SSC18-WKVI-05

Cesium Iodide Thallium-doped Incident Energy Spectrometer (CITIES): A Hard X-Ray Detector for CubeSats

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ABSTRACT

This paper describes the design and operation of the detector known as the Cesium Iodide Thallium-doped Incident Energy Spectrometer (CITIES). The CITIES design implements CsI(Tl) scintillation crystals to detect hard x-rays (HXRs) and gamma rays from the Sun and other astrophysical sources in the range of 10 keV - 400 keV. Laboratory tests to characterize the operation of CITIES are discussed. CITIES is used on two CubeSat missions through the University of Minnesota; Experiment for X-Ray Characterization and Timing (EXACT) and Signal of Opportunity CubeSat Ranging and Timing Experiment System (SOCRATES). EXACT's objective is to better understand HXR emissions from solar flare activity which have effects on the near-Earth environment. The mechanisms of flare-accelerated electrons are not well understood, but can be explored through the study of the HXR's they emit, providing a better understanding of the causes of space weather. The mission of SOCRATES is to serve as proof-of-concept for the positioning, navigation and timing (PNT) functionality of CITIES by using astrophysical sources such as pulsars and x-ray binaries for GPS-denied and deep space operations.

INTRODUCTION

The University of Minnesota Twin Cities' Department of Aerospace Engineering and Mechanics and the School of Physics and Astronomy began two different missions involving small satellites known as CubeSats. CubeSats are a platform for testing new technologies and experiments that require access to space. These small satellites are relatively inexpensive and have fast mission lifetimes when compared to full sized satellites which makes them great candidates for relatively easier access to space.

The Signal of Opportunity CubeSat Ranging and Timing Experiment System (SOCRATES) mission of the Aerospace Engineering and Mechanics department is meant to serve as a proof-of-concept for a GPS-denied or deep space navigation system consisting of a constellation of small satellites. This system would operate using radiation detectors to detect astrophysical sources with high time precision. Using multiple satellites with the same high time precision detector, they will be able to determine their position relative to each other by comparing the time of arrival of photons from the same astrophysical signal of opportunity.

The School of Physics and Astronomy also has a mission to study hard x-ray (HXR) emissions from solar flare activity, the Experiment for X-ray Characterization and Timing (EXACT). By measuring the HXR emissions from the Sun, EXACT will be able to produce an energy spectrum to show the timescales of electrons accelerated by flares. This information can be used to narrow down theories of how flares accelerate the electrons, leading to knowledge about how energy is released in those flares. Both the coronal heating problem and space weather models can benefit from knowing how solar flares release their energy.

Both missions are implemented on the 3U CubeSat platform, where 1U is used as the unit of measurement for these small satellites. 1U specifically is 10 cm x 10 cm x 10 cm. Applying this to the 3U size of SOCRATES and EXACT, these Cubesats are 10 cm x 10 cm x 30 cm.

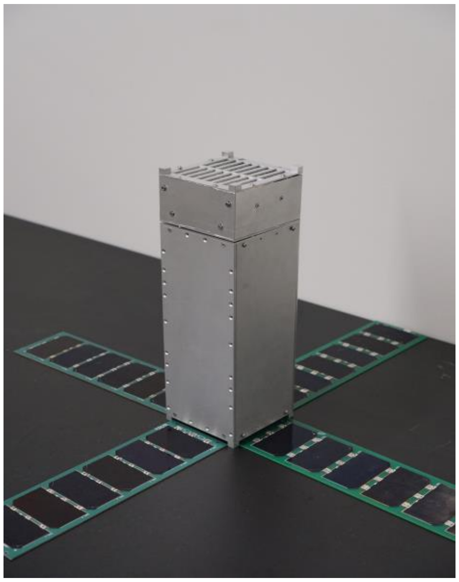

Figure 1: The EXACT and SOCRATES structure and solar panels put together without hinges.

It was decided that a single detection system could be designed that would satisfy the detection requirements of both missions. The energy range required is 10 keV - 400 keV to be able to see HXR's from the Sun within the range of 10 keV - 100 keV, and the other astronomical sources that are up to 400 keV. To be able to extract useful information from the data collected, the minimum required resolution is 25 percent. Resolution is defined here by the following equation.

$$Resolution\ \% = \frac{E\ at\ Peak}{FWHM\ of\ Peak} \qquad (1)$$

E at Peak corresponds to the peak of a Gaussian distribution centered at an observed energy in a gathered spectrum. FHWM of Peak corresponds to the full width at half maximum of this observed Gaussian. Both resolution and these values will be discussed further in the testing section. The accuracy of photon time of arrival needs to be 4 μs. The detection area needs to be as large as it can be in the space provided to collect enough photons and the detector needs to be made at a relatively low cost. These requirements pointed towards developing a scintillation detector.

SCINTILLATION DETECTORS

In the most basic sense, to scintillate means to glow, which translates to the idea that scintillation detectors function on the idea of converting the kinetic energy of high energy particles into visible light.[1] This allows for the visualization of otherwise undetectable radiation. The component of a scintillation detector which acts as the detection medium is known as the scintillator. The scintillator can range from many different materials including inorganic, organic, solid, and liquid scintillators. Each category has benefits and drawbacks in comparison to one another. Inorganic scintillators are generally crystalline and tend to be brighter than their organic counterparts, but have a longer response time due to the scintillated light having a longer decay time. Different options within these categories can also have very different responses. Sodium iodide is generally considered the standard for inorganic scintillators, but it is relatively fragile in high mechanical stress environments.[1] Cesium iodide on the other hand is more durable than other scintillators while maintaining a high light output.

In the case of inorganic scintillators, the conversion of a high energy particle's energy into visible light is accomplished through the excitation of electrons in the valence band to the conduction band, resulting in an electron - hole pair. Relaxing from the conduction band results in the release of photons with energy corresponding to the band gap between the valence and conduction bands.

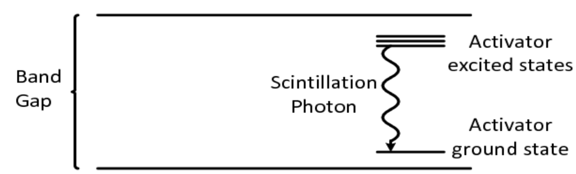

Figure 2: Depiction of the band structure described.[1]

Most pure inorganic scintillators have a band gap large enough that the photons released would not be in the visible range. This results in an inefficient process that has not accomplished the goal of converting the initial energy to visible light. Impurities, which are called activators, are added to the crystalline lattice of the scintillator to combat this issue. These impurities are also commonly referred to as dopants. The addition of activators yields energy states within the band gap of the scintillator which are now accessible, seen by the activator excited states within figure 2. Specific impurities are generally chosen to allow for energy states that will result in visible light upon relaxing. Thallium is an example in the case of the scintillation crystal cesium iodide.

Scintillators convert the high energy particle's kinetic energy into visible light, but additional stages are still needed to convert this light into a usable signal. Many options exist to accomplish this such as photomultiplier tubes, silicon photomultipliers, and other photosensitive devices. Factors such as size, sensitivity, and power consumption all contribute to deciding on a device to capture the scintillated photons. Further readout electronics are also needed to refine the output of the photosensitive device which vary from system to system. Typically, the signal undergoes at least one stage of shaping and one stage of amplification.

DESIGN OF CITIES

The CITIES system is a scintillation detector which consists of 16 identical channels. Each channel is composed of different components described here. Cesium iodide crystals doped with thallium act as the detection medium for CITIES. These crystals are manufactured by Alpha Spectra Inc. Cesium iodide was specifically selected as it does not have a cleavage plane, making it well suited for situations with high mechanical stress, helping mitigate the risk of a crystal fracturing during a rocket launch.[2] Cesium iodide crystals are less affected by temperature variations in comparison to other options as well. The combination of these factors makes cesium iodide the ideal choice for a CubeSat based device. The crystals' scintillated photons have a range of 320 to 550 nm wavelengths which dictates the choice of photosensitive device to couple to the crystals.

C-Series silicon photomultipliers (SiPMs) made by the company SensL begin the system's electronics. The SiPM is optically coupled with optical grease to the scintillation crystal in each channel and collects the scintillated photons generated by each high energy event. Optical grease assists in coupling the crystal and SiPM while also matching the index of refraction of the crystal, facilitating the travel of the scintillated photons to the SiPM's entrance window. Each SiPM has a spectral range from 300 to 950 nm with a peak sensitivity to wavelengths of 420 nm. This aligns with the emission spectrum for the cesium iodide crystals making the SiPM a good fit for the crystal's scintillation spectrum. A large gain can be achieved with a low bias voltage of ~28 V with this device, helping to stay within the constraints of the CubeSat platform. Next, a charge sensitive preamplifier collects the charge carriers generated by the SiPM.

Cr-112 charge sensitive preamplifiers (CSPs) from Cremat Inc. are used in CITIES. These modules output voltage pulses with amplitudes proportional to the number of charge carriers collected. Each stage in CITIES is linearly proportional which makes eventual calibration simpler. These voltage pulses are sawtooth in shape with rise times on the nanosecond scale. While the signals carry information, additional signal processing is undergone to further refine the output of the signal.

A Cr-200 4 μs shaping amplifiers from Cremat Inc. follows the CSP in each channel. This device integrates and shapes the input signal based upon its integration time which is given by the module name, 4 μs in this case. Its output follows a Gaussian distribution with amplitude linearly proportional to the input. The signal is now much easier to process and extract information from in comparison to the fast and varying output of the CSP. An additional device follows the shaping amplifier which completes the analog signal processing electronics. The CR-210 baseline restorer module maintains a consistent baseline for the signal, preventing the "zero" of the signal from shifting.

The initial stages of each channel are charge and light sensitive, so precautions are taken to mitigate noise that would otherwise corrupt the system. A milled aluminum housing is used to encase everything until the shaping amplifiers of each channel. This includes the scintillation crystal, SiPM, and CSP. The output from the CSP is run through a coaxial MMCX cable to the shaping amplifiers to reduce noise on the line. The aluminum housing also has windows cut out above the scintillation crystals which are covered with a windowing material, thin aluminum. The windowing material maintains a light tight environment for the system. The purpose of these windows is to let high energy photons of interest pass through with minimal attenuation while blocking lower energy photons. Overall, the aluminum housing serves to provide an electromagnetic and light tight environment for the charge sensitive and light sensitive stages of CITIES.

CITIES is designed to be modular. Each stage can be replaced without affecting the other components in a channel. This helps to make testing of the system easier and keep costs low in the case of malfunctioning components.

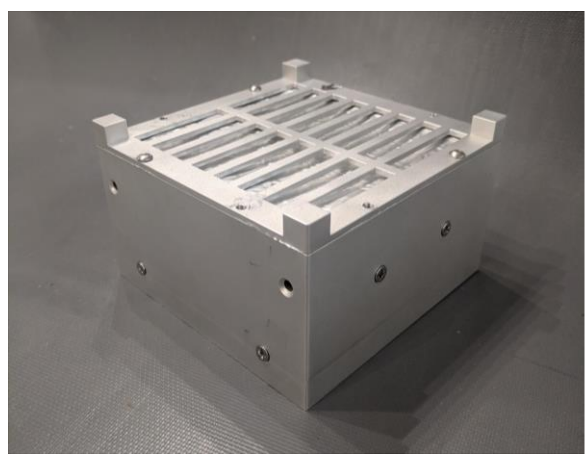

Figure 3: Current revision of the aluminum housing of CITIES.

As seen in the above figure, the 16 detection channels of CITIES are together in 2 groups of 8. Within the aluminum housing, the scintillation crystals are held in a tray which optically couples them to their respective SiPM. The PCB which houses the SiPM and CSP electronics are fastened to the inner walls of the aluminum housing on opposite sides. Finally, MMCX cables are used to transfer the output of the CSPs from the aluminum housing which concludes the charge sensitive stages of CITIES.

The space required for each channel's remaining electronics do not fit on one PCB that fits the form factor of a CubeSat. Two identical PCBs are instead used, each holding 8 of the channels. After the analog signal processing is completed, MMCX cables are once again used to transfer the output of the shaping amplifier. The analog signal is then converted using an ADC into a digital signal. Other subsystems within the satellite then use the digital signal to extract information about the initial high energy event, such as the time of occurrence and energy of the photon.

TESTING

To test the detector, radiation sources are used. Included are Americium 241 (Am-241), Barium 133 (Ba-133), Sodium 22 (Na-22), Bismuth 207 (Bi-207), Cesium 137 (Cs-137), and Cobalt 60 (Co-60). These sources were used for their known energy spectra with definite emission lines. This allows for the measurement of the resolution for the detector, with resolution being defined previously. Compiling the measured ADC values given by our system and comparing to the known energy lines of the radiation sources allows the system to be properly calibrated. The system's output can be translated directly to an energy value after calibration.

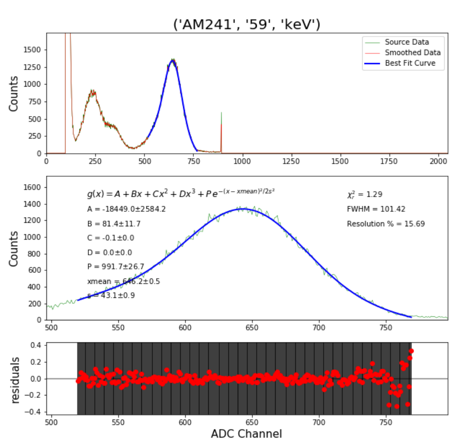

Figure 4: Spectrum of Am-241 using the first channel of the CITIES detector.

The current version of the CITIES detector can reach a resolution of 15.69% at the 59 keV emission line of Am-241. This spectrum is shown in figure 4 above.

CITIES does not directly record energies of the incident photons, but everything from beginning to end is linearly proportional to that energy. The direct output of the detector is in bins of digital values from analog to digital converters (ADC values) that can be traced back to energy bin values. To determine the relationship between ADC and energy values, multiple spectra were taken of different radioactive isotopes that have well known energy emission spectra. Calibration hasn't been done on the current version on the detector, but it has been with a previous revision. The way it was calibrated in the past is the same way the detector will be calibrated in the future.

Table 1: Radioactive Isotopes and Energy Emissions Used for Calibration

Radiation Source	Energy Emissions (keV)	Measured ADC Value
Am-241	59	45.2
Ba-133	356	245.3
Na-22	511	354.3
Bi-207	570	401.8
Cs-137	662	449.6
Co-60	1173	803.6

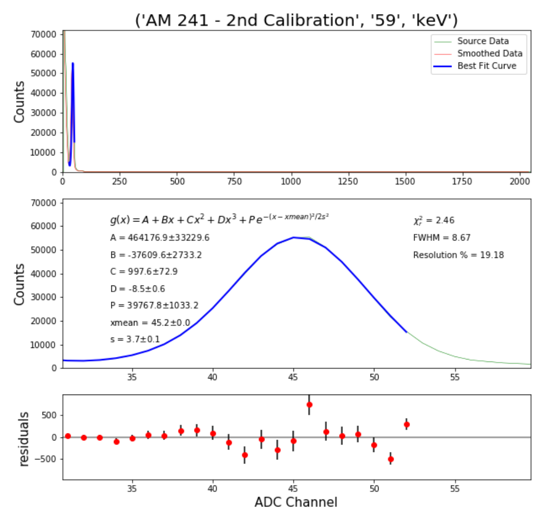

Figure 5: Spectrum of Am-241 using a previous revision of the detector.

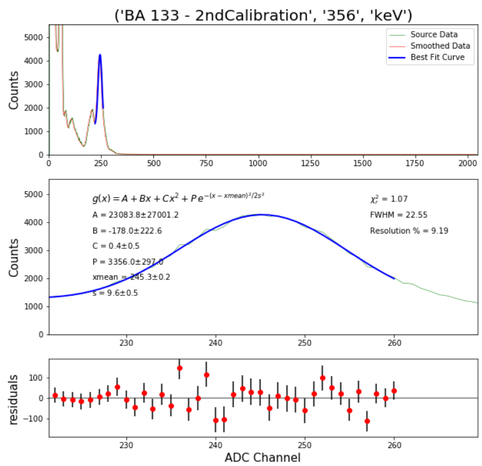

Figure 6: Spectrum of Ba-133 using a previous revision of the detector.

An in-house written data analysis script written in Python is used to process the data gathered during experimentation. Figures 5 and 6 display that output from using this script. The first graph shows the full spectrum gathered with the ADC values along the x-axis and number of counts along the y-axis, the second is a windowed version of the first, and the third shows residuals. A curve fitting algorithm is used within the script and is overlain in blue on both figure 1 and figure 2. This fit curve is what is used to determine the peak ADC value and FWHM of the approximately Gaussian shape. These determined values are used for calibration and calculating resolution.

For each radiation source, the spectrum collected by CITIES was compared to multiple spectra for that same source online. The comparison made it possible to find where the desired energy emission peaks are in our data. An initial approximation of the ADC value is required for data analysis and this process provides an educated guess. Both the energy emissions and their corresponding ADC value were recorded to find the equation that allows for converting between ADC values and energy.

The line of best fit that is found through calibration gives the equation that can be used to label the spectra collected as counts per energy bin instead of counts per ADC bin. Calibration of the system is required whenever changes are made that affect the overall output of the system. This can include using modules with different sensitivities, reassembling the system, and applying a different bias voltage. An example calibration plot is shown in figure 11.

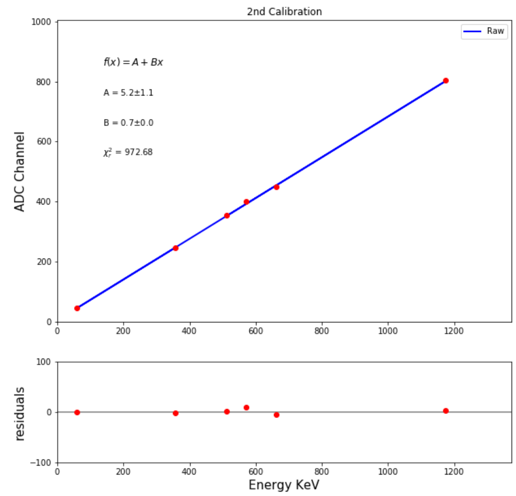

Figure 11: Plot of ADC channel vs. energy in keV.

Timing accuracy requirement is something that needs to be accounted for in our electronics, but tracking how that affects other characteristics of the detector is also needed. The scintillation crystal is the slowest element of detector, where the primary decay of scintillated photons is 1 µs and a secondary decay of approximately 8 µs. In order to combat the secondary decay time, the Cr-200 shaping amplifier chips have different shaping times that would be able to control the crystal timing. Tests were done with Am-241 to be able to compare resolutions with the different available Cr-200 shaping amplifiers; 2 µs, 4µs, and 8 µs.

Table 2: Comparing Resolution with Different Cr-200 Cremat Chips

Shaping Time	ADC Resolution
2 µs	24.28%
4 µs	25.16%
8 µs	35.37%

The resolution continued to improve the smaller the time frame that each Cr-200 chip had, with the largest improvement being between the 8 µs and the 4 µs shaping times. The rest of the satellite wasn't optimized to handle the amount of data that would be generated with a 2 µs shaping time, but is capable at 4 µs. Since the requirement is an accuracy of 4 µs, the 4 µs Cr-200 shaping amplifier is used on CITIES.

There are many options in terms of crystal and photodevice sizes. Different combinations of crystal geometry and photodevice size were tested to pick the optimal combination. SiPMs and Avalanche Photodiodes (APDs) were the two candidates originally tested. The isotope used to compare resolutions was Am-241 at the 59 keV emission line. Once the data was collected a general trend was observed. The closer the dimensions of the crystal that connects with the photodevice and the dimensions of the photodevice are to each other, the better the resolution achieved.

Table 3: Comparing Resolution for Different Combinations of Crystals and Photodevices

Device	4x4x4 mm	9x9x9 mm	4x4x40 mm	9x9x40 mm
5x5 mm APD	11.49%	30.03%	16.50%	20.07%
10x10 mm APD	NA	16.25%	NA	23.05%
6x6 mm SiPM	11.80%	23.66%	16.92%	25.16%

Since the photodevices were not able to be made any larger, that lead to conflicting requirements of a large detection area and good resolution. The 4 mm x 4 mm x 4 mm crystal resulted in the best resolution every time it was used, but it would lead to a small detection area or make the detector much more expensive. On the other hand, large crystals provide a large detection area but forfeit good resolution. A large detection area can be achieved while maintaining a resolution within the missions' requirements by using 7 mm x 7 mm x 40 mm crystal with the 6 mm x 6 mm SiPM and having 16 identical detection channels. This gives a total detection area of 25.2 cm^2 and best resolution of 15.69%.

CONCLUSION

The CubeSat missions SOCRATES and EXACT require a radiation detector that fulfills each missions' requirements while fitting within the constraints of the CubeSat platform. The CITIES system fills this role as a low-cost scintillation detector with large detection area. SOCRATES will use CITIES to provide proof-of-concept of a ranging technique using astrophysical sources. EXACT will observe solar flare spectra to better understand HXR emissions. This mission will fill the gap of solar observers that is soon to come as current solar observers, such as FERMI, RHESSI, and WIND, are beyond their expected mission lifetimes already.[3] The CITIES system will continue to be developed and characterized for SOCRATES and EXACT as these missions mature. While CITIES is designed for these missions, the system is versatile and is able to be used on other platforms. It is expected that CITIES will act as a scientific payload on other future missions.

ACKNOWLEDGEMENTS

We would like to extend a special thanks to the Air Force's University Nanosat Program (UNP), NASA's Undergraduate Student Instrument Project (USIP), the Minnesota Space Grant Consortium, and National Science Foundation (NSF grant AGS-1429512) for their contributions and support of Physics and Aerospace Engineering at the University of Minnesota.

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