Comparison of a High Purity Germanium Gamma Ray Spectrometer and a Multidimensional NaI(Tl) Scintillation Gamma Ray Spectrometer

A Senior Project

presented to

the Faculty of the Departments of Aerospace Engineering and Physics

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

Greg Stratton

July, 2011

Abstract: This report compares two different gamma ray spectrometers in terms of performance, operation, and apparatus and also investigates the design and integration challenges of using gamma ray spectrometers in space. The first spectrometer is a one-dimensional high purity germanium (HPGe) spectrometer and the second is a multidimensional NaI(Tl) scintillation spectrometer (MGRS). The key results show that the HPGe exhibits 15 to 27 times better energy resolution than the MGRS, but the MGRS is 52 times more sensitive and removes 177 % more of the background radiation.

1.0.0 Introduction

Gamma ray spectroscopy measures electromagnetic radiation in the gamma ray spectrum of radioactive sources. This is performed through the process of the counting and measuring the energy of individual photons emitted from elements. The measurement of gamma rays is valuable for the determination of the elemental composition of a wide variety of sources. The measured energy of a gamma ray corresponds to the type of element and its isotope, while the number of counts corresponds to the abundance of the radioactive source. The process of measuring a gamma ray begins at the radioactive source, which emits high energy photons during its unstable decay. When one of the photons gets absorbed by a detector, there is a reaction that causes the electrons to get excited and give off energy. This energy given off by the electrons is then recorded by electronic sensors as an analog signal. After processing and often amplifying the signal, converters change the analog signal into a digital signal to be read by a computer. Finally, the computer records the energy level of each pulse and adds up all of the pulses onto a histogram. In measuring these gamma rays, there is significant noise and unwanted radiation that must be accounted for by using passive shielding such as lead or active shielding such as anti-coincidence detectors that veto unwanted radiation.

This process is high customizable and there are multiple methods of measuring gamma rays. This project compared two different types of gamma ray spectrometers in several different regards. Different types of detectors are used for different methods of recording the response of gamma rays exciting electrons. One common method of converting the energy of the gamma

rays photons is called scintillation, which involves turning the energy into visible light. Many materials are used for this detection including inorganic crystals and organic plastics, but the most commonly used are alkali halide salts and of them, NaI(Tl) crystals are one of the most common[1]. Even though these crystals were the original primary detector type when gamma ray spectroscopy first began in the 1940s, they still exhibit among the highest sensitivity of any gamma ray spectrometer today. Other common scintillation detectors include CsI(Na or Tl) and bismuth germinate (BGO) crystals and various organic plastic materials. The other common method, used by solid state semiconductors, creates electron/hole pairs that converts the energy of gamma rays into electricity. These detectors use significantly different materials and hardware compared to scintillation detectors. High purity germanium detectors stand out as the most commonly used solid state detector material, but other commonly used materials include Si(Li)[2] and CdZnTe (cadmium-zinc-telluride) detectors. Each detector type carries its own advantages and disadvantages, which is the primary investigation of this report.

Additionally, gamma ray spectrometers can be used remotely, which gives them to applications in inhabitable environments such as in space. This ability along with the incredible radiation environments of space make these instruments a frequent primary component of a spacecraft payload. Many different space applications for gamma ray spectrometers include Mars orbiter and lander missions, lunar missions, asteroid missions, and cosmic observatory missions. The reason why the detection and measurement of high energy radiation has so many applications is because there are countless different sources that produce gamma rays. Radiation from gamma ray bursts, the most powerful explosions in the universe, are measured to determine their potency and origins[3]. Many other cosmic sources of gamma rays in the universe include but are not limited to stars, neutron stars, black holes, and many other unknown sources[4].

Additionally, the measurement of gamma rays emitted from bodies within our own solar system can be used to determine origins and elemental composition. Table 1 shows several of the missions that have featured gamma ray spectrometers on their payload.

Table 1. Sampling of previous and current spacecraft using gamma ray spectrometers.

Mission	Primary Space Agency	Types of Gamma Ray Spectrometers	Years in Operation
Cosmos/sun sampling missions			
Compton Gamma-Ray Observatory[5]	NASA	• 8 NaI(Tl) scintillators with 8 CsI(Na) scintillator active anti-coincidence shields • 4 NaI(Tl) scintillators with 4 CsI(Na) crystals in active anti-coincidence with barrel-shaped CsI shield in electronic anti-coincidence, surrounded the central detector on the sides and provided coarse collimation. 7 photomultiplier tubes • Liquid scintillator array that detects photons and compton scatters them onto NaI(Tl) scintillator array. Each detector has plastic anti-coincidence shield. Used to make map of sky.	1991-2000
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)	ESA	• 128 x 128 cadmium-telluride tiles backed by a 64 x 64 plane of Caesium-Iodide tiles with passive lead shielding and active BGO detector shielding to make up gamma ray imaging system[6]. • 19 hexagonal HPGe detectors cooled by Stirling cooling process. Plastic anticoincidence shield around and below the detectors[6].	2002-Present
Fermi[7]	NASA	• Large Area Telescope: uses pair production of electrons/positrons on tungsten sheets that are tracked by silicon detectors to determine path of electrons and positrons. CsI scintillator crystals measure the energy and plastic detectors for active anti-coincidence shielding. • GLAST Burst Monitor: 12 low-energy NaI(Tl) detectors and 2 high energy BGO detectors used to detect gamma ray bursts.	2008-Present
Solar System body sampling missions			
Near Earth Asteroid Rendezvous (NEAR)[8]	NASA	• NaI(Tl) scintillator detector in a cup shield of BGO anti-coincidence shielding	1996-2001

2001 Mars Odyssey[9]	NASA	• Large HPGe detector mounted at the end of a boom for reduced noise from spacecraft. Cooled to 90 K operating temperature via radiator.	2001-present

The first gamma ray spectrometer tested for this project uses a single high purity germanium crystal detector, which is clearly a relevant material used in several space applications. Dr. Roger Grismore has possessed this spectrometer for a few years, since a student first assembled it for a Cal Poly senior project. This instrument is primarily used only as a compliment to Dr. Roger Grismore's primary system, the multidimensional NaI(Tl) gamma ray spectrometer (MGRS). The MGRS was first assembled at Indiana State University in 1972 and moved to Cal Poly in 1987, where it resides today[10]. The original configuration employed a liquid-scintillation ring detector as anti-coincidence shielding but the ring was upgraded to a plastic Bicron BC-400 detector during the move to Cal Poly. The plastic ring detector eventually degraded and was upgraded again to an NaI(Tl) crystal ring detector this year, in 2011. This detector has been used for many Cal Poly senior projects and to publish many scientific papers, and has potential for many more papers after the recent upgrade to the new ring detector. This report investigates the design and integration challenges of using gamma ray spectrometers on spacecraft as well as their compared performance characteristics.

2.0.0 Experimental Apparatus

The key component of this project lies in the experimental apparatus because the focus is on the comparison between the two different instruments. The two experiments that were performed differed in three primary ways: detector type, detector number and placement, and electronics hardware. The detector type varied on the material of the detector. This plays a significant role in the way that the gamma ray spectrometer must be used because each detector works differently and must be stored differently. The number and placement of the detectors is important because gamma ray spectrometers can use many different configurations in order to best suit the needs of the application as well as optimize the performance. The electronics hardware determines many aspects of the gamma ray spectrometer,

including the performance, energy range, and resolution. These three hardware distinctions are the primary aspects of comparison between the two spectrometers.

2.1.0 HPGe Spectrometer

2.1.1 Detector Type

The first gamma ray spectrometer is the one dimensional High Purity Germanium spectrometer. The detector type is High Purity Germanium, which is a semiconductor that must be temperature controlled with liquid Nitrogen to 77 K due to excessive leakage current at higher temperatures[2]. Because the issue with leakage current only applies during operation, HPGe detectors can be stored at room temperature as long as there is no contamination in the Germanium from residual vapors. The Cal Poly HPGe used in this experiment is always kept at liquid Nitrogen temperatures in order to mitigate this risk. One of the requirements for detecting high energy gamma rays is that the detector must have a depletion depth of at least 10 mm in order to absorb the energy[2]. Germanium crystals can achieve this depth, but they must have a level of impurity of 10^{10} atoms/cm^3 in order to reach a resistance high enough. This is an extremely low impurity level, which gives the detector its name of high purity Germanium.

These requirements for low operation temperature retaining purity of the Germanium are the two primary challenges for integration on a spacecraft. The operating temperature range of HPGe detectors is usually between 72 K and120 K, although the sensitivity efficiency decreases as temperatures decreases[11]. The two primary options for attaining this temperature range for operation is through using active cryogenics or passive cooling through the use of sun shielding and radiators. Choosing between active and passive cooling is based on the application of the detector. For example, an application that requires the HPGe detector to point at the sun to measure radiation might need to use active cooling because passive cooling might not be adequate for reaching the correct temperature. On the other hand, an application that requires a long duration test for each sample may make the use of cryogenics unpractical because it would need to be used all the time.

Additionally, HPGe detectors have the challenge of retaining purity by protecting against contaminants. First, the launch environment poses a major challenge due to the high g-loading and vibrations. The detector must be adequately isolated and designed in order to ensure that loose particles moving around during launch do not contaminate the Germanium crystal. The other contaminant in the space environment is from cosmic rays with charged particles and neutrons. When exposed for long periods of time, this radiation damages the detector and causes a loss in resolution. The damage varies with operation temperature and whether the crystal is a *p*-type or *n*-type semiconductor[12]. Because of this problem, HPGe detectors must additionally be designed for the duration of the mission. Short duration missions do not need to account for this as much as long term interplanetary missions that last several years. The 2001 Mars Odyssey mission, which used an HPGe detector over a long period, preserved the life of the crystal by periodically raising its temperature to 100° C to anneal the radiation damage[9].

2.1.2 Configuration

The thermal requirements of the HPGe detector severely limit the configuration options for gamma ray spectroscopy experiments. Each detector needs its own bulky vacuum enclosure for the liquid nitrogen cooling system, so it is extremely difficult to incorporate additional HPGe detectors to make arrays or add anticoincidence shielding. Because of this and the high cost of each HPGe detector and cooling system, this experiment used a single HPGe detector in coaxial orientation. The coaxial shape is a cylinder with a hole for the electrical connection cut out in the middle. The detector is 45 mm in diameter and 46 mm high, and the active volume of the crystal is 68 cm^3. The crystal cylinder is a *p*-type semiconductor, while the outer surface is a thin, lithium diffused *n*-type semiconductor layer that serves as one n^+ electrical contact. The other electrical contact is a p^+ contact made on the inner surface[2]. Additionally, the spectrometer is surrounded by 0.102 meter thick bricks of low-radioactivity lead shielding.

2.1.3 Electronic Hardware

The electronic hardware for the HPGe spectrometer is a package purchased from Canberra Instruments' Model PCA-3 Third Generation Personal-Computer Analyzer. The signal from the detector goes to a card connected to an IBM computer. This card consists of a microprocessor, memory, and an internal A/D converter. The microprocessor runs at 10 MHz and the memory consists of about 65,000 bytes. Additionally, the maximum number of counts that can be stored to a histogram is 3 bytes of data, or about 16 million counts. The internal A/D converter is a 100 MHz Wilkinson, which has a conversion gain capable of 8K to 256. This card provides the data to the software on the computer. The advantages of this system are that all of the hardware is in one place and the A/D converter can be controlled by the computer.

2.2.0 Multidimensional Gamma Ray Spectrometer

2.2.1 Detector Type

Each of the detectors used for this spectrometer is made of NaI(Tl) crystal, which is the most common type of inorganic material used for scintillation detectors. Each detector is an individual transparent crystal that absorbs and emits readable radiation through the process of scintillation. The scintillation process involves electrons in the crystal absorbing gamma radiation and raising them to higher energy levels. After the electrons are raised to an excited state, the electrons return to their original ground state and give off electromagnetic radiation in the visible light spectrum. Pure crystal has a wide energy gap between the ground state and excited states, so issues arise with the process being inefficient and photons falling out of the visible light spectrum[2]. Due to this, the crystals are doped with a thallium impurity in specific locations in the crystal lattice in order to act as an intermediate state that increases the probability of electron excitation and ensures that the energy emitted by the electron is in the visible light spectrum.

NaI(Tl) is the most commonly used scintillation detector because it has the highest sensitivity, or light output, and the crystals can be easily manufactured into many different shapes and sizes. There are only two challenges posed by the material. First, NaI crystals are brittle and somewhat fragile, which

poses a challenge for the shock of launch conditions. Cracking of the crystal can be prevented by incorporating dampers that reduce the shock of launch. The second is that sodium iodide crystal is hygroscopic, which means that it will easily absorb water vapor that would contaminate and damage the crystal. The solution to this problem is that all NaI crystals must be hermetically sealed in order to be isolated from water vapor in the atmosphere. This is not a problem in the space environment, but it does mean that all crystals must be sealed off during integration and testing, which brings up the issue of inspecting a crystal for cracks and other deformities after a test. The problem can be solved by inspection in a dry environment with no water vapor or by using separate qualification testing hardware from the flight hardware. Gamma ray spectrometers have always been a major part of a spacecraft payload, so separate testing hardware is almost always used for qualification testing.

2.2.2 Configuration

The configuration of the scintillation detectors consists of two NaI(Tl) crystals at the top and bottom running in coincidence and a NaI(Tl) crystal ring surrounding the sample to act as active anticoincidence shielding. This configuration is used in order to maximize the counting efficiency of the spectrometer. Figure 1 shows the orientation of the detectors in the spectrometer. First, the ring detector is used to help remove radiation that is not coming from the sample container. The sample is placed in the hole in the middle of this ring. This ring is an annulus shape of 0.271 m outer diameter, 0.05 m wall thickness, and 0.279 m high. The other two detectors are the ones actually providing positive counts while running in coincidence, which means that they produce a three dimensional plot with two of the axes representing the channels for each detector and the third axis representing the number of counts. These detectors are 0.152 m in diameter and 0.102 m high with 0.067 m long pure NaI light pipes that feed the 5 inch photomultiplier tubes. Additionally, there is a crane capable of raising and lowering the upper detector in order to gain access to the sample area. Like with the HPGe, the spectrometer is surrounded by 0.102 meter thick bricks of low-radioactivity lead shielding.

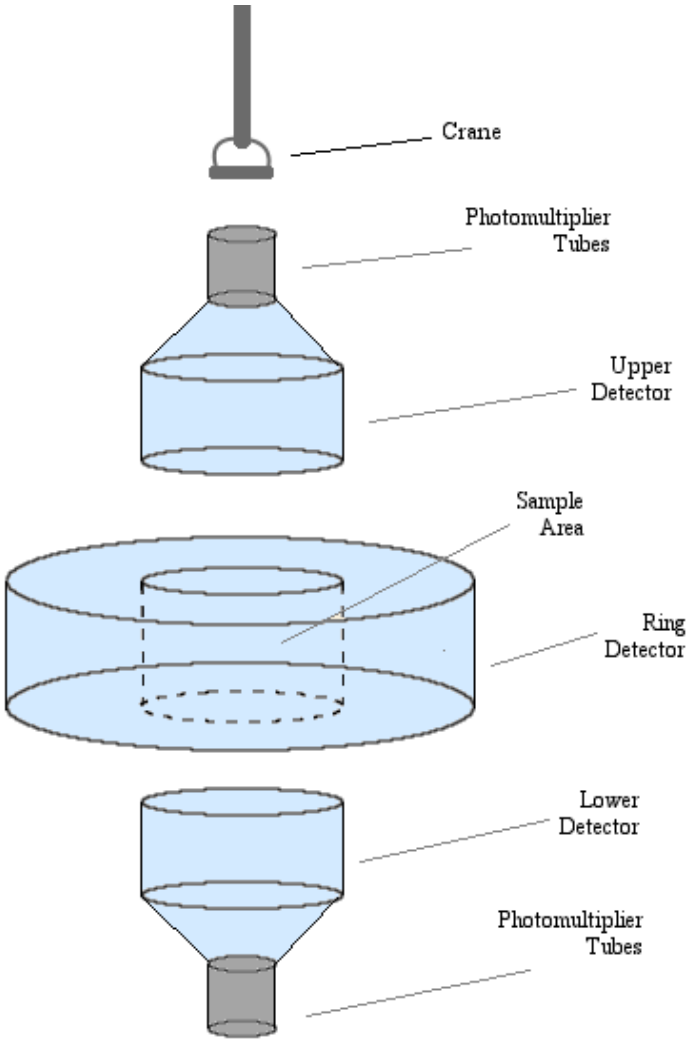

Figure 1. Schematic of multidimensional gamma ray spectrometer. Ring photomultiplier tubes are not shown along with other hardware and housing.

There are several different combinations of ways that photons can hit any of the detectors in order to record a count. Table 2 shows all of these combinations that the spectrometer uses in order to maximize the probability that the photons are coming from the sample.

Table 2. Counting scenarios of the MGRS configuration. "x" represents recorded count. "-" represents veto count. "S" represents singles count. "+" represents coincidence count.

Ring	X	X	X	X			
Upper		X		X	X		X
Lower			X	X		X	X
Result	-	-	-	-	S	S	+

The minus signs represent a veto count, which means that the count is not recorded. An “S” represents a singles spectrum event, which means that the photon only hit the upper or lower detector and has a lower probability of having come from the sample. A plus sign represents a coincidence count, which means that it is plotted on the three dimensional plot. Every gamma ray that is absorbed by the ring is vetoed because there is a high probability that it originated from a source other than the sample, or from a photon Compton-scattered from one of the main detectors. Singles counting events could still originate from the sample, but there is also a high probability that the gamma ray originated from elsewhere, so these are still counted, but noted as singles. This leaves two different possible scenarios: a single photon could hit one detector and Compton scatter onto the other or the sample could produce two gamma rays that hit both the upper and lower detector. In the first case, there is a much greater probability of Compton scattering bouncing onto the ring, so most of these events are vetoed. The counts hitting the two main detectors are still recorded onto the two-dimensional plot, so the X-axis and Y-axis energies can be added together to equal the original photon energy. In the second case, both detectors record legitimate counts, which gives a high degree of confidence that these events are coming from the sample.

2.2.3 Electronic Hardware

The first piece of hardware that a scintillation detector needs is a photomultiplier, which is used to measure the light pulses inside the NaI(Tl) crystal and convert them into an electrical signal. When the light photons from scintillations first reach the PMT, a photocathode, that is photosensitive, converts photons into low-energy electrons. These electrons then move into the electron multiplier structure,

which is enclosed in a vacuum. This structure, or tube, essentially acts as an amplifier as the electrons are moving through it because electrons are being collected while moving through the tube. What begins with an undetectable signal of a few hundred electrons ends with $10^7 - 10^{10}$ electrons, which gives the analogue signal collected at the anode of the PMT[2]. The upper and lower detectors each use 0.127 m photomultiplier tubes that view the crystals through the NaI light pipes. In order to be able to view all the pulses the anticoincidence shield employs eight 0.038 m PMTs spaced around the ring. Each photomultiplier tube gives a voltage signal with each pulse that is directly proportional to the energy level of the gamma rays that activate the detectors.

The pulse signals from the PMTs are then amplified by homemade pre-amplifiers, made by Dr. Roger Grismore, before moving to the Ortec amplifier and discriminator units. The gain of each amplifier is properly calibrated for the voltage to be converted by the A/D converter into a digital signal. The ring signals are summed and amplified by dual sum and inverter amplifiers and are then fed into an integral discriminator. In this unit, the discriminator removes the low-level noise being produced by the electronics. The signals of all three detectors eventually meet up at the Central coincidence circuit. This circuit inputs the upper and lower detectors in coincidence and the ring detector in anticoincidence. It is at this unit where the pulses from the ring detector veto counts from the other two detectors. Next, the signals of the upper and lower detectors migrate to the two A/D converters. Each ADC is a NS-621 50 MHz, 8192-channel unit that inputs pulses from one of the detectors. The ADCs, produced by Northern Scientific, are calibrated to the correct baseline when converting to the digital signal. These ADCs feed to the two parameter unit, also from Northern Scientific, which organizes the counts into coincident and singles counts. Finally, the data is sent to two electronic boards in the computer storing the data. The first board, the CIO-DIO24 simply writes the data into the individual channels of the spectrum, and the second board, the CIO-DIO24H, sends CLEAR pulses to the two parameter unit in order to reset the clock scalars[10]. The computer board memory is capable of achieving at least 1000 x 1000 channels and up to 2.14×10^9 counts/channel for the coincidence spectra. Figure 2 shows the functional block diagram of the set up for the multidimensional spectrometer.

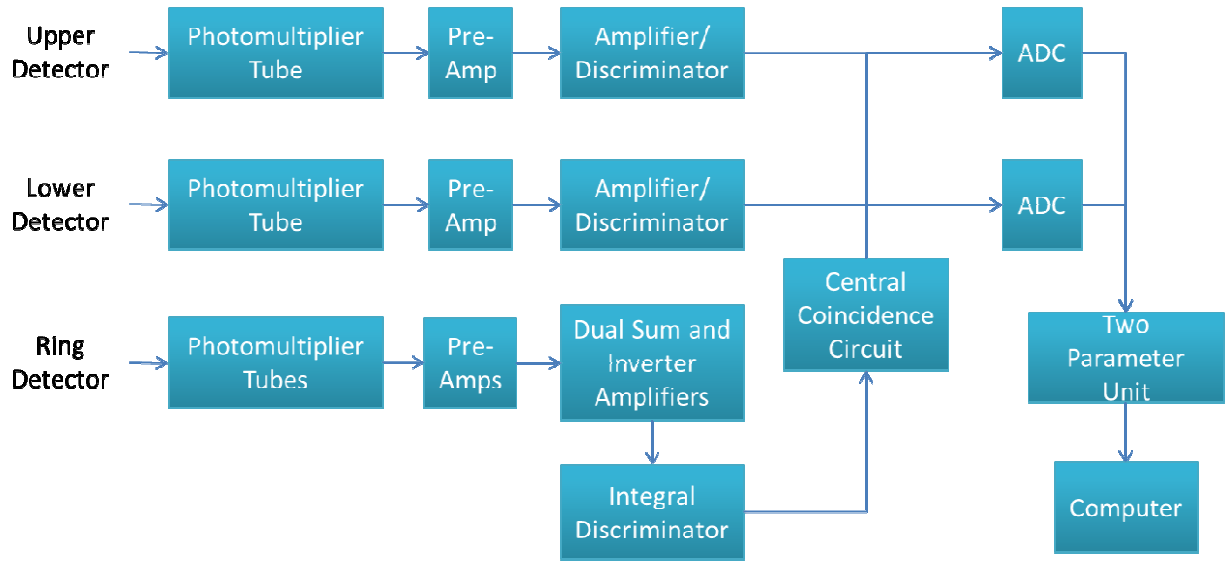

Figure 2. Functional block diagram of the MGRS.

2.3.0 Meteorite Sample

The sample is a small meteorite sample captured in Lake Labyrinth, Australia. The meteorite was purchased by Dr. Roger Grismore for the purpose of gamma ray analysis. This sample has been tested before, but no conclusions have been definitively made about the presence of radioactive material.

3.0.0 Experimental Procedure

3.1.0 HPGe Spectrometer

The spectrometer was first calibrated using ^{137}Cs and ^{60}Co sources that produce four different peaks throughout the spectrum. The two adjustments made in calibration are the gain and the baseline. The gain adjusts the range of radiation that can be detected, which in turn sets the channel resolution. The baseline adjusts the location of the spectrum with respect to the radiation energy level. An analogy to better understand the two terms could be to describe the gain to move like an accordion that squeezes the spectrum together or pulls the spectrum apart and the baseline to move like a slider that slides the spectrum along the x-axis. With two variables, only one calibration source is not acceptable for correctly adjusting the gain and baseline, so any spectrometer calibration requires at least two calibration peaks.

Additionally, spacing the calibration peaks apart improves the accuracy of the calibration. The two calibration sources used decay at the following energy levels:

^{137}Cs = 0.6616 MeV

^{60}Co = 1.1732 MeV

^{60}Co = 1.3325 MeV

With a resolution of the HPGe detector of 1keV/channel, the corresponding channel numbers for these three peaks are channels 661.6, 1,173.2, and 1,332.5, respectively. The baseline and gain were adjusted after performing 10 minute runs at a time with the calibration sources. Each adjustment was made by twisting dials connected to electronics on the computer. After each run, the peaks were inspected to measure the distance from the correct channels as well as the change in gain and baseline. Once the spectrum fell within 0.5 keV of the calibration peaks, the detector was prepared for a full run. Figure 3 shows an example of a calibration run performed by the HPGe spectrometer.

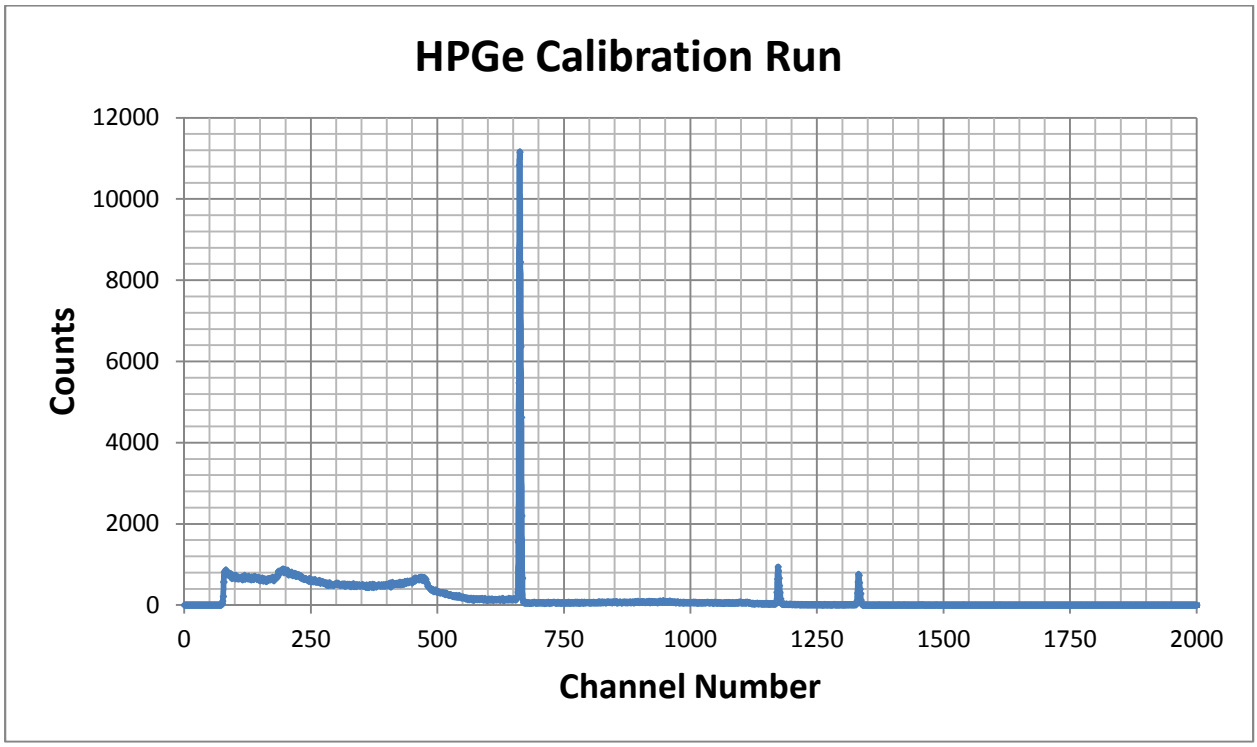

Figure 3. HPGe calibration run example using ^{137}Cs and ^{60}Co calibration sources.

The runs were performed using Canberra Instruments PCA3 software. About three days into each run, a digital spectrum stabilizer was applied to correct for drift in the electronics over the duration of the test. This tool requires defined peaks to use as regions of interest in the high energy and low energy regions of the spectrum. The regions of interest used for the DSS were at 511 keV, which represents the annihilation of electrons and positrons, and 1.460 MeV, which represents the decay of ^{40}K. The first peak is naturally occurring everywhere and the second peak is a common source that is not removed from the high level counting configuration of the HPGe spectrometer. With the two regions of the interest set, the digital spectrum stabilizer was activated to control the zero level and gain through the internal ADC by the 511 keV and 1.460 MeV peaks, respectively. Figure 4 shows the functional block diagram of the HPGe spectrometer with the DSS activated to give closed loop feedback control to the internal A/D converter.

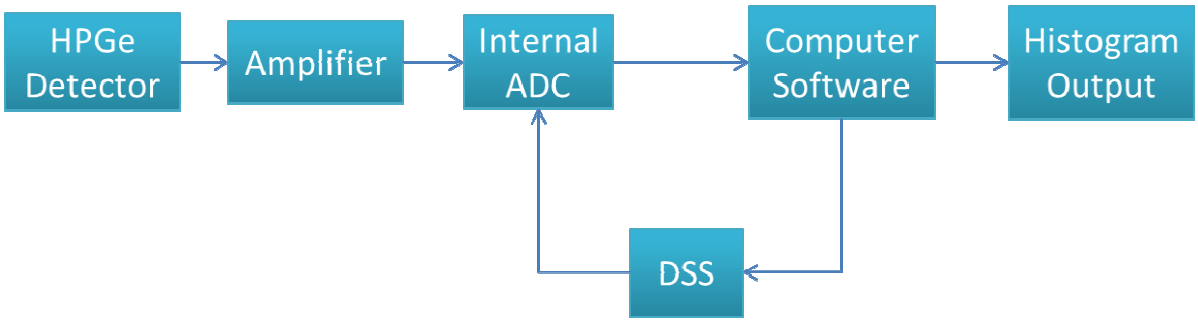

Figure 4. Functional block diagram of HPGe gamma ray spectrometer.

The purpose of a background run is to measure everything that is producing gamma radiation during the sample run that is not produced by the sample, so that it can be subtracted from the sample run to only examine the products of the sample. The background run included two zip-lock plastic bags of the same type to be used to contain the sample during the sample run. This run was performed for a total of 2,618,955 seconds, or 30.3 days. After the background run completed, the meteorite sample was placed in two zip-lock bags and set in the sample containment area. This sample run was performed for 3,440,957 seconds, or 39.8 days. The two runs are not required to operate the same amount of time

because they can be scaled to match the run time. Weekly file saves were made in order to prepare in case of power failure and the Digital Spectrum Stabilizer was performed on the sample run as well. After the sample run completed, the data was ready to begin analysis.

3.2.0 Multidimensional Gamma Ray Spectrometer

Partly due to the fact that this spectrometer utilizes three separate detectors, the calibration process was significantly more tedious and intensive than process for the single HPGe detector. Additionally, the electronic amplifiers and A/D converters were external to the computers, so this added to amount of manual reconfigurations that needed to be performed. The first step of the calibration procedure was calibrating the rings detector. Because the ring detector was only used in anticoincidence, the accuracy of calibration is not as important as having a high sensitivity. The calibration involved individually running each of the eight photomultiplier tubes with the ^{137}Cs and ^{60}Co sources. The voltages of each PMT was then adjusted and the runs were then repeated until the calibration peaks fell as close to possible on top of each other for the eight PMTs. The other step of calibrating the ring counter was setting the discriminator level, so that it would not record counts from the noise of the electronics. Without this step, the anticoincidence shielding would veto almost every count because of the constant noise.

Next, the upper and lower detectors were calibrated with the ^{137}Cs and ^{60}Co sources. For the calibration the two ADC's were set to anticoincidence and the mode was set to "X + Y" with the ring detector disconnected in order to produce two separate x-y plots that makes inspection easier for calibration. Additionally, the group size was set to 1024 channels and the conversion gain was set to 2048. A program called MCAMPX.EXE was used to run 7 minute runs for calibration. At first the calibration spectra were inspected using LOTUSWORKS spreadsheet software, and high level adjustments were made to the gain and baseline in order to place the peaks to within about 5 channels of their correct values. Once this was achieved, software titled CALDISKNEW.EXE was utilized to perform Gaussian fits on the peaks to locate the center of each peak. The program then displays the location of the zero-level and ^{60}Co sum peak, which is the highest energy peak, for both of the detectors.

Adjustments were made to the amplifier gain and A/D converter's zero-level to reach the following levels:

Upper and Lower Crystal Baseline = 0.0 +/- 0.2 channels

Upper and Lower Crystal ^{60}Co Sum Gain = 501.1 +/ 1.0 channels

where the channel resolution comes out to be 5 keV/channel. Figure 5 shows the final calibration of the two detectors overlaid on each other for the background run. The calibration was performed on both the background and sample runs to re-fit the spectra after drift that occurred during the run. This process was the most tedious component of the experiment because the gain and baseline levels were not independent of each other, so changing one would also result in changing the other. The lower detector, which is the older of the two detectors, was especially difficult in locating the correct baseline. Multiple days were spent and ADC units were switched out before managing to calibrate the detectors together.

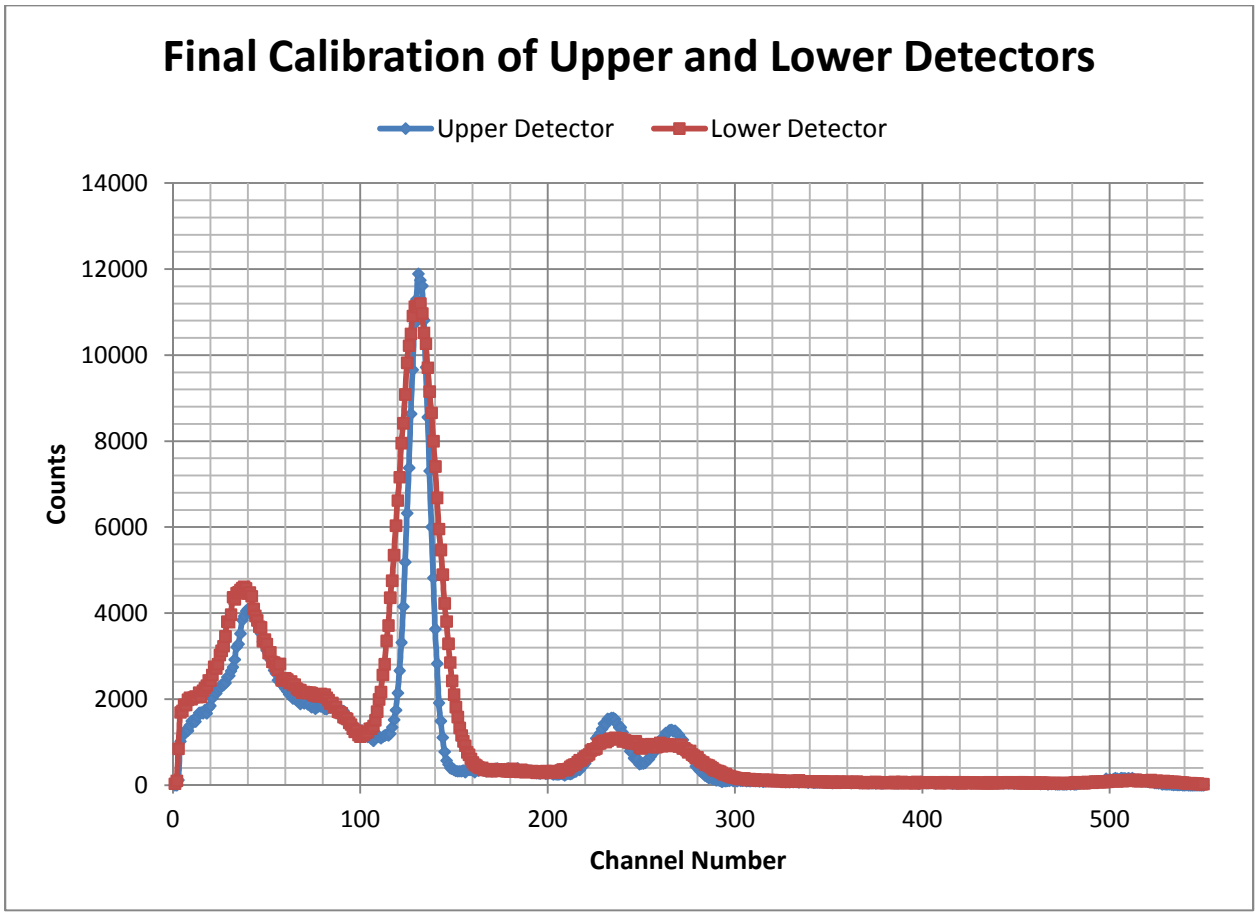

Figure 5. MGRS calibration run example using ^{137}Cs and ^{60}Co calibration sources.

The assumption that ground calibration is adequate for the duration of any spacecraft mission is a false one because the electronics are very sensitive to shifting the gain and baseline. This issue must be incorporated into the concept of operations in order to either control the shift, allow for recalibration, or both. Temperature and voltage are the two primary factors that adversely affect the calibration of scintillation detectors. In order to minimize the drift during operation, a spacecraft must maintain the temperature which can pose a challenge in harsh transient environments. The voltage must be kept within fractions of a volt in order to additionally minimize the drift. NASA's NEAR spacecraft ran into these problems during the design of their mission. The thermal issues were addressed by thermally isolating their gamma ray spectrometer and using heaters to actively control the temperature. The high-voltage power supplies employed a feedback control system in order to stabilize the voltage to the photomultiplier tubes[8]. In flight calibration is often performed by calibrating the detectors to the 0.511 and 1.022 MeV peaks which are the first and second escape peaks of the annihilation of electrons and positrons[8]. Additionally, in flight calibrations can be validated using ground testing on exact flight spares that are not flown on the mission.

For the actual runs the upper and lower detectors needed to be switched to coincidence counting and the ring detector needed to be turned back on for active shielding. The mode was set to "XY + SINGLES", which means that all the counts that hit the upper and lower crystals are recorded on a three-dimensional plot with the single counts added to it. The group size was set to 128 for producing the 126 x 126 channel spectrum and the conversion gain was set to 512. The sample run was performed first and lasted for 50,000 minutes, or 34.7 days. Once the run completed, the upper and lower detectors of the spectrometer were recalibrated, the sample was removed along with its plastic bags, two new plastic bags were placed inside the sample area, and the spectrometer was re-run for another 50,000 minute back ground run. The software used to perform the runs saved the total recorded data nightly in case of a power or electronics failure. A power failure did occur once during the sample run and, fortunately, the most recent save file could be used, but there was a several day delay because the failure occurred on a Saturday and the spectrometer required recalibration. Due to this and the added delays of calibrating and

recalibrating the spectrometer, there was not enough time to finish the back ground for this report. A previous background run performed by another student from when the spectrometer used a plastic ring detector instead of an NaI(Tl) crystal detector was used instead.

4.0.0 Analysis

4.1.0 Calibrating and Subtracting the Backgrounds

4.1.1 HPGe Spectrometer

In order to obtain a useable spectrum, the background and sample runs needed to be calibrated and then the background could be subtracted from sample run. Calibration involved locating three naturally occurring peaks for both runs: ^{226}Ra, ^{228}Ac, and ^{214}Bi, which occur at 186.05 keV, 911.205 keV, and 1,764.494 keV, respectively. These peaks were located to within the nearest 0.1 channel and entered into a program called QUADTRFM.EXE, which performs a quadratic transformation and outputs values for the curvature, slope (gain), and baseline changes. Next, the background and sample files were each imported into 2ADJ2048.EXE along with their respective outputted values from the previous step. This program performed the appropriate calibration on the background and sample runs in order to correct the channels to the closest 1 keV. Finally, both calibrated spectra were imported into SUBTRACT.EXE, which scaled the two runs to the same time and then subtracted the background from the sample run. The resulting run was the final run capable of being used for spectral analysis on the meteorite sample.

4.1.2 Multidimensional Type Gamma Ray Spectrometer

Because of the added variables and dimensionality of this spectrometer, the analysis to obtain useable data required a few more steps than for the HPGe. In order to calibrate the background and sample plots, each 126 x 126 plot needed to have peeled off the two one-dimensional plots from the singles spectra. Once separated with SNGL126.EXE, the plots were inspected to look for the three characteristic peaks at 0.511 MeV, 1.461 MeV, and 2.223 MeV. The peak at 0.511 MeV occurs because of positron annihilation (found everywhere in nature), and ^{40}K is a contaminant occurring naturally in photomultiplier tube glass. The 2.223 MeV peak is from deuterium formation, which occurs everywhere

because neutrons coming from cosmic rays will penetrate any surface in the spectrometer, which means that this even occurs in the sample containment area. The analysis of these three peaks involved accurately finding their centers using a least squares fitting program called CALI126. These values were then entered into QUADTRFM.EXE, which outputted values for the curvature, slope (gain), and baseline changes. Next, programs called 2XADJ126 and 2ADJS126 used the quadratic transformation values and imported all of the plots in order to adjust them to correctly calibrated plots. Once the 126 x 126 channel plots had been correctly calibrated, the background run was subtracted from the sample. Finally, a BASIC program called SPECTRUM.BAS was used to display the counts along with the counting error for each channel. The reason why this spectrometer only uses 126 x 126 channels is because the BASIC programming language used for analysis is limited to only 64Kb of memory for long integer arrays[10]. The displayed values of this program were used for the final printout used for spectral analysis on the meteorite sample.

4.2.0 Gamma Ray Spectrometer Performance Analysis

Due to the focus on performance rather than sample analysis for this report, the final HPGe spectrum and the key peak areas of the multidimensional spectrometer spectrum can be viewed in the Appendix. The analysis of the performance of the two gamma ray spectrometers uses a few common performance characteristics, including energy resolution, detection efficiency, and dead time. The following section outlines where these performance characteristics come from and what they mean.

4.2.1 Energy Resolution

An informal definition of the energy resolution is as the minimum amount of energy that can separate two different gamma ray peaks from each other. A high value for the resolution means that peaks must be spaced far apart from each other in order to distinguish them, while a low value allows for more leniency in the required distance between peaks. A formal definition of the energy resolution of a spectrometer is represented by the following equation[2]:

$$R = \frac{FWHM}{H_0}$$

where R represents the resolution as a percentage of the total energy, FWHM represents the full width at half maximum, and H_0 represents the centroid of the peak. The FWHM is, as it sounds, the width of a peak at half of its maximum height. The centroid of the peak is the location along the x-axis of the centroid of the peak. Both of these values are in electron volts, which cancel out to give the percentage value for energy resolution. These values are assuming Gaussian peaks in the gamma ray spectra.

4.2.2 Detection Efficiency and Sensitivity

The efficiency of a gamma ray detector either revolves around how well it is counting all of the gamma rays emitted by the source or how well it is counting all of the gamma rays that are incident onto the detector. 100% efficiency for the first category means that the detector is able to count all of the gamma rays that are emitted by a source. This efficiency is shown by the following equation[2]:

$$\varepsilon_{abs.} = \frac{number\ of\ pulses\ recorded}{number\ of\ radiation\ quanta\ emitted\ by\ source}$$

where $\varepsilon_{abs.}$ represents the absolute efficiency of the detector. For the second category, 100% efficiency means being able to count all of the gamma rays that are incident onto the detector, which is shown by the following equation:

$$\varepsilon_{int.} = \frac{number\ of\ pulses\ recorded}{number\ of\ radiation\ quanta\ incident\ on\ the\ detector}$$

where $\varepsilon_{int.}$ represents the intrinsic efficiency of the detector. The second category does not factor in whether or not gamma rays from the source are entirely missing the detector. These efficiencies require knowledge of either the strength of the source or the amount of radiation incident on the detector for their measurement.

Because testers also only want to see the radiation that is coming from the source, another aspect of the sensitivity performance is the spectrometers ability to neglect noise and unwanted radiation. There are multiple ways to measure this, but one way is to measure how often the spectrometer is recording counts with nothing in the sample area. Ideally, only counts from the sample area are being recorded, so there should be no counts during a background run.

4.2.3 Dead Time

In gamma ray spectrometers, there is a minimum amount of time that must pass after a recorded count in order to be able to measure the next count. This amount of time is called the dead time and is a performance characteristic of gamma ray spectrometers. The dead time is viewed as a loss in time because no counts can be made during the time. Both spectrometers record the total live time, which is the amount of time that counts could have been made, and the total time. The percentage of dead can be expressed by the following equation:

$$\frac{\qquad\qquad}{\qquad\qquad}$$

where the dead time is a percentage of the total time. The lower the dead time, the more time allowed to record gamma ray interactions.

5.0.0 Results and Discussion

5.1.0 Energy Resolution

The measured energy resolutions are from brief calibration runs for both spectrometers. The points of measured resolution are all taken at the ^{137}Cs peak, the lowest energy peak, and the ^{60}Co 1.3325 MeV peak, the highest energy peak, for the upper and lower detectors of the MGRS and the HPGe detector. Table displays the results of the resolutions from the calibration runs of the spectrometers.

Table 3. Energy resolution results of the MGRS and HPGe spectrometer.

	Lower Detector		Upper Detector		HPGe Detector	
Calibration Peak	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co
FWHM (keV)	120	151	67	77	4.5	4.5
H_0 (keV)	661.6	1,332.5	661.6	1,332.5	661.6	1,332.5
% Resolution	18.2 %	11.3 %	10.2 %	5.8 %	0.7 %	0.3 %

Clearly, the HPGe detector exhibits a major difference compared to both of the detectors of the MGRS. The HPGe has about 27 times greater resolution than the lower detector's at the first peak and about 34 times greater at the second peak. For the upper detector, the HPGe demonstrates about 15 times greater

resolution at the lower energy end and about 17 times greater resolution at the higher energy end. The primary reason for the significant difference in resolution between the HPGe and NaI(Tl) detectors is because there are many more fluctuations in the process of converting the gamma ray photons to photoelectrons and then collecting them in the photomultiplier tubes for scintillation detectors. More fluctuations, of course, mean poorer resolution. As the photon energies increase, more photoelectrons are produced, and the resulting improvement in photoelectron statistics means better percent resolution at higher energies for the scintillation detectors.

There are several factors that contribute to a scintillation spectrometer's resolution. First is the photoelectron statistics, the primary reason for resolution loss for scintillation detectors. These are the statistical fluctuations noted before with the photomultiplier. Next is the intrinsic crystal resolution. This occurs from non-uniformity in the crystal, and is the most likely cause of the difference in resolution between the lower and upper detectors. Non-uniformities in the crystal cause fluctuations in the amount of light produced during scintillation depending upon where the gamma ray is absorbed in the crystal, and this results in a loss of resolution[2]. Several years ago, the upper detector was damaged and returned to the manufacturer for repair. While at the manufacturer, additional repairs were made to the crystal to improve its resolution performance. This explains the significant difference in resolution between the upper and lower crystals. The two primary contributing factors to resolution loss in the HPGe are incomplete charge collection at the electrical contacts and from electrical noise at the amplifier. Clearly, these two factors do not lead to large fluctuations. One final item to note about the measured resolutions is that they were recorded from short calibration runs on the order of minutes. A common resolution loss that did not come into effect was the drift that occurs during long runs. With the digital spectrum stabilizer on the HPGe, the NaI(Tl) crystals most likely exhibit even greater loss in resolution because they are more prone to drift during long runs.

5.2.0 Detection Efficiency and Sensitivity

The resources were not available for this project to find the efficiencies of the spectrometers, due to the need for a source with known strength. However, previous work performed by Dr. Roger Grismore

was a sensitivity analysis on the ^{26}Al peak at 1.809 MeV. Measuring ^{26}Al has been one of the primary purposes of the spectrometers, so this analysis was performed on both of the spectrometers. The results showed that the MGRS exhibits a sensitivity, or absolute efficiency, 52 times greater than that for the HPGe spectrometer. This high sensitivity of the MGRS is the defining characteristic of NaI(Tl) detectors and the reason why they are so widely used today. Their high density allows the crystals to absorb and respond at extremely high efficiencies, which is the challenge, because a material must be able to convert gamma ray energies.

For the HPGe detector the background level was measured from 231 keV all the way to the end of its spectrum at 2.047 MeV. For the MGRS, the measurement was taken from 200 keV to the end of its spectrum at 2.52 MeV. The background radiation of the two spectrometers is as follows:

HPGe background radiation = 52.8 counts/minute

MGRS background radiation = 3.27 counts/minute

The background radiation detected by the HPGe is 1,615 % greater than the background for the MGRS. This difference is quite impressive considering that the NaI(Tl) detectors are 52 times more sensitive than the HPGe detector. This means that the MGRS is capable of detecting far lower levels of radiation, but at the same time can cut out a huge percentage of unwanted radiation. These results show that the anti-coincidence shielding on the MGRS is very desirable for the purpose of removing unwanted radiation from the spectrum.

5.3.0 Dead Time

The runs used for this analysis were the full sample runs for each of the spectrometers. These runs were used because they show the dead times with the counting rate of an actual sample as opposed to counting rates that are less with no sample involved. Table 4 shows the equally scaled dead times and dead time percentages for the two spectrometers.

Table 4. Dead time results of the MGRS and HPGe spectrometer. HPGe dead time is scaled to standard run time of 50,000 minutes.

	HPGe	MGRS
Dead time (scaled to 50,000 min total time, min)	2.180	85.22
% Dead time	0.00436	0.170

The MGRS exhibits a dead time which is 3,900% larger than that of the HPGe. However, the present dead time of the MGRS is largely due to the slowness of the 25 MHz microprocessor of the computer controlling the spectrometer. Using a faster microprocessor, it has been shown that the dead time could be reduced to 0.044%. Even still, the percent dead time for the MGRS is a significant one that would add up to significant lost count time over long use, but there are simple explanations for the large difference in dead time in the two spectrometers. First, the counting pulses from the MGRS are about 2-3 microseconds in time duration, which is probably ten times longer than those from the HPGe. That means that each count ties up the pulse analysis system for much more dead time. The pulse length, which correlates to the dead time, of NaI(Tl) crystals is longer compared to other scintillation detectors, especially liquid scintillators. However, they are much less dense then NaI(Tl), and so also have lower intrinsic efficiency. Additionally, the difference in configuration also leads to a greater dead time in the MGRS. The three detectors in the MGRS are required to operate in sync to be able to have coincidence between the upper and lower detectors and anti-coincidence with the ring detector. As an example of this synchronization, if the ring counter is experiencing dead time, while the upper and lower detectors receive counts, the spectrometer will not know whether or not the counts in the upper and lower detectors are acceptable counts because the ring detector is currently unable to count anything. This means that a count in any of the detectors leads to dead time for the other two detectors even if they are still able to count gamma rays. The increased processor time required for the analysis of longer pulses and requirement for synchronization in the MGRS pay a penalty for a significant increase in dead time compared to the HPGe, but it is still a very small percentage of the total time.

6.0.0 Conclusion

In a variety of aspects, the two gamma ray spectrometers tested for this project show significant trade-offs, but the question is which of the two is the better spectrometer. The answer is that the better spectrometer entirely depends on the situation and requirements. The HPGe spectrometer has an excellent energy resolution, but lacks in sensitivity and requires low operating temperatures. The MGRS with NaI(Tl) detectors excels in sensitivity, but lacks in energy resolution, dead time, and the present unit lacks the ability to use digital spectrum stabilization for feedback control. This could be corrected by replacing the present ADC's with units having digital stabilization ability.

With advantages and disadvantages of each spectrometer, the major trade-off in most applications is whether the application needs high resolution or high sensitivity. Some applications of gamma ray spectrometers create complex gamma ray spectra that require high resolution to be able to distinguish between all of the peaks. An example of these applications is counting large samples, such as those from Mars or the Sun. Other applications desire to know what radiation is present and are not as much concerned with how much radiation is present. These also place HPGe spectrometers at an advantage because they will better be able to identify exactly at what energy a source is emitting radiation. Other applications of gamma ray spectrometers have less complex gamma ray spectra, or they are only looking for radiation at a few specific energy levels. These applications give an advantage to NaI(Tl) detectors because they can detect much lower levels of radiation and indicate how strongly they are radiating. Applications like these are actually quite common and could include missions to Mars that are specifically looking for things like any history of previous life on Mars. Finally, detectors used for active anti-coincidence shielding are much more concerned with sensitivity than resolution, so this should almost exclusively be performed by scintillation detectors. Ideally, both types of spectrometer should be used to complement each other's strengths.

One final item to discuss is the configuration of spectrometers. Multidimensional gamma ray spectrometers demonstrate a significant improvement in giving certainty about whether or not gamma rays are coming from the sample, when compared to one-dimensional spectrometers. Synching detectors

in coincidence and anti-coincidence is a useful tool in ensuring that counted gamma rays are only originating from a specific direction or location. This essentially gives gamma ray spectrometers a field of view just like with cameras but without using optics. Even though the HPGe detector of the present study is one-dimensional, they are not limited to this configuration. A recommendation would be to use multidimensional gamma ray spectrometers whenever the opportunity arises.

7.0.0 References

1. Mattson, Barbara. “Scintillators as Gamma-ray Detectors.” NASA’s Imagine the Universe. 1997. Goddard Space Flight Center. Last Updated: November 23, 2010. <http://imagine.gsfc.nasa.gov/docs/science/how_l2/gamma_scintillators.html>
2. Knoll, Glenn F. *Radiation Detection and Measurement*. New York: John Wiley & Sons, Inc. Second Edition. 1989.
3. Gehrels, Neil. “The Swift Gamma-Ray Burst Mission.” Swift: Catching Gamma Ray Bursts on the Fly. Goddard Space Flight Center. Last Updated: May 27, 2011. <http://swift.gsfc.nasa.gov/docs/swift/swiftsc.html>
4. “INTEGRAL Objectives.” Science Programme. European Space Agency. Last Updated: July 3, 2003. <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31169>
5. Gehrels Neil. “The CGRO Mission (1991 – 2000).” CGRO Science Support Center. Goddard Space Flight Center. Last Updated: November 30, 2005. <http://heasarc.gsfc.nasa.gov/docs/cgro/index.html>
6. “INTEGRAL Instruments.” Science Programme. European Space Agency. Last Updated: March 30, 2011. < http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31175&fbodylongid=720> and <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31175&fbodylongid=719>.
7. Jenner, Lynn. “Fermi Spacecraft and Instruments.” NASA. Last Updated: August 28, 2008. <http://www.nasa.gov/mission_pages/GLAST/spacecraft/index.html>.
8. Goldsten, John O. “The NEAR X-Ray/Gamma-Ray Spectrometer.” Johns Hopkins APL Technical Digest, Volume 19, Number 2. 1998. <http://www.jhuapl.edu/techdigest/TD/td1902/goldsten.pdf>
9. “GRS Instrumentation.” 2001 Mars Odyssey. Lunar and Planetary Lab. The University of Arizona. <http://grs.lpl.arizona.edu/content/about/gamma>
10. R. Grismore, R.A. Llewellyn, J.W. Hilsinger, A.S. Ginn, L.G. James, M.D. Brown. “A very-low-level gamma-ray analysis system for modest laboratories.” Amsterdam: Elsevier Science B.V. Nuclear Instruments & Methods in Physics Research Section A Volume 402 164-170. 1998.
11. E.L. Hulla, R.H. Pehl, N.W. Maddenb, P.N. Lukeb, C.P. Corkb, D.L. Maloneb, J.S. Xinga, K. Komisarcika, J.D. Vanderwerpa and D.L. Friesel. “Temperature sensitivity of surface channel effects on high-purity germanium detectors.” Nuclear Instruments and Methods in Physics Research Section A. Volume 364, Issue 3, October 15, 1995.
12. M. Koenen, J. Briicknerl, M. Korfer, I. Taylor, H. Wake. “Radiation Damage in Large-Volume n- and p-Type High-Purity Germanium Detectors Irradiated by 1.5 GeV Protons.” IEEE Transactions on Nuclear Science. Vol. 42, No. 4, August, 1995.

8.0.0 Appendix

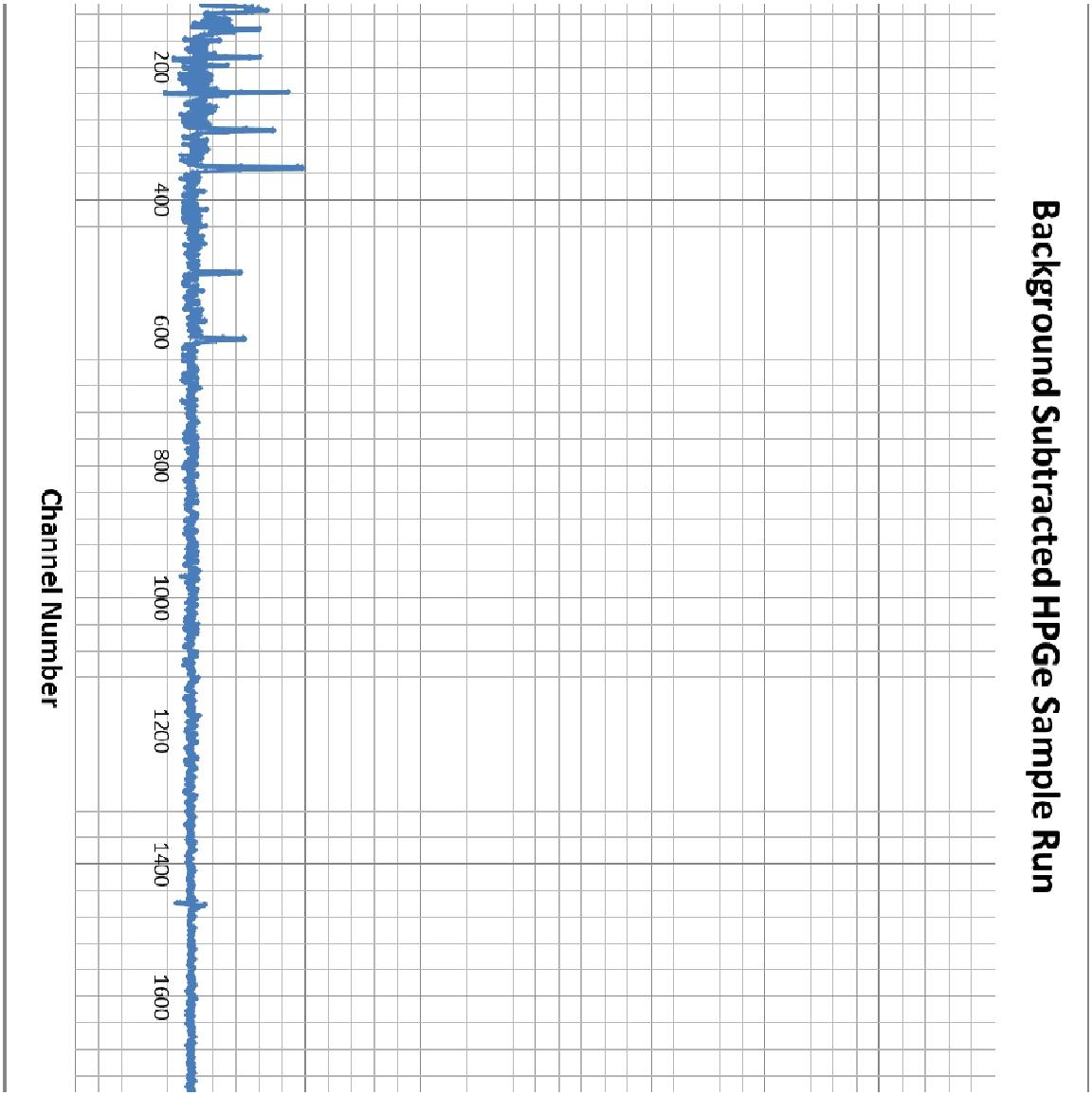

Table: Regions of interest from the MGRS two dimensional spectrum of the background subtracted sample run.

	X-Axis Channels	Y-Axis Channels
Region 1	23 - 30	113 – 118
Region 2	117 - 122	23 – 27
Region 3	24 - 31	23 - 29