Designing a Low-Energy, Narrow-FoV Gamma-Ray Observatory

Anthony Nesbitt, Brookdale Community College

Objective

To determine the feasibility of designing a small, narrow field-of-view detector of low energy gamma rays and construct a prototype.

Background

Gamma rays are the highest-energy form of electromagnetic radiation, with high frequencies and short wavelengths.

- Gamma rays require special equipment to detect and analyze, as they cannot be seen like normal light.
- Gamma rays from space do not penetrate all the way through Earth's atmosphere and can only be indirectly observed from the surface using Cherenkov effect observatories.
- Space-based observatories can perform direct observation of celestial gamma rays using scintillators and pair-production imagers.

Figure 1. VERITAS observatory (https://veritas.sao.arizona.edu/)

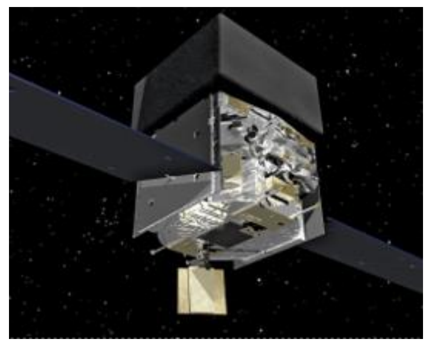

Figure 2. FERMI observatory (Dooling D., Encyclopedia Britannica)

Preliminary Research

- The first stage of the project was to determine whether a ground-based setup could observe and study cosmic gamma rays, and if so, by which methods.
- Celestial gamma ray photons only penetrate Earth's atmosphere to a depth of around ten kilometers above ground level, leaving us with two options:
  1) Develop a Cherenkov effect observatory
     - **Pros:** ground level setup
     - **Cons:** large space requirements, subject to light pollution/interference.
  2) Develop a direct-observation observatory that would need to be carried up to the correct altitude.
     - **Pros:** direct observation
     - **Cons:** needs to be carried to high altitude, ground-based testing would need to be done with radioactive test sources

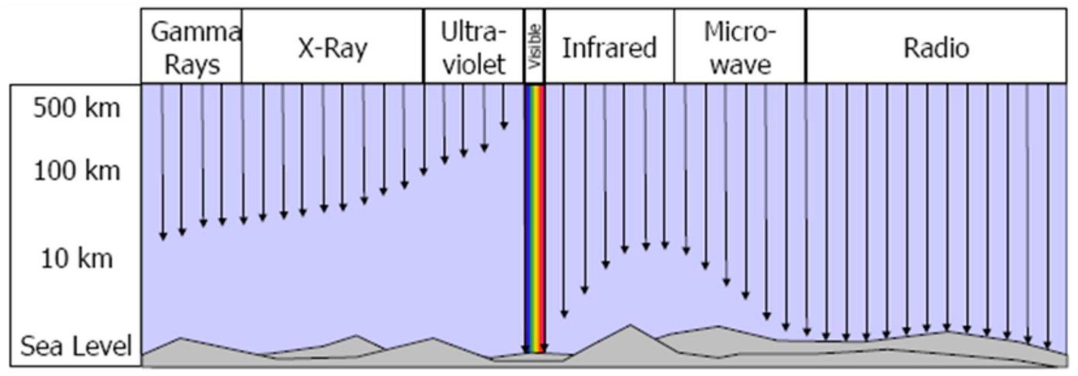

Figure 3. Atmospheric penetration of electromagnetic radiation (L3Harris Geospatial, *Atmospheric windows and optical sensors)*

Research and Design

Evaluating Materials

- Research turned towards methods of directly detecting low-energy gamma rays, settling on scintillating materials.
- There were no available scintillators that were sensitive only to gamma rays.
- Thallium-doped sodium iodide crystals, NaI(Tl), were found to be an excellent choice for detecting many forms of radiation, especially gamma rays.
  - However, this necessitated the use of some form of "veto" to remove signals that were caused by radiation other than gamma rays.
  - A plastic scintillator, BC-408, was found to be very sensitive to all forms of radiation except for gamma rays, to which it had minimal sensitivity.

Design Considerations

- A directional component to the observatory was desired, giving it a narrow FoV. However, gamma rays cannot be refracted easily, necessitating experimental apparatuses. Multiple options were considered.
  - "Lenses" made from high-density, high Z-number materials.
  - An experimental multi-material layered refractor, as proposed in a paper from Los Alamos.
  - A "pinhole camera" setup using holes drilled in stacked lead sheets, avoiding the refraction issue altogether.
- Cost concerns and production capability were deciding factors, multiple lead sheets with holes drilled in them would be used.

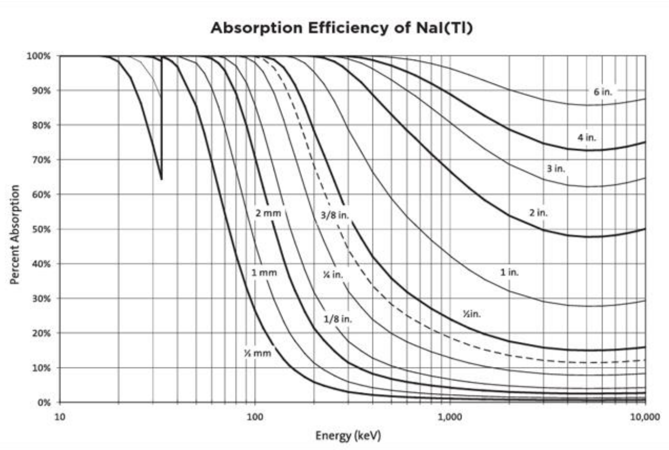

Figure 4. Gamma absorption efficiency of NaI(Tl) crystals. *(Efficiency Calculations for Selected Scintillators,* Luxium Solutions)

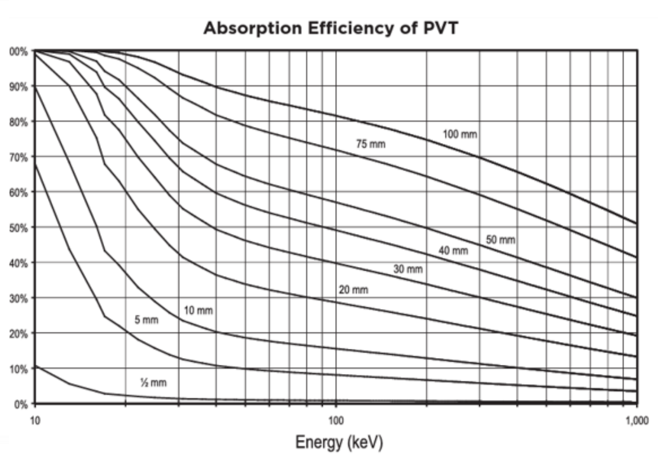

Figure 5. Gamma absorption efficiency of plastic scintillators (BC-408). *(Efficiency Calculations for Selected Scintillators,* Luxium Solutions)

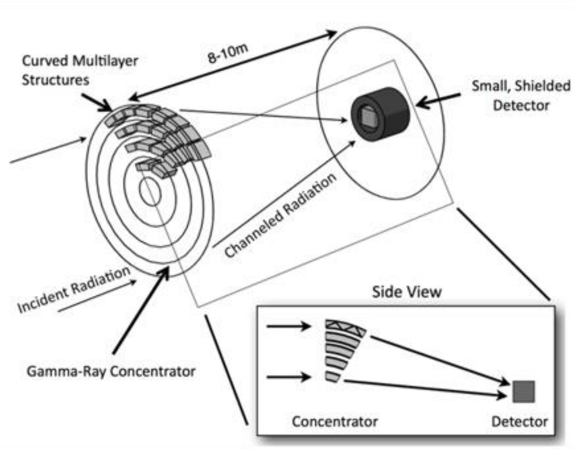

Figure 6. Experimental gamma ray concentrator proposed at Los Alamos. (Shirazi et al., 2020)

Design and Construction

- Construction of a prototype began as soon as a final design was selected, using materials that were available in the lab.
- Some components could be fabricated through use of a 3D printer, or through recycling parts from old/damaged equipment
- Focus pivoted towards acquiring the missing items needed to create a prototype:
  - 2" NaI(Tl) crystal
  - Lead sheeting
  - Arduino Mega 2560
  - Electrical trough
  - Misc. electrical components
  - GPS components

Figure 7. Assembling the BC-408 scintillation counter and installing it into the prototype housing. The NaI(Tl) scintillation counter was assembled in a similar process. Both are shown in the housing at bottom right. Brackets were custom-designed and 3d printed.

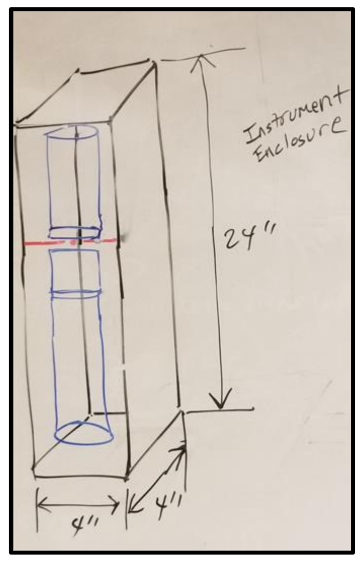

Figure 8. Dimensions for the prototype enclosure.

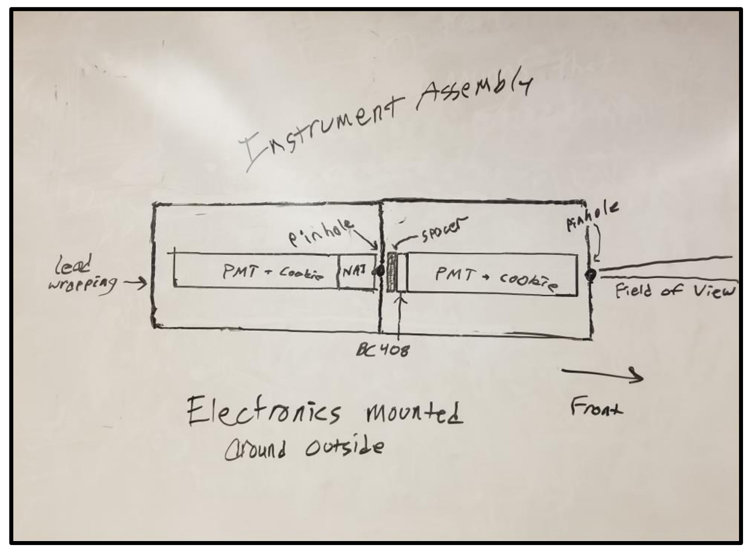

Figure 9. Final design concept, to be refined and prototyped.

Current Results

- Instrument has excellent gamma ray detection capabilities. Directional capabilities TBD.
- Issues arising with low energy gamma rays being unable to propagate far through atmosphere, vacuum chamber may be needed.
- Lead plating may not be thick enough to restrict FoV to desired levels during limited testing, may need to thicken or use a different method.

Limitations

- Cannot test prototype using celestial gamma rays
- Issues with ancient NIM crate electronics.
- Supplier/cost issues while acquiring NaI(Tl) crystal.
- Reworking data acquisition board to accommodate 408 veto functionality.
- Current veto method only works in line with FoV, need to redesign to cover 360 degrees to block muons.
- Special safety measures needed when working with lead.
- Prototype currently works off external power, needs to be made self-sufficient.

Ongoing/Future Work

Ongoing:

- Lead shielding being and installed.
- Data Acquisition Board PCBs are being produced.
- Calibration of the photomultiplier tubes ongoing.
- Move data collection to DAQ board.

Future:

- Make improvements to the design.
  - Several new ideas have been floated, doing away with lead sheeting in favor of nested NaI(Tl) scintillators.
  - Revisiting the experimental gamma ray lenses.
- Move power supply onboard to make observatory self-sufficient.

Conclusions

- It is possible to design and build a relatively small, narrow-FoV gamma ray observatory on a relatively modest budget.
- Our current design works but is flawed and needs adjustment.
  - Lead is probably not the best way to restrict FoV.
  - More advanced designs will require more time, money, and advanced equipment than is currently available to us.
- Our design can be scaled down even further, potentially to sizes that could be easily carried to altitude without needing a dedicated satellite or flight platform.

Acknowledgements

This work was supported by the New Jersey Space Grant Consortium and Brookdale Community College. I would like to thank my mentor, Dr. Raul Armendariz, as well as Karina Ochs and Ana Teodorescu for running the fellowship at Brookdale.