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Threat Detection Using a Modular Cosmic Ray Muon Tomography System

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Research Foundation Of The City University Of New York

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Final Report

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14. ABSTRACT
Our research focuses on leveraging developments in computing hardware and modern particle physics detectors to produce a simple, effective, robust, modular threat assessment system to non-destructively detect concealed contraband radioactive materials. Mobility and weather resistance are central to our design. The baseline design calls for the use of single board computers (SBC) and charged particle detectors that are very mature and reliable in their design and operation. Our particle probe for screening materials is naturally-occurring cosmic-ray muons. We aimed to develop this Lego-like system to demonstrate simple tomography of brick-size shielding for transport of radioactive materials within packaging as large as a 55-gallon oil drum. The goal was to significantly reduce costs compared to custom detector system designs, by using commercial off-the-shelf components. System design focused on producing equipment that a trained but non-expert operator can operate.

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Final Technical Report

Threat Detection Using a Modular Cosmic Ray Muon Tomography System

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Overview

Our research focuses on leveraging developments in computing hardware and modern particle physics detectors to produce a simple, effective, robust, modular threat assessment system to non-destructively detect concealed contraband radioactive materials. Mobility and weather resistance are central to our design. The baseline design calls for the use of single board computers (SBC) and charged particle detectors that are very mature and reliable in their design and operation. Our particle probe for screening materials is naturally-occurring cosmic-ray muons. We aimed to develop this “Lego”-like system to demonstrate simple tomography of brick-size shielding for transport of radioactive materials within packaging as large as a 55-gallon oil drum. The goal was to significantly reduce costs compared to custom detector system designs, by using commercial off-the-shelf components. System design was focused on producing equipment that a trained but non-expert operator can operate.

Our specific objectives for the research program were to:

- build a suite of compact scintillation detectors,
- construct modular, weather tight modules for these detectors,
- demonstrate simple tomography of small mock threats (ie 55 gallon-drum scale and smaller targets containing the mock threat),
- use the design and construction process to drive student development and education, and,
- to perform detailed studies of the real world backgrounds important for cosmic ray tomography, and their dependence on factors including terrestrial weather and solar sources.

We achieved most of these goals in some form, and learned many lessons in the process that we have applied to other projects, or will apply in our project management in the future.

System Design

The system design we originally proposed is outlined in Figure 1. An object or container considered a potential threat would be surrounded by a set of detector modules, each consisting of a scintillating plastic "pixel element" connected to a photomultiplier tube and read out by a single board computer (SBC) such as a Raspberry Pi or Beaglebone Black running Linux and custom software. These detector modules are connected to an ethernet network switch, and send their independent data streams over this network to a ruggedized Linux server. The data streams from each of the modules are merged and we then look for coincidences between modules, indicating the passage of a muon through both detectors and the potential threat object. Shadows or enhancements in the rates between module pairs caused by density variations are tomographically imaged by such an arrangement. Such an organization allows easy modifications to the number and configuration of detector modules to address various threat geometries, detector failures, etc.

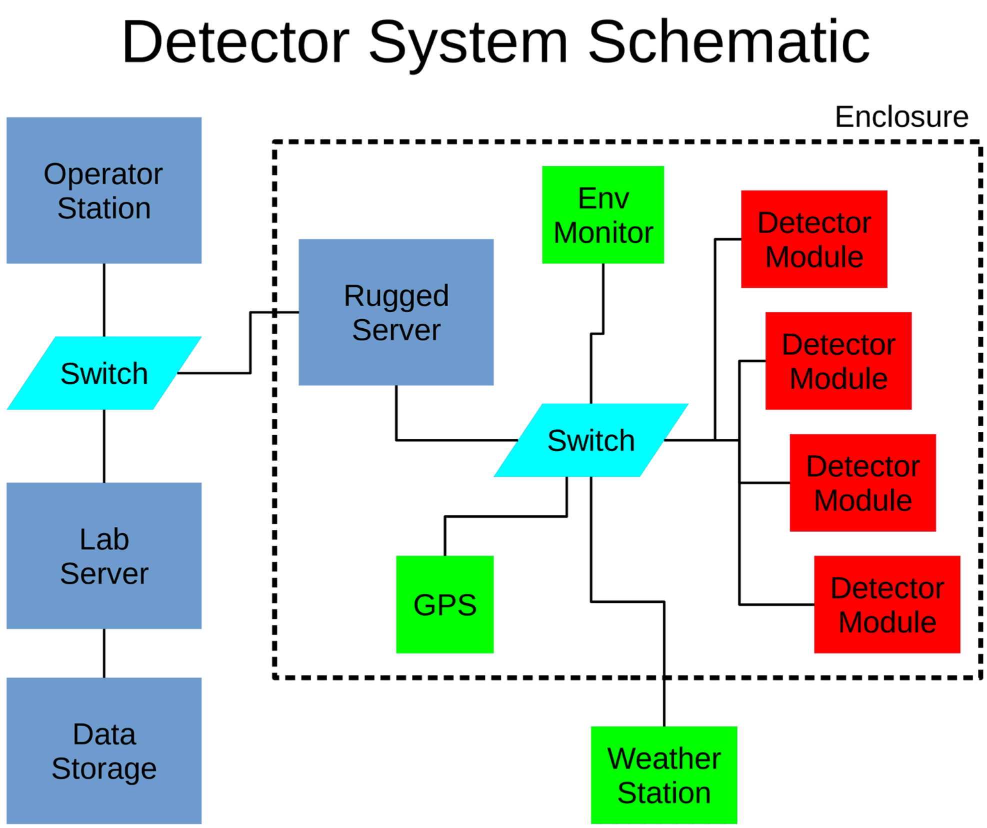

Figure 1: Schematic overview of the detector system envisioned in our original proposal.

With each module being an independent data acquisition system, attaining and maintaining time synchronization between modules becomes the difficult problem. Our design relies on the Network Time Protocol (NTP) to synchronize each of the modules to a master clock provided by a GPS disciplined clock master. And because environmental conditions – such as local temperature and atmospheric pressure – are known to modulate the local muon rate at ground level, the system includes additional sensor modules to collect the needed data.

While the concept is straightforward, there were a number of implementation challenges that we had to overcome – some of which were unexpected – which we document below.

Personnel

The project PIs – Dr. James L. Popp and Dr. Kevin R. Lynch – are faculty in the Department of Earth and Physical Sciences (E&PS) at York College of The City University of New York (CUNY). We are both tenured Associate Professors of Physics. Our primary field of study is accelerator-based muon physics. We bring to this project expertise in particle detector design, construction, and operation, data acquisition, software development, and materials science. During the course of this project, Lynch received tenure and promotion. We have three laboratory spaces on campus for pursuit of our work, one more than when the project started, and we are actively utilizing all of our available space.

Our original proposal called for funding significant graduate student effort. Unfortunately, we did struggle to retain good students on the project. In the first year, we recruited Mr. Enxi Yu, a doctoral candidate at The Graduate Center of CUNY to join us in carrying out this research. As a doctoral candidate he had completed his basic course work and passed his qualifying examinations. In August of 2015 he began his training as a graduate researcher in high-energy physics. The project was budgeted for half-time support for a graduate student and we provided Mr. Yu with that support, which is supplemented by his employment in the E&PS department teaching laboratory classes for our physics gateway courses. Unfortunately, for personal reasons, Yu was unable to continue with us beyond the end of the spring 2016 semester. Given the timing of his departure, we were unable to immediately replace Yu with another matriculated graduate student. Unfortunately, this late personnel disruption significantly delayed our planned schedule for 2016.

Over the summer of 2016, Mr. Luis Maduro, a former York undergraduate physics major, joined our department as an Adjunct instructor and worked with us on this project throughout the 2016-2017 academic year. He helped us make significant progress in detector module prototyping during that time. Figure 1 shows Maduro with one of the prototype detector modules he built in fall 2016. Again, for personal reasons, Mr. Maduro was unable to continue into full-time graduate students, and left in summer of 2017 to pursue job opportunities; he is currently a Master's level student in Medical Physics at Hofstra University.

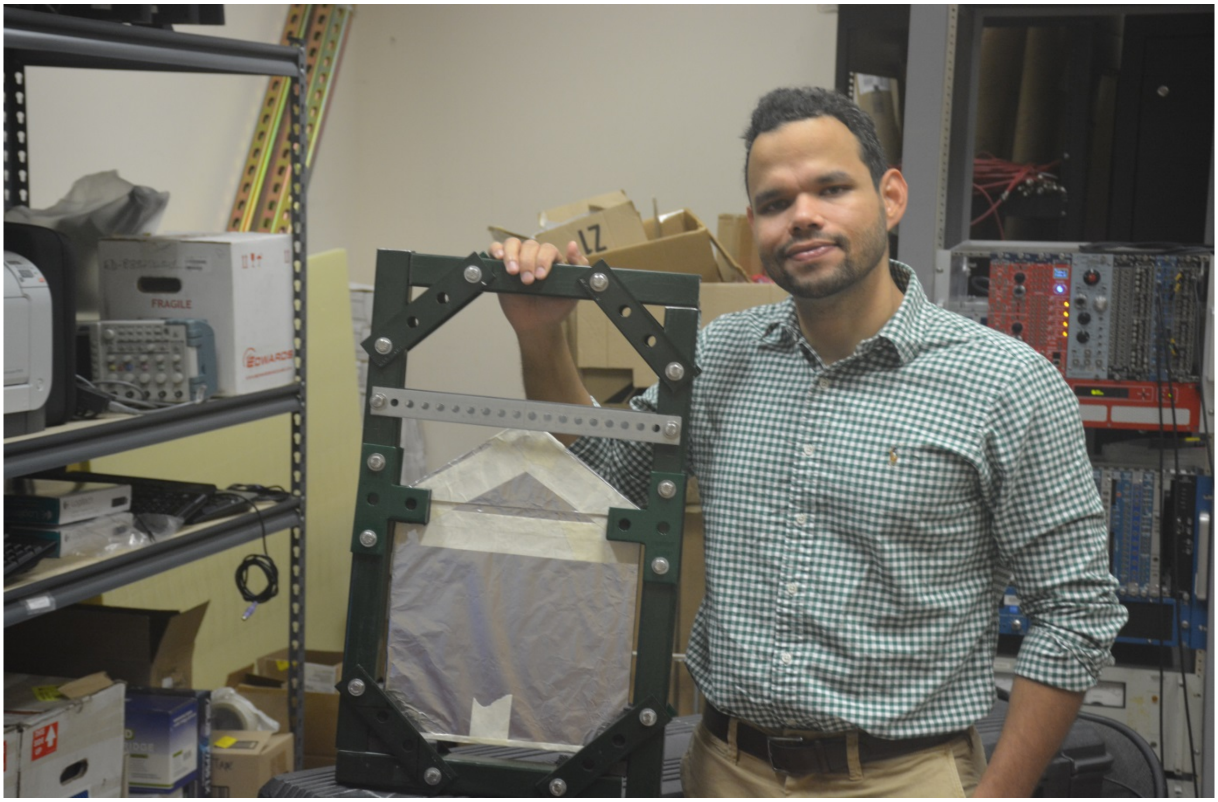

Figure 2: Mr. Luis Maduro in our laboratory with one of the four prototype detector modules he built in fall of 2016.

Ms. Helenka Casler – a PhD student in the CUNY Graduate Center Physics program – came to us on a six week research rotation during her first year in the CUNY program. She holds a Master's degree from Drexel University, where she studied atomic phyiscs; she brings multiple years of industrial software experience working on client-server networked services and has helped us make significant progress in our software. She joined our group full-time in 2017, funded for a year by the York Office of Academic Affairs to work on this AFOSR research and perform teaching duties. She is currently funded full-time by a Department of Energy grant to pursue her doctoral dissertation research in accelerator based particle physics. She has continued to provide support with software issues to this project on an as-needed basis.

Given the timing of these graduate student departures and movements, beginning in January of 2017, we started to lean more heavily on undergraduate student involvement in the project. About ten undergraduate students have pursued specific tasks on the project – both with AFOSR support and outside support from our Office of Academic Affairs, the NASA Space Grant program, and Department of Education funding to support summer research.

Two of these students truly stood out as extremely productive in advancing the work. Mr. Christopher Tandoi transferred into our physics program with an Associate degree from Queensburough Community College at the beginning of the fall 2016 semester. He received academic credit for his laboratory work during the spring and fall 2017 semesters, and wrote an undergraduate thesis on his work for us. He was supported by the NASA Space Grant program to work with us over the summer. He graduated with honors at the end of the 2017 semester, and was planning to work for us full time through the spring 2018 semester. Unfortunately for us, his research expertise was recognized beyond York, and he was recruited into a research internship at NASA's Goddard Spaceflight Center for spring and summer of 2018. In the year since – based largely on the expertise and skills he acquired working for this project – he worked full time at the Ohio State University building scintillation detectors for high energy physics projects at the CERN laboratory. He will be entering the doctoral program in Astrophysics at the University of Illinois at Urbana-Champaign in fall 2019.

Beginning in January of 2017, undergraduate Mr. Tawhid Pranto has begun working on our AFOSR research. Mr. Pranto is a York undergraduate physics major who has worked in our research group since late 2016; he has previously worked on our Fermi National Accelerator Laboratory funded project. He was awarded the Eugene Levin Scholarship and Research Internship; this is a York College scholarship funded in memory of York Physics Professor Eugene Levin and awarded to promising science majors. The funding includes both full tuition coverage and a summer research stipend. Mr. Pranto worked with us through the end of his studies in fall 2018. He currently teaches in our undergraduate physics program, and will be pursuing a PhD in condensed matter physics in the CUNY Graduate Center Physics program in fall of 2019.

During the period of 2018-2019, nine other undergraduate students participated in this project and received various levels of laboratory training: Shaista Ahmad, Louisa Bawie, Kirk Gardner, Moradeke Okunoye, Tanusri Sarkar, Siedah Hall, Hira Shafi, and Chase Warren.

Overall, while we did struggle early with retaining graduate students, those other students who participated in the project learned significant amount of physics, research skills and laboratory discipline. We are quite pleased that this project has enabled a number of them to pursue graduate education or full-time employment.

Infrastructure Support

In its ultimate form, we envisioned a weather tight, field deployable system, requiring demonstration of all-weather capability. As noted, interpretation of the physics data required the collection of weather data. To support both of these ends we required outdoor structure modifications to the main York College campus buildings.

To this end, we selected a Davis Vantage Pro2 Plus integrated weather sensor suite. This unit measures rain fall, temperature, humidity, wind speed and direction. In addition, we also record solar and ultra-violet radiation. This solar-powered unit sends data using a wireless system to the remote console via low-power radio. We worked with the York College Executive Director of Facilities & Planning to arrange installation of the mechanical support so we can obtain an unobstructed southward view on the roof of the fourth floor of the Academic Core Building. York College also pledged $2.5k to provide electrical power and internet service for the project, visible in Figure 3.

The weather station has since been configured to perform real-time reporting to the Weather Underground service. We have built a weatherproof router and network switch that will provide network connectivity from this outdoor wiring panel to both the instrumentation shed and detector modules that we plan to mount on the roof for long-term exposure tests. Finally, we have built a weatherproof, GPS-disciplined network time protocol server that will

Figure 3: Roof-top Weather Station, with permanent power and network connections shown just to the right of the support pole.

coordinate the time stamps across all computers in the data acquisition network (including the SBCs).

We also purchased a small instrumentation shed for storage and operation of equipment, with plans to mount it on the roof-top. During our initial discussions with the building operations staff, there was some concern that such a semi-permanent roof installation would require significant engineering study, multiple levels of approvals, and expensive installation by licensed and bonded contractors. Fortunately, none of this came to pass, as the type of lightweight shed we purchased was not significant enough to meet the engineering thresholds. The shed was successfully installed near our permanent weather station on the roof in mid-2016; see Figure 4. York College Facilities management again absorbed the construction and installation, at no cost to the research project. The shed is mounted in a sheltered area a few floors directly above our office space. It is secured with padlocks and not visible neither from ground level nor from any vantage point within the building, and out of the way of any regular maintenance activities. We continue to use the shed to house electronic test and measurement equipment and computers that we are using in our system development, and which themselves are not weather tight. It will also be used as a secure storage room for weather tight devices when not in use.

Figure 4: Roof-top Instrumentation Shed, with prototype detector modules shown in front.

Detectors: Design Studies and Construction

There are essentially three detector options available to us for coincidence counting of charged muons passing through matter. Option one is to use plastic sheets doped with scintillating compounds to enhance light output. Option two is to use clear un-doped plastic sheets and detect Cherenkov light. Option three is to use gas-filled chambers and seek to detect ionization electrons. While we explored all options, we chose in the end to build scintillating plastic detectors as originally envisioned in our proposal, read out by photomultiplier tube. The modular detector concept requires a weather and light tight enclosure containing the detector elements and SBCs in good geometric alignment. After exploring other options, we again stuck with our original proposal, and mounted the detector elements in equipment cases designed for transportation of firearms; see Figure 5.

Figure 5: Scintillating paddle and PMT readout mounted in a firearms case.

Photodetectors

Our original proposal envisioned a system using as much commercial, off-the-shelf technology as possible, to minimize both cost and custom development. To realize that goal, we evaluated numerous photodetectors before selecting a candidate device for our prototypes. This gave us a surprising amount of difficulty over the course of the project. In a typical high energy physics experiment, PMTs are powered by large, central high voltage power supplies, which are not an option for a portable, modular system. We required devices which could be powered off noisy low voltage DC while providing steady high voltage outputs to minimize gain drift.

Our first device was a low cost PMT driven by a DC-DC high voltage converter. This device had unacceptable gain drift over the course of a typical hour long measurement period. We then selected a PMT with an integrated high voltage power supply as well as a discriminated TTL output signal, which could be operated with a low current, low voltage DC input that could be met by all the SBCs we were considering. Unfortunately, the device – while otherwise quite a nice piece of equipment - did not meet our needs due to a significant self-triggering dark signal rate (around 30Hz), which exceeds our expected signal rate (around 15Hz). Next, we purchased second-hand a number of different 5V powered PMTs with analog outputs, but found them to be mildly activated by their previous usage in a nuclear physics accelerator environment, making them also unsuitable for our low count-rate requirements.

Our final failed attempt was to switch to solid state Silicon Photomultiplier (SiPM) devices from SensL. SiPMs have a number of advantages over the traditional vacuum photomultiplier tubes: they are more mechanically robust, they operate at much lower voltages, are nearly immune to magnetic fields, and they require much less real estate in the finished product; their two main drawbacks are shared with many solid state parts: gain is very sensitive to temperature and voltage fluctuations than are tube devices, and reliability in a development environment are typically not good. Fortunately, they are normally available with packaging that provides temperature compensation, and voltages can usually be stabilized with relatively low cost and difficulty. Our tests showed excellent timing properties, and output voltages compatible with our electronics. Unfortunately, we had reliability problems that we were not able to solve, even with help from the manufacturer.

For most of our quantitative tests, we returned to our original analog output PMTs with DC-DC converters. While they were unacceptable for a production system, we were able to sufficiently mitigate the gain problems for laboratory tests. Although the AFOSR funded portion of this project is completed, we see great utility in other areas for these detectors and so are continuing to seek additional funding to address this photodetector issue and complete a robust detector module.

The final piece of the detector hardware puzzle is the interface between the photodetectors and the SBCs. First, the voltage output levels from either PMTs or SiPMs are generally incompatible with the SBC inputs (either 5V or 3.3V TTL compatible). Second, the pulse output lengths are generally too short and the pulse heights too small to directly trigger the interrupt hardware on the SBCs. We prototyped and developed a number of discriminator-plus-pulse-stretching circuits, eventually producing a Raspberry Pi compatible board that can be driven by either positive or negative voltage photodetector pulses; see Figure 6. This module will prove useful for other uses beyond this project, both in research and teaching contexts.

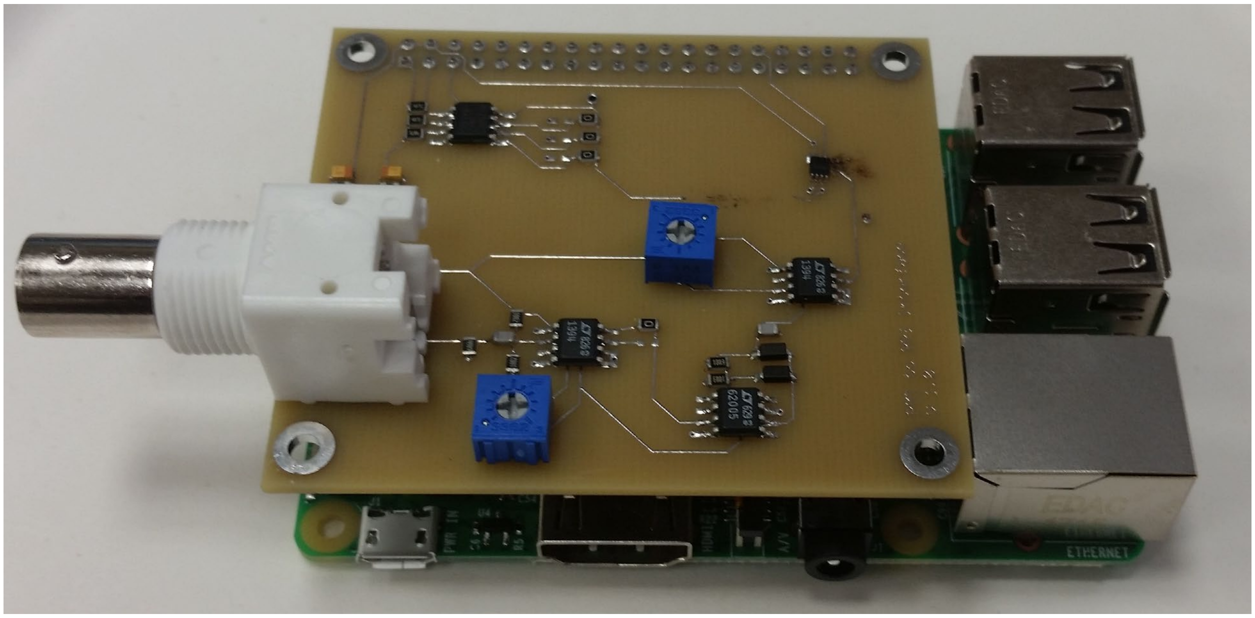

Figure 6: The Raspberry Pi compatible discriminator module.

Software Developments

Because so much of this project involves independent, network connected devices, software is critical component. In particular, minimizing software latency is critical to doing software, rather than hardware, based event timing.

All low-cost SBCs – including those we use – run some variant of the Linux operating system. Linux code is both open source, and well documented online. The Linux security and programming model provides a strict separation between privileged – or "kernel mode" - operations, such as those that operate directly on hardware, and unprivileged – or "user mode" - operations that all users are permitted to perform. User mode programming is significantly more forgiving of mistakes than kernel mode work, where the smallest errors can result in significant security issues or routine system crashes. Additionally, significantly fewer – and more primitive – tools exist for kernel development and debugging.

Given these issues, in our initial tests of coincidence timing we used a user-space python library to access the GPIO pins; we found the additional software layers required to perform this work in user space added significant timing delay and jitter. These timing proved to us that user mode programming was unsuitable for this application, and we developed a Linux kernel driver – a muon timer – for the Beaglebone Black SBC (which we later ported to the Raspberry Pi line of SBCs). The driver provides interrupt handling and latch reset control for our electronics, as well as a test pulser output for debugging purposes. The driver provides time stamping of interrupts along with binary readout and, an additional timer to recover from "lost" interrupts and full support for standard UNIX file semantics. The code for this component is extremely robust: it has been run with a 10Hz self-driven pulse input for more than three million pulses without encountering any error conditions. This well exceeds our development requirements. The code for this component is publicly available on the Github service: https://github.com/krlynch/muon_timer. We will be using this driver beyond the AFOSR project in areas as diverse as our other high energy physics experiments and advanced undergraduate laboratory experiments in condensed matter and gravity.

Our students wrote two generations of software utilizing this driver to measure coincidences between independent detectors. The first generation – largely written by Tandoi – had each independent detector module log its detection events to CSV files, which we later combined offline to find coincidences. The second generation – largely written by Casler – utilizes the http network protocol to start and stop acquisition on individual nodes, and pull data to the central logging server. Currently, this version of the software does not do online coincidence finding, but combs through the data offline in a similar manner to the first generation software. Again, since we see utility to these detectors beyond the AFOSR project, we plan to have students continue this development work in future with enhancements for online coincidence finding.

Evaluation of coincidence timing

The most important functional requirement for the success of our system is to be able to detect coincident events between separate detector modules. Scintillation events in our detector paddles generate electrical signal pulses from the PMT, which feeds a threshold detector circuit. Over-threshold pulses are passed to the GPIO inputs of the associated SBC which generates an interrupt event which is timestamped by our custom Linux kernel driver. Since each detector module has a separate SBC, the kernel timers must be externally synchronized across all SBCs in the system by system, which we do by means of the Network Time Protocol, driven from a custom GPS disciplined NTP server. The stability of this method is sufficient for 10microsecond scale coincidence timing, which should be sufficient for our needs; see Figure 7.

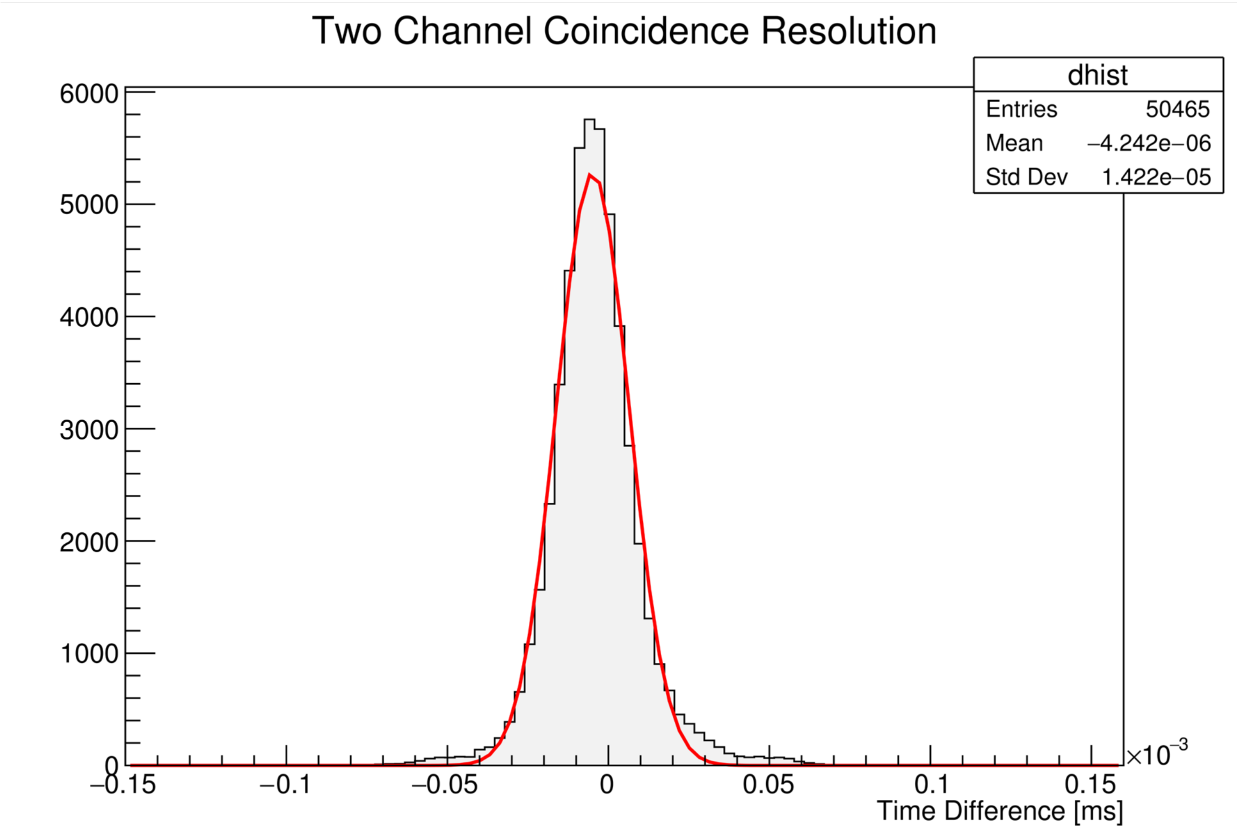

Figure 7: Coincidence timing for a pair of independent detector modules using NTP for synchronization. We recorded the times of a stream of events as recorded by two different SBCs, and then took the difference. The overall offset is not physically relevant (as it can be subtracted in operation); the Gaussian shape and 14microsecond width tells us that the differences are random and well within our requirements.

We have since changed our SBCs to a faster model which should achieve better resolution than reported here.

Having demonstrated sufficient timing resolution, we need to ensure that the timing is stable across hour scales. To this end, we have performed two tests: coincidence counting over long scales, and cosmic event counts over long scales. In the coincidence counting, we again drove pairs of SBCs with the same event stream, and tracked the time difference stability over many hours. The results of these tests show that the NTP based timing system and the electronics are sufficiently stable at the 10 microsecond scale. The second test was to record cosmic ray event data and measure actual coincidences over many hours; see Figure 8. With our original

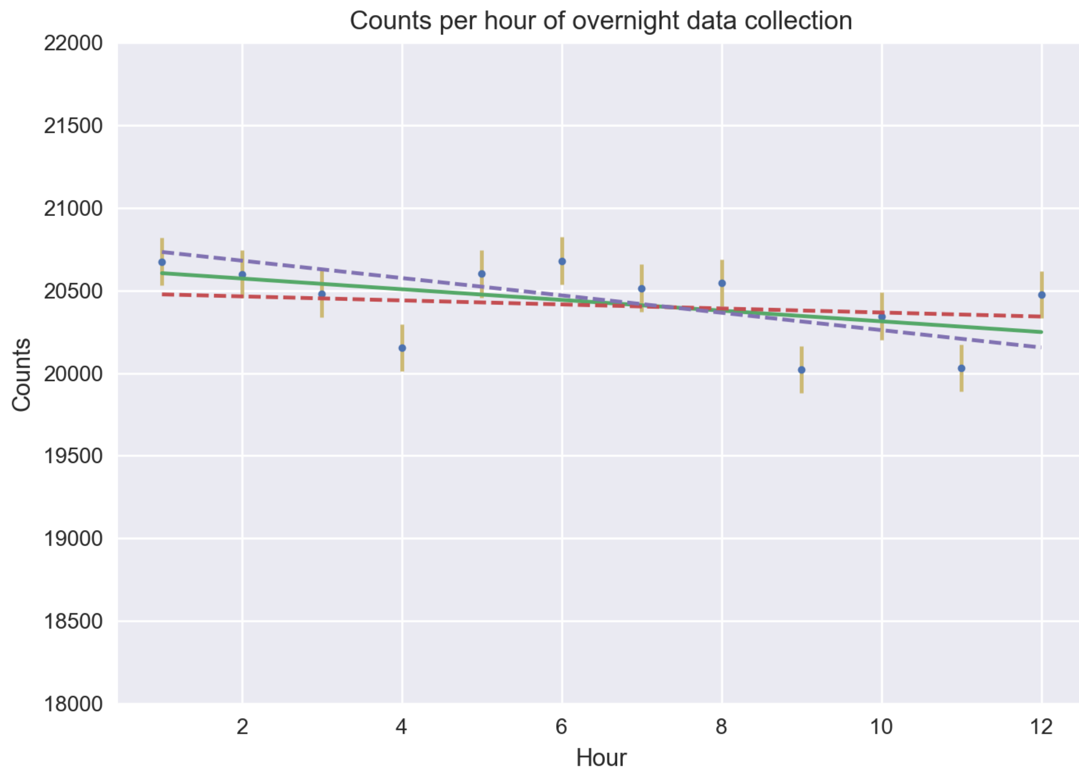

Figure 8: The stability of cosmic ray coincidence counting rates as measured in an overnight run with our NTP driven SBC system. The slope of the fit performed here is consistent with zero; other runs similarly show count rate stability at the level required by our design.

PMT based acquisition, we saw significant sag in gain and counting rates over time in this test. The data from these tests have all been consistent with stable counting rates.

We next tested against a known mock threat, namely, a lead brick placed in known position relative to a scintillator pair. Each scintillator tile measures one foot by one foot, and the pair was separated by approximately six inches. The brick was passed through the space between the scintillator pair, in 2.5 inch steps; at each position, the count rate was measured in 30 minute intervals. To test repeatability, this test was repeated multiple times; the results were consistent, run to run. A pair of runs are overlaid in Figure 9. It is clear that we can observe the presence of this mock threat between the tiles. There are two main differences between this test and a full scale system. First, this test was not a blind search for the mock threat; we knew the location and density of the object. Second, the fully scaled out system will contain more scintillator paddles, hence will include more coincidence counting pairs.

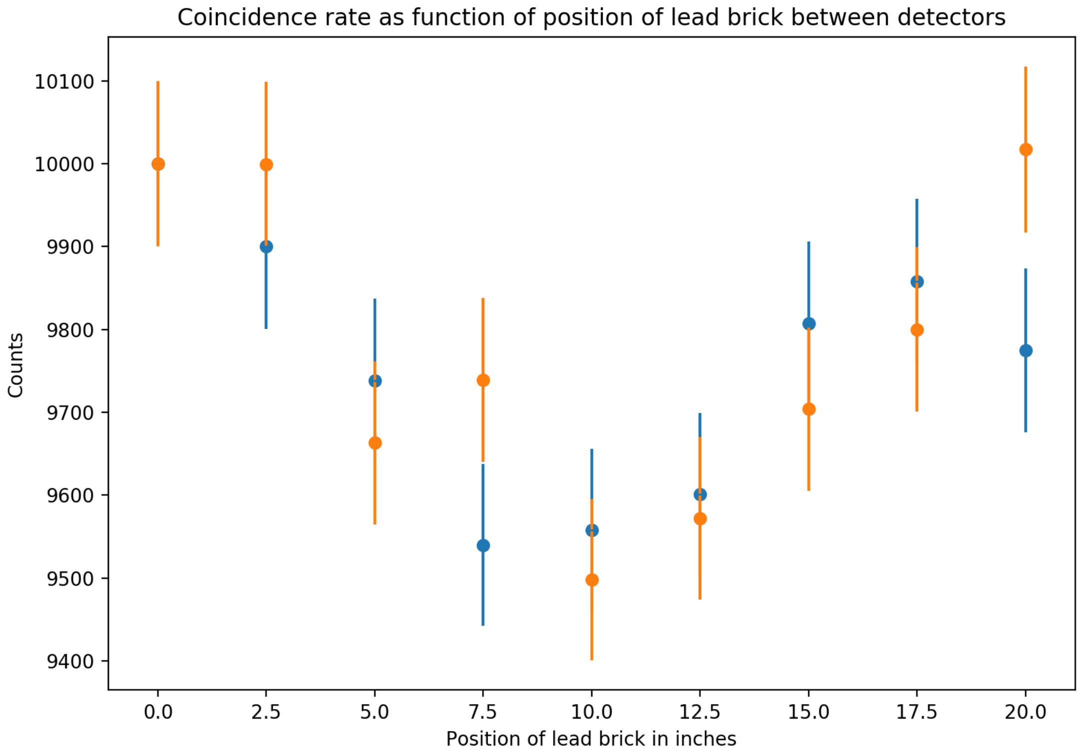

Figure 9: Data for a tomographic observation of a lead brick. The orange and blue points are data from two separate passes of a lead brick between scintillator tiles, using our NTP based SBC timing system, with coincidences discovered in software.

Future Work

During the course of the project, we demonstrated all of the fundamental building blocks required to meet our objectives, we did not in the end build out a full prototype system. We were able to procure the necessary materials and supplies to complete a four detector module system. We intend to continue developing the system as time and alternate resources permit, and to pursue additional funding to complete the system as originally envisioned.

The techniques and equipment we developed during the course of the project are finding use in other arenas. We are collaborating with Dr. Raul Armendariz at Queensburough Community College in bringing up a distributed Cosmic Ray Observatory, where we are contributing many of the ideas and techniques from this project. The Linux timing driver is finding use in a variety of advanced undergraduate laboratory experiments and in our high energy physics work. We also plan to utilize the detector modules to perform local cosmic ray counting experiments to allow our students to investigate cosmic ray coincidence and shower rates.