knowledge of mechanical and electronic design details, but also from the general principles of experimental design, project management, and problem solving gained from being responsible for the entire research program. The principal students in the GAMCIT project have all since moved on to prestigious graduate programs in their subjects of interest, and many received lucrative fellowship offers based in large part on their experience with GAMCIT.

2. Introduction

2.1 What are Gamma-Ray Bursts?

In the late 1960s, the United States launched an array of satellites to detect violations of nuclear test ban treaties. These *Vela* satellites, despite their failure to detect any terrestrial nuclear detonations, uncovered a scientific mystery that would puzzle astronomers for at least a quarter of a century. Short, intense bursts of high-energy photons (gamma rays) occurred from seemingly random directions in the sky. Scientists were completely unable to match these bursts with any known astronomical processes.

Today, gamma ray bursts remain one of the outstanding mysteries in astronomy. Gamma ray bursts are perhaps the least understood astronomical phenomenon, despite the fact that they occur several times a day and may be the result of the largest energy releases in the universe. Scientists have been completely unable to pin down the origin of these events – at present over one hundred theories are “on the market” to explain the bursts. For decades, the distance to the burst sources was unknown by twelve orders of magnitude – some burst theories placed the sources at the outskirts of the solar system, others placed them at the edge of the known universe. To put this uncertainty in perspective, this would be equivalent to not knowing the distance to an object to the extent that it could be as close as the width of a human hair or it could be as far as the other side of the Earth.

Since the energy from any source falls off as the square of the distance to the source, this uncertainty in distance translates to an extraordinary (24 orders of magnitude) uncertainty in the energy release from the burst source. To contemplate this difference in energy, consider the energy released by dropping a staple through a distance of one-hundredth of an inch. Then consider the energy released by a 20 Megaton nuclear bomb. These two energy releases differ by roughly 24 orders of magnitude.

The greatest advances in gamma ray astrophysics before the time of GAMCIT's launch came from CGRO. Results from CGRO indicate that gamma ray bursts are distributed isotropically in the sky (equal amounts in every direction). This isotropy of bursts suggests that the sources are not inside our Galaxy, as we would then expect to see a clear majority of bursts in the galactic plane (the "Milky Way" as seen in the night sky). Another important CGRO result is that there appears to be a relative lack of fainter bursts in comparison to brighter ones. This suggests that the burst sources are "bounded" in space (that they do not extend to arbitrarily large distances).

In recent years, there have been two favorite classes of theoretical models of gamma ray bursts. One camp, championed by Don Lamb at the University of Chicago, suggests that the bursts originate in an extended halo around our galaxy. The opposing camp suggests that the bursts come from distant cosmological objects far outside the galaxy. At the time of GAMCIT's flight, neither camp even claimed to have determined the exact objects that cause the bursts, and neither side had conclusive evidence against the other theory.

While many experiments have been developed to study these bursts, their origin is still one of the great mysteries of modern astrophysics. Gamma ray astrophysics is still in its youth, and there is much that is not yet understood. In particular, further studies of the temporal structure of the bursts, the energy distribution of the bursts, and the intensity of the bursts at other energies and wavelengths are desperately needed. Further discoveries in these areas are expected to tightly constrain the models that describe the possible sources of these bursts. For a brief discussion of the exciting developments in this field since GAMCIT's flight, see the section "Current Status of the Field" at the end of this document.

2.2 The Get-Away Special Program

Since 1982, NASA's Goddard Space Flight Center has offered educational, commercial, and military institutions the opportunity to fly small (5 cubic feet, 200 pound) payloads on the Space Shuttle on a space-available basis, for a nominal fee. These payloads, known as Get Away Special canisters (or GAScans), are flown on the side of the Shuttle's payload bay or on bridges across the payload bay, essentially to fill empty space on the Shuttle. To date, over 150 of these payloads have flown in space.

GAS payloads all contain scientific or engineering oriented experiments, but NASA does not attempt to judge the scientific or technical merit of the experiments. The only requirement imposed by NASA is that the payload must undergo an intensive safety review process to ensure that the experiment poses no threat to the Space Shuttle or its crew. This safety review process nominally takes about one year, but for technically complex experiments like GAMCIT it can take as long as three years.

One important aspect of GAS payloads (and in fact the reason that they can be flown so inexpensively) is that they may not constrain the activities of the Shuttle in any way. In particular, GAS payloads cannot dictate the orientation of the Space Shuttle – a GAS experiment is very much "along for the ride."

2.3 Brief History and Motivation

The first Caltech GAScan was flown on STS-7 in June of 1983. The payload reservation, labeled G-033, was donated to Caltech by movie director Steven Spielberg after he received the reservation as a gift. Working late nights and holidays, fifteen undergraduate members of Caltech's now-defunct Student Space Organization designed and built two experiments, as well as the computer that ran and monitored the payload. One of the experiments examined the separation of oil and water in microgravity. The other grew radish seeds, testing the theory that roots grow downward because gravity forces dense structures (amyloplasts) to settle to the bottom of root cells.

Due to a regrettable error during the integration of the payload, the primary payload fuse was accidentally replaced with a fuse of lower current rating. When the experiment was activated by the Shuttle crew, the underrated fuse blew, leaving the experiment without power for the entire mission. Sadly, this payload was never reflown.

The GAMCIT experiment was originally conceived of in 1990 by Senior Research Fellow John Grunsfeld of Caltech's Space Radiation Laboratory. Dr. Grunsfeld approached the Caltech chapter of the Students for the Exploration and Development of Space (SEDS), and suggested that they team up to design and build the experiment.

In 1990 and 1991, Caltech SEDS pursued feasibility studies into a number of possible Shuttle experiments. In addition to the GAMCIT concept, students also considered experiments in protein crystal growth, granular systems, and the dynamics of magnetoelastic ribbons. In early 1992, Caltech SEDS decided to pursue the GAMCIT experiment.

The motivation for selecting the GAMCIT experiment hinged on a number of points: it was an experiment that could contribute significantly to science, it could be executed at low cost, it would provide an outstanding educational opportunity to the students involved, and it could be completed and flown within the tenure of a Caltech undergraduate.

2.4 SEDS and GAMCIT's Educational Mission

SEDS is a student organization that was founded in 1980 at MIT and Princeton and consists of an international group of high school, undergraduate, and graduate students from a diverse range of educational backgrounds who are working to promote space as a whole. SEDS is a chapter-based organization with chapters throughout the United States, Canada, United Kingdom, Latin America, and the Middle East. The Caltech chapter of SEDS has historically been one of the world's largest and most active chapters.

The SEDS mission statement reads: "SEDS is an independent, student-based organization which promotes the exploration and development of space. SEDS pursues this mission by educating people about the benefits of space, by supporting a network of interested students, by providing an opportunity for members to develop their leadership skills, and inspiring people through our involvement in space-related projects. SEDS believes in a space-faring civilization and that focussing the enthusiasm of young people is the key to our future in space."

One of the key components of the Caltech SEDS GAMCIT project is the educational mission. Not only should GAMCIT be scientifically productive and technically successful, but above all the students involved (mostly undergraduates) should be enriched by the experience of working on the project. Designing and constructing space hardware from the ground up is an educational experience that is not available in traditional undergraduate coursework. We are very proud that Caltech so strongly supports this type of "out-of-the-classroom" learning environment that is possible only through technical projects such as GAMCIT.

3. Experimental Concept

GAMCIT has two primary design goals: to detect gamma rays and to attempt to capture gamma ray bursts on film using an optical camera.

The GAMCIT mission takes advantage of its short mission life (about seven days) by storing the time of arrival and the energy of every gamma ray photon received. This detailed accounting of photons is not possible for longer-term missions (such as CGRO) because of the enormous quantity of data that is generated. The advantage of this approach is that much more detailed studies of the time history of gamma ray bursts can be performed, possibly yielding clues to the bursts' origins. The fact that all photons are recorded, not just those near triggered bursts, also means that a careful statistical analysis of the gamma ray background could be performed to search for the existence of very short bursts that may be missed by CGRO.

At the same time as GAMCIT records the gamma ray photons, it also constantly analyzes the gamma ray count rates to determine if a gamma ray burst is occurring. When the onboard computer determines that a burst occurs, it triggers a 35-mm film camera. Since GAMCIT has no pointing capability (since GAScans cannot give the Space Shuttle instructions), and since gamma ray bursts occur from random directions at random times, it is likely that any given gamma ray burst would not be within the camera's field of view. Over the life of GAMCIT's mission we estimate a few percent probability of catching a burst in the camera's field of view. While this is a high-risk mission goal, the potential scientific return would be enormous – a detection of an optical flash coincident with a gamma ray burst would strictly constrain the models of burst origins, and a non-detection would be just as valuable. The importance of the detection of an optical counterpart is evident from the discoveries of 1997 (see Current Status of the Field, below). In the optical counterpart search, GAMCIT also takes advantage of its short mission life by using a film camera instead of a CCD in order to increase spatial resolution.

Many ground-based searches for optical transients have been performed, but GAMCIT was designed to be unique in that its search is truly simultaneous with the gamma ray burst. Present ground-based searches (or rather, those before 1997) had time lags of at least fifteen seconds and usually several minutes between the time of the burst and the time of the optical observation. Since GAMCIT has its own gamma ray detectors, this delay is designed to be as short as one sixteenth of a second.

4. Chronicle of Payload Development

4.1 Design and Construction

While the conceptual foundations of GAMCIT were established in 1990, Caltech SEDS did not decide to pursue this experiment until early in 1992, after a careful feasibility study had been performed. Students spent the first half of 1992 crystallizing the payload concept and studying how the necessary components might be fit into the allowed payload envelope.

In August 1992, the project's advisor, Dr. Grunsfeld, left Caltech to join the astronaut corps at Johnson Space Center (he has since flown on STS-67 in March 1995 and on STS-81 in January 1997). Despite his departure, he has kept in very close touch with the SEDS students, providing advice and support along the way. Before he left, Dr. Grunsfeld recruited Caltech faculty, staff, and alumni, as well as two JPL scientists to serve on a Board of Advisors for the project.

In the fall of 1992, Professor Maarten Schmidt signed on as the lead advisor for the GAMCIT project. Throughout the 1992-93 school year, students researched the various options for different components (for example, film camera versus CCD). As many as twenty students were involved at this stage, many earning course credit through the Mechanical Engineering department.

In the summer of 1993, five students were awarded SURFs (Summer Undergraduate Research Fellowships) to produce a preliminary design of the experiment. This opportunity was an invaluable one, as it allowed the two mechanical engineering and three electrical engineering students to concentrate on the project outside of the normal academic pressure of Caltech. This summer work yielded a complete preliminary mechanical design of the payload (along with a mockup and several component prototypes), as well as preliminary schematics for the data acquisition and control systems.

During the 1993-94 academic year, the mechanical and electronic designs underwent analysis and refinement. A detailed thermal analysis of the complete experiment was performed, along with stress and fracture analyses for NASA. Because of the complicated nature of the payload (specifically, the opening door which allows the payload direct access to space and contains a custom pressure bulkhead), the students were subjected to a complex and time-consuming NASA safety review process to ensure the payload would pose no risk to the Space Shuttle. In early 1994, a preliminary form of the comprehensive safety data package was finally approved by NASA safety managers.

Unfortunately there was no funding available for student stipends during the summer of 1994. Consequently, students working in other departments were only able to contribute to the experiment part-time, and progress was slow. Nevertheless, by the end of 1994, many structural components had been machined, and the mechanical design was complete.

Early in 1995, Goddard Space Flight Center approved the final version of the safety data package, and construction began in earnest. By April the structure of the payload was complete, and the electronics were in testing. An Electro-Magnetic Interference test was successfully completed in April at JPL, clearing the way for delivery of the payload.

4.2 First Integration Attempt

In May of 1995, the payload was fully assembled, and the students accompanied it to the Kennedy Space Center for final testing and integration into Space Shuttle hardware. During integration, NASA technicians informed us that the electrical interface schematics they had provided earlier were in error. As a result, due to the short time left before the GAS hardware had to be installed into the Space Shuttle, the electrical engineering students took the bulk of the payload back to their hotel room to rewire the circuitry.

A key part of the testing and payload certification process is the leak test. This test must be performed on payloads with custom pressure bulkheads in order to ensure that the gases contained inside the experiment do not leak into the Shuttle's payload bay in excess of established acceptable levels. Since the main structure of the experiment was being rewired, the leak test proceeded with only the pressure bulkhead.

When the leak test was first performed, the pressure bulkhead experienced a leak that was outside of the acceptable margins. In order to pinpoint the source of the leak, the students reluctantly agreed to allow NASA technicians to insert a small quantity of helium into the canister (helium can be detected coming through leaks with special testing equipment, but could also damage the sensitive photomultiplier tubes mounted on the inside of the bulkhead). Rather than flowing the helium into the container and letting some of the gas inside vent out, NASA technicians pulled a partial vacuum on the inside of the canister in order to backfill with helium. This procedure had not been authorized by the students and was not part of any standard test protocol.

When this vacuum was pulled on the inside of the payload, the custom pressure bulkhead fractured catastrophically. This bulkhead was carefully designed to withstand the vacuum of space on the outside, but could not withstand a vacuum on the inside without the supporting structure (which was being rewired). This serious error, caused by lack of procedural control, caused the payload to be totally unflightworthy. At this time, the principal students in the project were graduating, project funds were exhausted, and the fate of GAMCIT was uncertain.

4.3 Picking up the Pieces

As a result of the disaster during integration, NASA safety managers changed their minds about many of the safety aspects of the payload. Much of the payload had to be redesigned and rebuilt to accommodate these new safety rules. Since most of the students involved in the project had graduated, there were few people around to work on the payload. In the fall of 1995, the three principal students (one still in Pasadena, one in Chicago, and one in Ann Arbor) decided to pull the project back together despite the distance. Mike Coward, in Pasadena, worked to accommodate the new safety changes as they affected the electronics. Al Ratner, in Ann Arbor, worked long-distance with Caltech's student shop to refabricate the pressure bulkhead. Ben McCall, in Chicago, revised and resubmitted all the safety paperwork. Caltech administrators obtained a grant from the Ahmanson Foundation which supplied the necessary funds to reconstruct and redeliver the payload.

In February 1996, Ben and Al returned to Caltech to help put the payload back together. It was an intensive effort – in the course of a few weeks the entire payload was reconstructed to comply with the new safety restrictions. Several major obstacles were overcome, including a serious problem with the battery containment system. After weeks of nonstop work day and night, the experiment was finally ready for delivery in March.

4.4 Second Integration Attempt

When the payload arrived at Goddard Space Flight Center for the first step of integration, it was immediately greeted with new safety concerns. Aspects of the payload that had been approved without issue at the first integration attempt were suddenly major safety concerns. Students spent many hours discussing these new safety concerns with safety managers, and a few changes were made to the payload at the last minute. Meanwhile, students worked on the last-minute electronic debugging and completed the assembly of the battery containment system and the rest of the payload.

The battery containment system proved to be a major issue that nearly derailed GAMCIT's flight. Due to safety restrictions, the batteries must be contained in a nonconductive and separately sealed container, which is then vented to space if the batteries outgas. The novel design of GAMCIT's battery system made the optimum use of available space but also proved very difficult to seal. Eventually all of the joints in the system had to be encased in epoxy in order to effect a tight seal. However, after sealing it was determined that some of the epoxy had leaked into the system and blocked the internal airways before curing. This meant that while the battery system was sealed, it would not be vented.

While students were studying ways to solve this problem, time ran out at Goddard and all of the GAS hardware for the flight had to be moved to Kennedy Space Center. The students flew down to Kennedy with a new approach – they drilled holes into the battery system to open up new airways, then sealed the resulting holes with a faster curing epoxy. This approach, though tedious, proved effective and the battery system finally held pressure and had sufficient venting.

When the payload was finally fitted into the actual GAS canister, however, the entire system did not hold pressure. The leak was slightly over the allowable levels, but it was indeed outside of the specifications. Evidence from previous tests of the GAMCIT bulkhead suggested that it had almost no leaks, and some other tests proved that the battery venting system was not responsible for the leak. However, the GAS project had never encountered leaks this large in their hardware, and therefore assumed the leak was caused by our hardware. NASA technicians replaced some of the seals in the canister itself, but to no avail. Time was running out, and it appeared that GAMCIT would not in fact fly.

The students appealed to NASA safety managers, arguing that the slight leak that was present was not a threat to the Space Shuttle due to the lack of outgassing or hazardous materials inside the canister. Additionally, students suggested that the canister be filled with a very dense inert gas known as sulfur hexafluoride (SF_6), in order to reduce the rate of gas escaping through the fixed leak. Evidently these arguments, along with the arguments made by NASA technicians, were effective, as GAMCIT was granted a waiver for the small leak. Finally GAMCIT was mounted on the Space Shuttle Endeavour!

5. The Flight of Endeavour (STS-77)

The Space Shuttle Endeavour roared perfectly into orbit on May 19, 1996, cheered on by the students who worked on the project and our lead advisor, Astronaut John Grunsfeld. The launch occurred just before dawn, and the Shuttle's exhaust plume cast a shadow on the sky as the sun rose.

Normally, GAS experimenters have no contact with NASA during the flight. GAS payloads simply go along for the ride and then are handed back to the experimenters once the Shuttle has landed. However, in GAMCIT's case, things were different.

On May 20th we received the following email (G-056 is GAMCIT's official designation):

```
The GAS Group A was performed on time starting at 0/06:09.  The G-056 Door was shown on video
opening at MET 0/06:13:02.  The end of GAS Group A was reported at 0/06:18:44.
```

Figure 1. Launch of Endeavour, with GAMCIT aboard.

This was very good news indeed, as it indicated that the payload had booted up and began operation normally. The door is not operated by NASA directly, but rather by the payload computer, which was evidently working as planned. Mike Coward responded by writing:

> `Yes! The door worked! I'm so happy. (It means that the computer booted, started running its program, and should be collecting data.)`

As time went by we received notifications from NASA's CGRO satellite about gamma ray bursts that had occurred. We believed that everything was well and GAMCIT was busy collecting data! However, on May 21st we received this email from the GAS project at NASA:

> `At 1:30 am this morning the crew observed that the G-056 door was closed. At this point we do not know why. We would like you to confirm that you have a malfunction input for over-temperature and that your payload does an orderly shutdown when it detects low battery voltage. Do you know of any other reasons that your experiment would not send the 12V door signal?`

Communications by phone with NASA personnel later that day indicated that at 11:00 am the crew observed the door to be open. Apparently no other observations were available during that time period. We also learned that the head of the Shuttle Small Payloads Division (which oversees GAS) had given an order to terminate power to GAMCIT if it closed again, thus shutting off the mission for the duration of the flight.

The students involved quickly scrambled to figure out what the possible source of this malfunction could be. The suggestion given by NASA, that our experiment had shut itself off due to over-temperature, seemed implausible given that the experiment had not been running long. The only plausible scenario, after a careful re-analysis of the flight software and microcode, was that a cosmic-ray had caused a Single Event Upset in the payload's microcontroller, causing it to reset the door. We quickly sent an e-mail to the head of the Small Payloads Division explaining this scenario and assuring them that it would happen infrequently and would pose no safety threat to the Shuttle. Our advisor, Astronaut John Grunsfeld, also pleaded our case by telephone.

The next day, May 22nd, we were notified that our efforts had succeeded:

> `I assume you already know that John and Ted discussed your info this morning and that they will let it go unless it closes and opens repeatedly. Anyway, congratulations.. Now we just need a burst!`

Finally, on May 28th, we were notified of the end of the mission:

> `The last GAS activities to shut off all remaining experiments was completed at MET 09/01:34:00. The G-056 Door was open and was commanded closed at 09/01:31:00. The crew also took video of the door closing but it was not shown on the downlink. Note: the CAPCOM very clearly called G-056 "John's experiment". They also asked if the G-056 Door Power Backup - status ON was correct.`

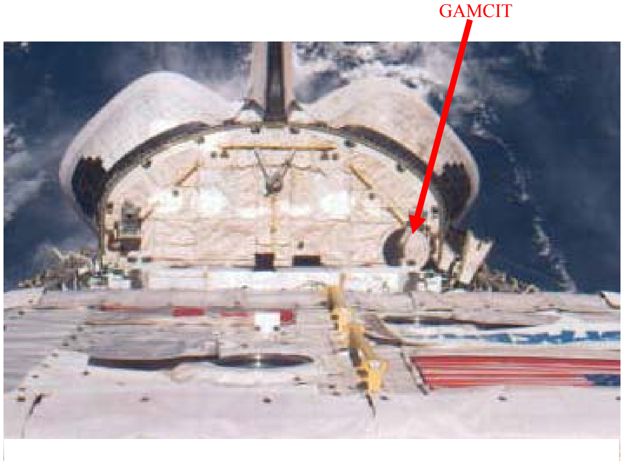

Figure 2. The open door of GAMCIT in the payload bay.

On Wednesday morning, May 29th, Space Shuttle

Endeavour glided in for a perfect landing at Kennedy Space Center. GAMCIT was back on Earth, and soon the experiment would be back at Caltech.

6. Results

6.1 Mechanical and System Performance

In mid-June, the students returned to Kennedy Space Center and opened up the payload for the first time since landing. We were very pleased to find that nothing at all had changed visually inside the payload! There were no loose cables or bolts…everything was just as we had left it during integration.

We also breathed a sigh of relief when we hooked up our external equipment and were able to boot up the payload successfully with external power (the onboard batteries had been exhausted during flight). We found that all of the hard drives were working properly, and that the payload had accumulated nearly two gigabytes worth of data (enough data to fill three CD-ROM discs)! The only slight disappointment is that a hard drive error had rendered a few of the data files unreadable, but this constituted a loss of much less than one percent of the data.

One great disappointment that was quickly evident was that the optical film camera had not advanced during flight. After a careful analysis of the housekeeping data, it was determined that the onboard computer had attempted to fire the camera some fifteen times during the mission. Subsequent electronic testing revealed that the trigger signal was reaching the camera's input properly. Evidently the source of the problem was that the camera had not been sufficiently insulated from the extreme vibrations that occur during the Shuttle launch, and the film had slipped off the drive mechanism. The camera used in the payload was never designed for an environment as extreme as a Shuttle launch, and the design team realized all along that it was taking a calculated risk by using the camera. While we were saddened to learn that we had no optical data, we were still very excited about the vast quantity of gamma ray and environmental data that had been successfully gathered.

6.2 Environmental Analysis

Figure 3 shows the temperature reading on the camera's temperature sensor (curve) and the times when the sun sensor indicated that the sun was within the field of view (vertical bars). This figure demonstrates that the sun sensor was working properly -- the sun sensor activated at the correct times (as estimated from the shuttle's orbital data). Additionally, we can see the impact of the solar heating on the optical camera.

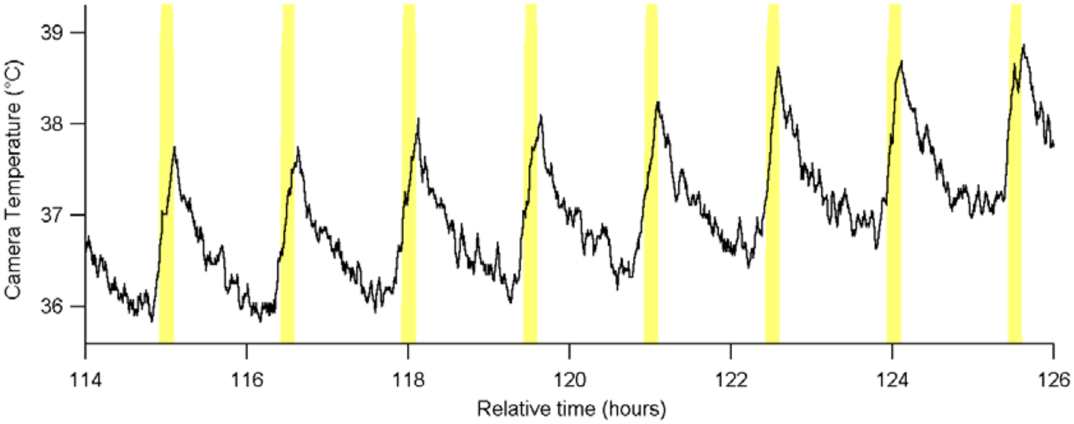

Figure 3. Camera temperature sensor (curve) and sun sensor (vertical bars).

In Figure 4, the top curve shows the temperature recorded by the sensor on the optical camera. The rapid variations are due to orbital variations in solar heating (see the figure above). In the middle of the top curve is a smoothed version of the same data, which emphasizes the long term variations in the camera temperature. These are caused by long term changes in the shuttle's orbit and attitude. The bottom curve shows the temperature recorded by a temperature sensor at the bottom of the experiment's main structure. It has also been smoothed, and the smoothed data are also shown. This figure demonstrates that the camera (which views space) is exposed to much higher temperature swings (1-2 °C) than the experiment interior. The figure also shows the thermal damping of the experiment, as the interior lags behind the long-term changes that the camera sensor sees.

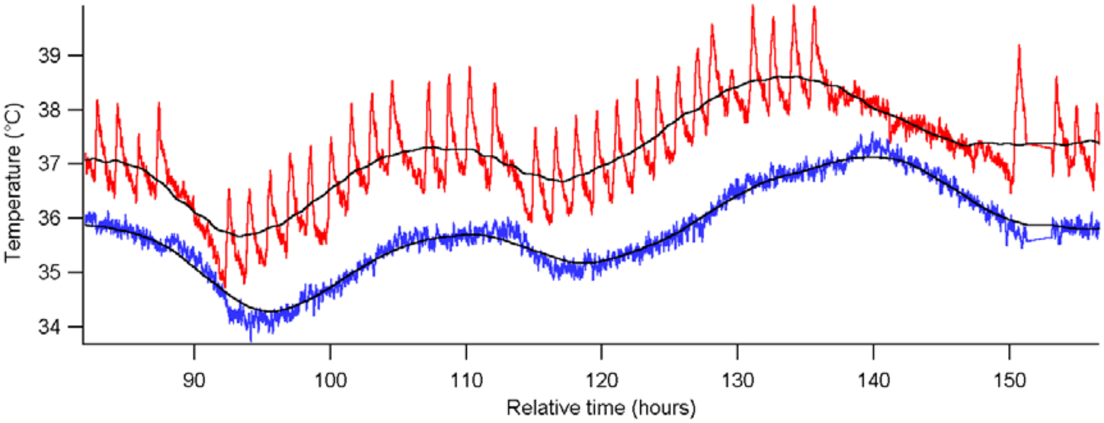

Figure 4. Camera temperature (top) and main structure temperature (bottom). Smoothed versions are also shown.

Figure 5 shows the temperatures recorded by temperature sensors on two of the experiment's hard disk drives. On the left side of the figure, the "top" hard drive is operating, and therefore is warmer than the "bottom" hard drive, which is in stand-by mode. At around 11 hours, the top hard drive turns off, and the bottom one turns on. This figure shows that our environmental monitoring yields data about the experiment operation as well as the environment that the experiment was in. It also gives a good indicator of power expenditure versus temperature rise for the hard drives.

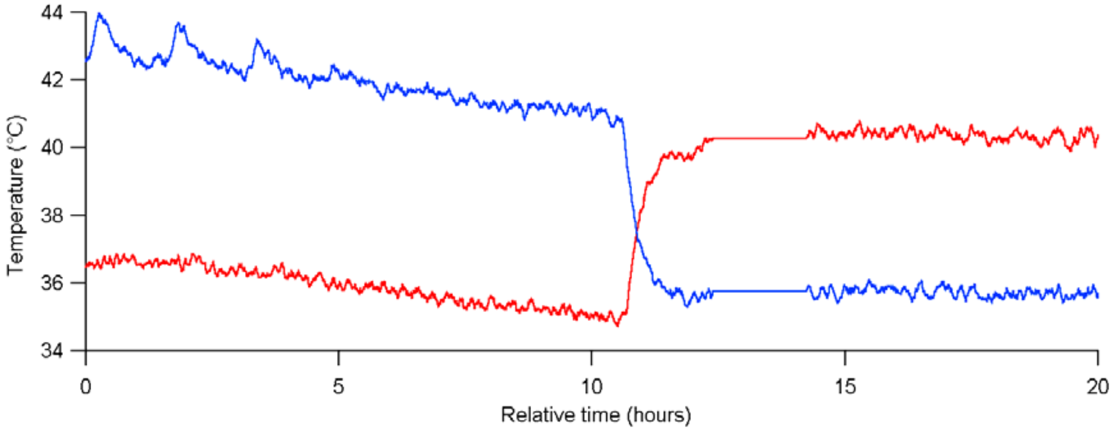

Figure 5. Two hard drive temperature sensors.

Figure 6 shows the data obtained from the onboard pressure and battery voltage sensors (the thick curve shows the battery voltage and the thin curve shows the internal pressure). [For battery voltages greater than 13 volts or less than 8 volts, this sensor is not reliable and was not calibrated.] Interestingly enough, the results show that the payload had an internal pressure of about 12 psi (slightly less than the atmosphere's pressure of 14.7 psi) and remained roughly constant throughout the flight. The minute variations that are observed are probably due to thermal fluctuations, which change the pressure of a fixed volume of gas. However, an overall downward trend is distinctly noticeable, and a least-squares fit gives an average leak rate of about 0.1 psi per day.

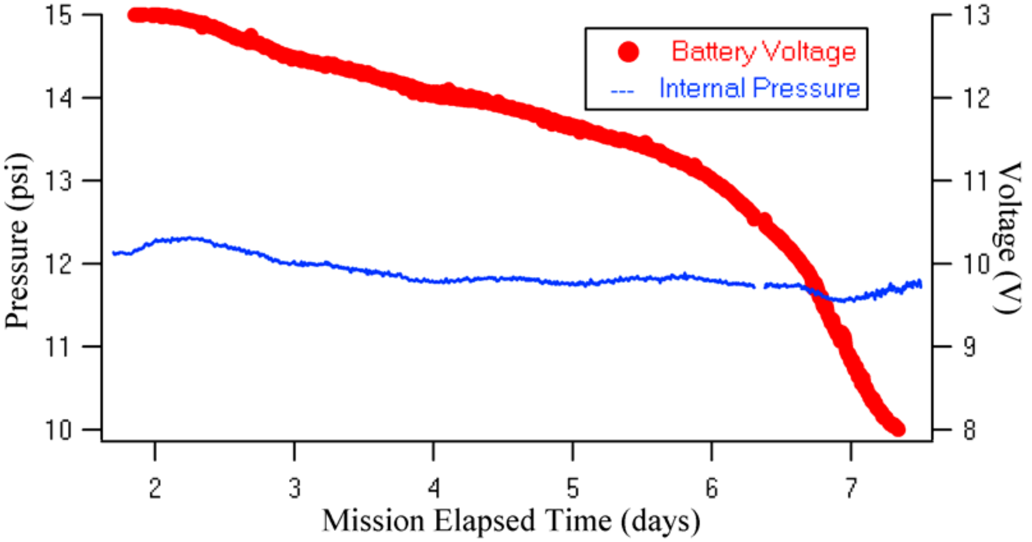

Figure 6. Battery voltage (thick) and pressure sensor (thin).

6.3 Global Positioning Satellite (GPS) Receiver

In order to accurately time the arrival of gamma rays, GAMCIT was designed to utilize a Global Positioning Satellite (GPS) antenna. These antennas, often found in handheld positioning devices, receive signals from a constellation of satellites in geosynchronous orbit. GAMCIT is the first GAScan (though not the first Shuttle payload) to utilize a GPS receiver. Despite the extremely limited visibility (due to periods when the Shuttle's payload bay faces Earth and blockage from the payload's door), GAMCIT consistently received timing information from the GPS satellites and even was able to obtain a few position "fixes" over the course of the flight. This aspect of the mission was far more successful than anticipated, and allowed the gamma ray data to be calibrated precisely to universal time.

6.4 Measurements of Charged Particle Background

As stated earlier, the gamma ray detectors on GAMCIT gathered nearly two gigabytes of data over the course of the mission. This data has been reprocessed to show the number of gamma ray counts received each second. In reality, not all of these counts are due to gamma rays – because of the way the detectors work, they are also sensitive to charged particles trapped in the Earth's magnetic field. By correlating the count rate with the latitude and longitude of the Shuttle at any given second, we can map out the Earth's magnetic field as measured by the number of charged particles.

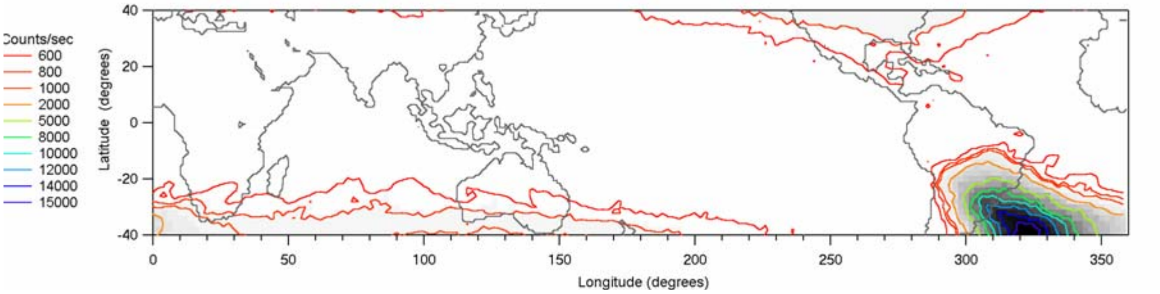

Figure 7. Charged particle contour map from GAMCIT.

Figure 7 shows a contour and grayscale map of the charged particle flux superimposed on a map of the region of the world that GAMCIT flew over. The most striking feature of the plot is the dark spot in the southern part of the Atlantic Ocean – this is not an instrumental artifact but indeed a true feature of the Earth's magnetic field that scientists call the South Atlantic Anomaly (SAA). The SAA is a region of intense charged particle flux (GAMCIT observed over 15,000 counts per second versus a normal background of less than 600) caused by the fact that Earth's magnetic field is not a perfect dipole.

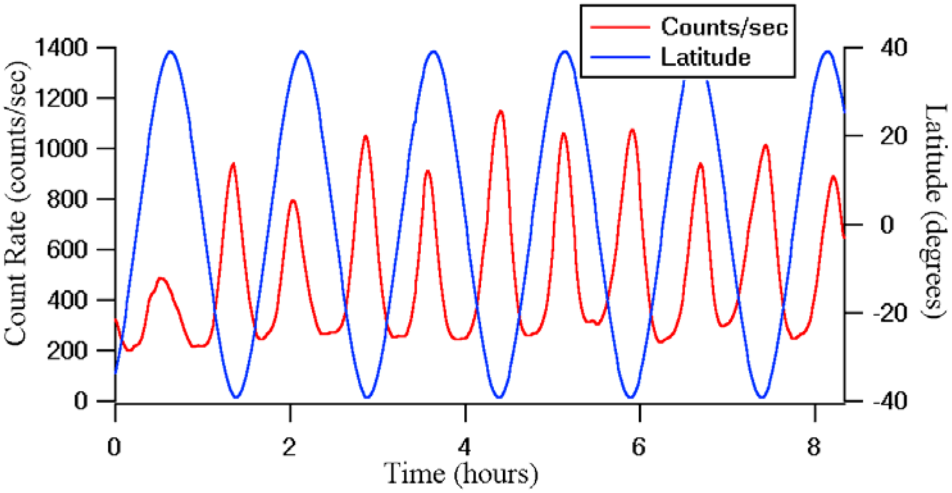

Figure 8. Charged particle count (red) and latitude (blue).

Another feature clearly evident in the plot is the variation of count rate with latitude – as GAMCIT travels closer to the poles (higher absolute value of latitude), the count rate increases. This effect is due to the fact that the magnetic field is stronger nearer the poles, and thus the charged particle flux is higher. While the effect is slightly visible in Figure 7, it can be very clearly seen by plotting count rate and latitude versus time, as demonstrated in Figure 8 for a short section of the data.

With this evidence in hand, we can conclusively state that the detectors did see the proper background levels and fluctuations expected in low-earth orbit. This is a very satisfying experimental confirmation that the detector system operated as expected.

6.5 Did the Door Really Close?

As mentioned above, the Endeavour crew reported that GAMCIT's door had closed and subsequently reopened during the flight. The students involved proposed a Single Event Upset of the microcontroller as the only plausible explanation for this activity, but were incredulous that this would have occurred. From a detailed analysis of the data obtained by the payload, we have conclusively established that the crew was in error and that the door did not, in fact, close. It is very fortunate indeed that we were able to persuade NASA managers to allow the experiment to continue despite this "closure"!

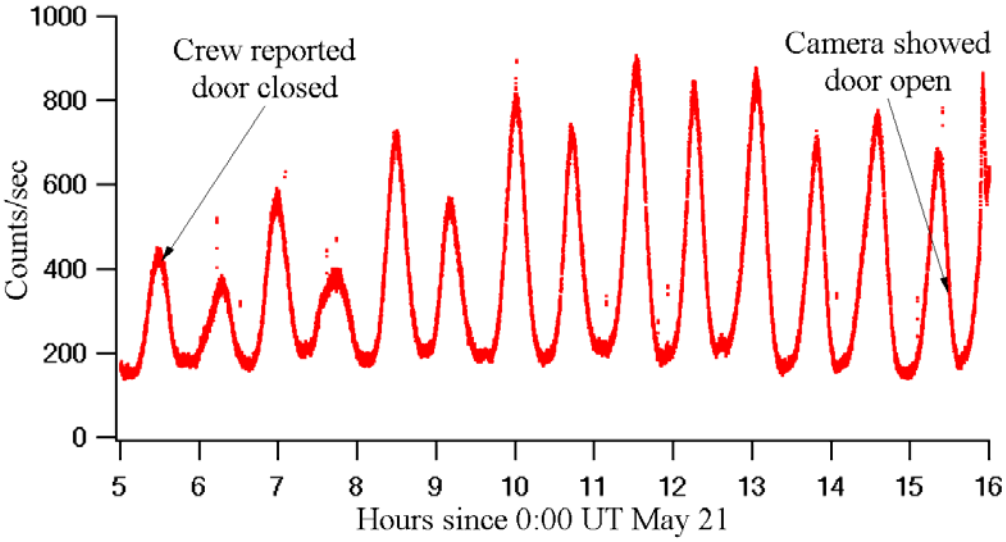

Figure 9. Orbital variations of charged particle background during supposed door closure.

The first piece of evidence supporting the conclusion that the door did not close is the continuity of the data stream. In order for the door to have closed, the main computer would have had to either issue a command to close the door, or be shut down. Had the computer issued a command to close the door, it would have recorded that information in the stream of housekeeping data – while the initial command to open the door (upon payload activation) did appear in the housekeeping data, there were no other door operation commands. Had the computer been shut down, it would have created a new directory for data files upon boot-up, and it would have reset the filenames to DATA0000. At de-integration at Kennedy Space Center, the students were able to quickly determine that there was no separate directory, and that the filenames had not been reset.

The second piece of evidence against a door closure is the presence of GPS timing signals during the period when the door was supposed to have been closed. These signals, as mentioned above, are sent from satellites in geosynchronous orbit, and could not have been received by GAMCIT's antenna had a thick aluminum plate (the door) been in front of it.

The third, and perhaps most convincing, piece of evidence is that the gamma ray background rates during the supposed closure were consistent with the background rates when the door was known to be open, and the expected orbital variations were seen, as is obvious from Figure 9.

Based on all of the available evidence, we are forced to conclude that GAMCIT's door did not actually close during the mission as reported by Endeavour's crew. Our calculations show that it was sunset when the call down was made that the door had closed, so perhaps some change in lighting led to this misunderstanding. We should also note that in a post-flight interview, one crew member expressed some doubt as to whether the door had actually closed. Whatever the circumstances, we are pleased that the experiment performed properly and that it was allowed to operate for the duration of the mission.

6.6 Some Problems with the Payload

In the process of analyzing the gamma ray data, some problems with the way the data were taken and stored came to light. The most serious problem was that due to a bug in the main computer's software, the detector that each gamma ray photon came from was not stored. In other words, each photon that was recorded might have come from either of the two detectors, and we have no way of knowing which.

On the face of it, this may sound like a minor glitch. However, because of the way the data is recorded, this actually causes some major trouble. Each detector has its own separate electronics which time-tag the photons as they are detected – the electronics write down which microsecond of the current 1/16th-second bin the photon arrived in. Each detector then sends a stream of these photon packets to the main computer, and the photons are then recorded onto the hard drive in the order in which the main computer queries these two streams. Without the information of which detector a photon came from, it is impossible to reconstruct the stream of photons from either detector. Additionally, due to an electronic glitch, one of the detectors reports photons a little slower than the other, causing the two streams of photons to become "out of sync" – this in turn makes it impossible to determine the count rates of photons on short time scales.

While GAMCIT was designed to study the temporal distribution of gamma rays at very short time scales (on the order of microseconds), this combination of glitches caused the count rates only to be valid on longer time scales (on the order of seconds). From other data recorded, it is possible to estimate how far "out of sync" the two photon streams were at any given time, but it is impossible to reconstruct the actual arrival sequence of photons.

The final data product that was generated from the mission specifies the approximate counts received per second for each second of the flight. However, due to the problems discussed above, these count rates are not completely precise – the data product also contains an estimate of the uncertainty for each second. If a gamma-ray burst were to be seen in the data, it would appear "smeared out" in time due to these problems – one detector stream would report the increased counts and then a short time later the other detector would report it.

It is unfortunate that this software bug (which was introduced shortly before flight) and this electronic glitch (which is probably caused by pickup noise) conspired together to seriously reduce the temporal resolution of the GAMCIT detectors. After over a year of trying to find an ingenious way to circumvent these problems with post-processing, we believe we have done the best we can to restore the original data set. We are very pleased that the data set that was produced has yielded such good results.

6.7 A Gamma Ray Burst!

Because of the problems with the data discussed above, "features" that appear in GAMCIT's data set alone are not rigorous enough to serve as credible scientific evidence of a gamma ray burst. However, it is very reasonable to compare our data with that of other orbiting gamma ray observatories to look for correlations. With this in mind, the eight gamma ray bursts observed by NASA's CGRO were analyzed carefully. Of these eight bursts, four occurred from directions in space that were on the other side of the Earth when viewed from GAMCIT. Since gamma-rays cannot penetrate the Earth, those bursts were not visible to GAMCIT. Another burst occurred outside of GAMCIT's field of view (on the other side of the Space Shuttle, which blocked the gamma rays).

Three bursts remained, which were in GAMCIT's field of view when they occurred. The first two of these bursts were fairly weak bursts and occurred at large angles to GAMCIT's line-of-sight. Because the detector "looks" smaller to an incident gamma ray burst at larger angles, the sensitivity is quite reduced. As expected, these bursts were not evident in the GAMCIT data set.

However, the third burst (which occurred at 2:23 UT on May 24) was only 9 degrees from GAMCIT's line-of-sight, as measured by NASA's CGRO. Additionally, it was a fairly bright burst, so we hoped that it would be evident in the data set. Sure enough, it is clearly seen at the correct time in the GAMCIT data set, as seen in Figure 10.

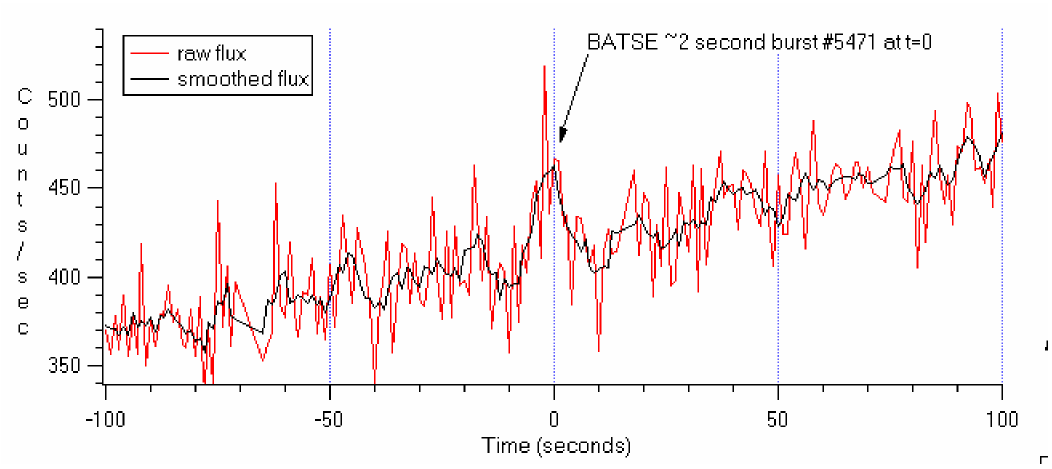

Figure 10. Gamma ray burst observed by GAMCIT.

While the feature in this graph might not be convincing evidence of a gamma ray burst when viewed in isolation, the fact that it is seen at exactly the same time as the CGRO burst, while pointed directly at the burst, is very convincing! Additionally, CGRO reported that this burst was approximately two seconds in duration – when the "uncertainty" in the GAMCIT count rates is taken into account, the profile of the peak in the plot is approximately what would be expected.

7. Conclusions

The flight of the GAMCIT payload could not in good faith be called a complete and total success. Its key shortcomings were the fact that the camera did not advance and the fact that a software bug and electronic glitch conspired to reduce the temporal resolution of the gamma ray data.

However, GAMCIT did successfully observe a gamma ray burst, and as a whole the experiment behaved as designed – mechanically, electronically, and as a complete system. The gamma ray detectors operated properly, as evidenced by the plot of count rate versus latitude and longitude. Additionally, the payload did operate as specified for the expected lifetime (about seven days), and it did not close its door at any point.

As a GAScan, then, it is only fair to consider GAMCIT moderately successful. Many GAScans that are launched suffer some sort of catastrophic failure, not unlike the first Caltech GAScan (where the fuse blew). The fact that GAMCIT operated essentially as designed and returned valuable data certainly ranks it in the upper echelons of GAScans.

As a project, however, GAMCIT must in all fairness be declared a resounding success. The driving philosophy behind the GAMCIT project has always been to aim for high scientific return but to ensure high educational return. In terms of educational return, GAMCIT definitely exceeded expectations. The students have benefited not only from knowledge of mechanical and electronic design details, but also from the general principles of experimental design, project management, and problem solving. All of the students who were deeply involved in the GAMCIT project have since moved on to prestigious graduate programs in their fields of interest, and many of them received lucrative fellowship offers based in no small part on their GAMCIT experiences. For all of us, GAMCIT was an invaluable educational experience, and certainly one of the defining aspects of our undergraduate careers.

8. Acknowledgements

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Trimble Navigation	donation of GPS unit
Duracell	donation of batteries
Hewlett-Packard	donation and loan of test equipment
Intel	donation of desktop computer
Amptek	loan of detector electronics
Hamamatsu	donation and loan of detectors
Delta Airlines	discount airfare for integration
Analog Devices	donation of electronic components
Fluke	donation of test equipment
AutoDesk	donation of mechanical CAD software
Xilinx	donation of electronic equipment
Samsung	donation of memory
EMJ America	loan of flight computer for test
Telatemp	donation of sensors for shipping
Bicron	donation of detectors
Melcher	donation of power supply
Teledyne Relays	donation of relays
Megatel	donation of flight computer

9. Current Status of the Field

The launch of the Italian BeppoSAX satellite in 1996 heralded a new era in gamma ray burst astrophysics. The BeppoSAX satellite combines gamma ray burst detectors with X-ray telescopes which are able to localize gamma ray burst sources precisely within hours of the burst. The precise locations from BeppoSAX can then be used by ground-based astronomers to followup with observations of the burst sources in optical, radio, and other wavelengths. In 1997, the first optical transient associated with a gamma ray burst was found, indirectly vindicating the original concept of the GAMCIT mission. For at least one gamma ray burst, a radio counterpart has also been observed. For one gamma ray burst, Caltech astronomers using the Keck telescope in Mauna Kea, Hawaii have observed spectral features in the optical transient which indicate that the burst occurred at cosmological distances, not in a halo surrounding the Milky Way galaxy. The problem of gamma ray bursts is by no means solved, but the data currently pouring in from BeppoSAX and ground-based observations will certainly shed more light on this mystery in the coming months and years.