Designing a Low-Energy, Narrow Field of View Gamma-Ray Observatory

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Overview

Background on celestial gamma ray observation.

Objectives of our project.

Design process and considerations for meeting said objectives.

Prototype construction and the challenges associated with such.

Ongoing and future work to be done on this project.

Findings and conclusions up to this point.

Objective

- Design a small, directional gamma-ray detector. Focus was given to lower-energy gamma rays and a narrow field of view.
- Cost, size, and complexity were all factors that we aimed to minimize.
- Any design should be able to be trained towards individual point-sources of gamma rays and collect data such as emission intensity and individual gamma energies.
- Construct a proof-of-concept prototype once a design was chosen.
- Subject the prototype to a battery of tests to determine effectiveness and modify if needed.

Background

- Gamma rays are the highest-energy form of electromagnetic radiation, with high frequencies and short wavelengths.(Stark)
- 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.
- Ground based detectors use Cherenkov effect, space-based telescopes use direct observation.

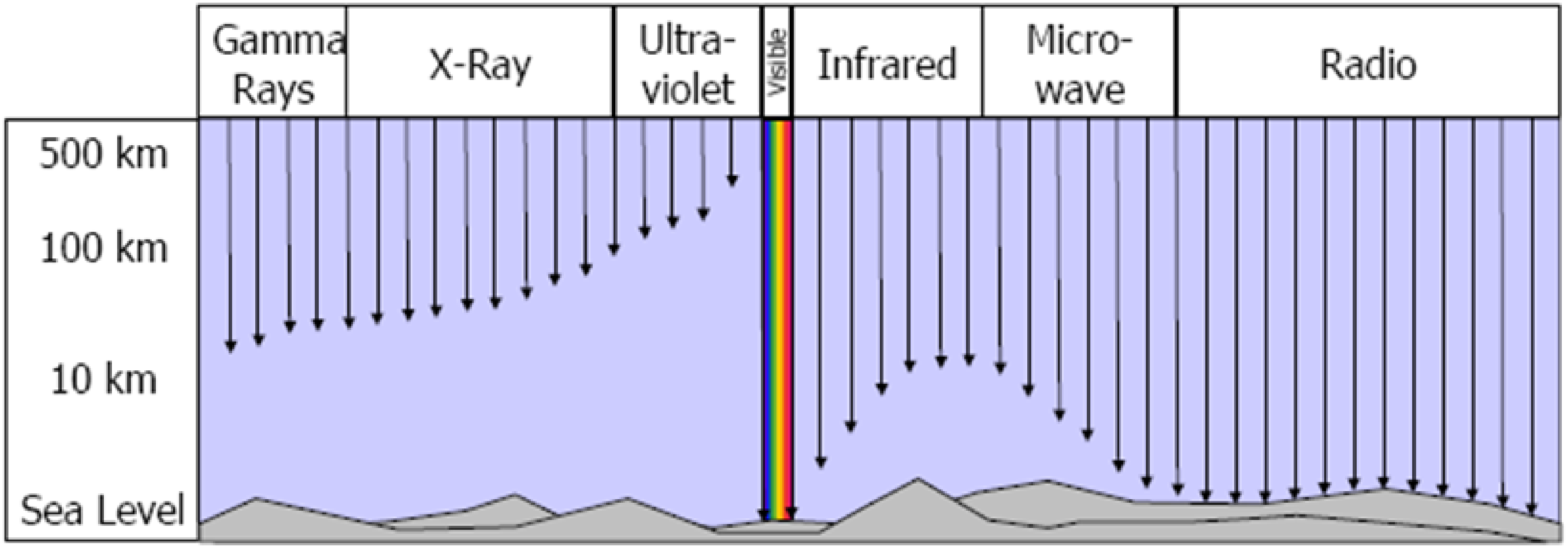


Figure 1: Atmospheric penetration of electromagnetic radiation. (L3Harris Geospatial)

Cherenkov Effect Observatories

- Indirect observation of celestial gamma rays through Cherenkov Effect, using large focusing mirrors or underground water tanks.(Richmond)
- Gamma ray enters atmosphere, hits particle, resultant particles glow in atmosphere and water and this glow can be observed.(Richmond)
- Pros: able to detect incoming gamma rays from ground level, more likely to catch extremely high energy particles, large FoV.
- Cons: Very large space requirements, can be susceptible to light pollution/interference and bad weather depending on setup.
- Examples: VERITAS, Milagro Gamma Ray Observatory.

Figure 2: VERITAS observatory.(Veritas)

Direct Observatories

- Direct observation of celestial gamma rays must happen outside the Earth's atmosphere, typically utilizing arrays of scintillators and pair-production imagers.(Dooling)
- Examples of satellite-borne gamma ray observatories: FERMI, Compton Gamma Ray Observatory.
- Pros: direct observation across all energies.
- Cons: Extreme costs and prerequisite launch infrastructure requirements.

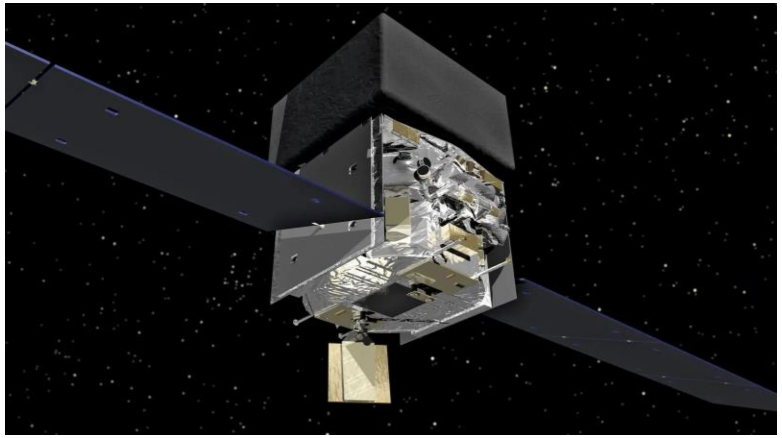


Figure 3: FERMI observatory (Dooling)

Preliminary Research

- The first stage of the project was to determine whether a ground-based setup could observe and study cosmic gamma rays.
- It was discovered that celestial gamma ray photons only penetrate Earth's atmosphere to a depth of around ten kilometers above ground level. (L3Harris Geospatial)
- Any direct observatory would have to be carried up to above 10km to collect data, and this had a large influence on the design itself.
- Any testing of a prototype on the ground would have to be carried out via the use of appropriate radioactive test sources.
- A Cherenkov observatory would take up large amounts of space, be expensive to build, and be subject to weather and NYC light pollution.
- It was decided to go with a direct gamma ray observatory.

Evaluating Materials

- Research turned towards methods of directly detecting low-energy gamma rays, settling on scintillating materials.
- Many types of scintillating crystals and plastics were considered; unfortunately, none were sensitive only to gamma rays.
- It was discovered that a plastic scintillator, BC-408, was very sensitive to all forms of radiation *except* gamma rays, to which its sensitivity was minimal at best.
- BC-408 could be used as a "veto;" if a signal was received from both it and a material that was sensitive to gamma rays, the signal would likely not be from a gamma ray and thus be discarded.

Evaluating Materials (cont.)

- Thallium-doped sodium iodide crystals, NaI(Tl), were found to be an excellent choice for detecting many forms of radiation, especially gamma rays.
  - ✓ Offered strong signal responses to <1MeV gamma rays.
  - ✓ Signal strengths proportional to the energy of detected gamma ray photons
  - ✓ Featured low background contamination from radioisotopes and good resistance against degradation caused by high-radiation environments, such as space.
- NaI(Tl) would be used as the main detector, and BC-408 would be included to veto any non-gamma ray detections.

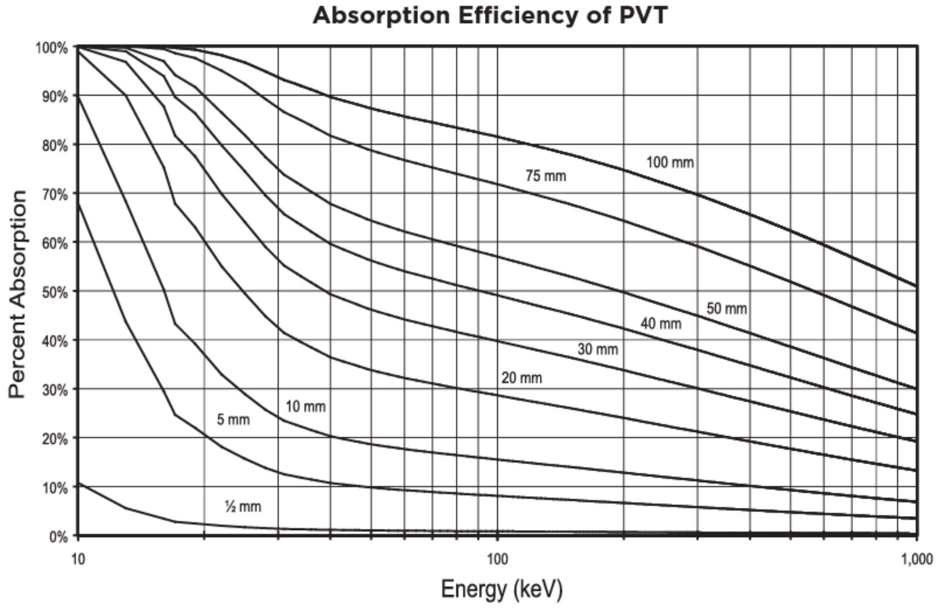


Figure 4: Gamma absorption efficiency of plastic scintillators(BC-408). (Luxium)

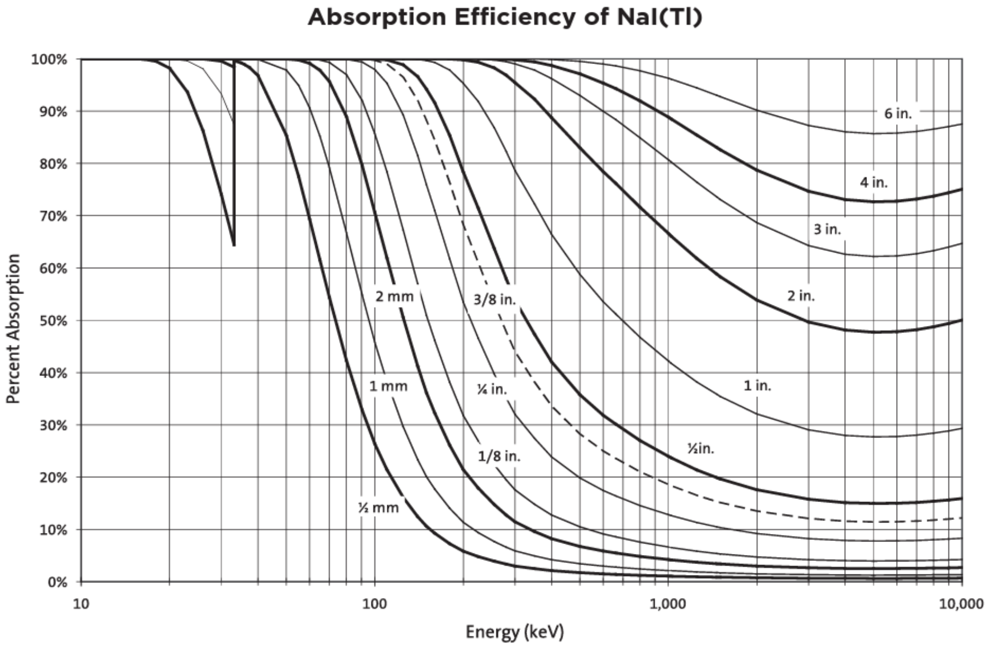


Figure 5: Gamma absorption efficiency of NaI(Tl) crystals. (Luxium)

Design Considerations

- As a directional component to the observatory was desired, multiple options were considered during the design process.
- Gamma rays cannot be refracted easily, necessitating experimental apparatuses.
  - "Lenses" made from high-density, high Z-number materials.
  - Experimental multi-material layered refractor proposed in a paper from Los Alamos. (Shirazi et al., 2020)
  - Lead "pinhole camera" setup, avoiding the refraction issue altogether.
- Cost concerns, production capability were deciding factors, stacked lead sheets with holes drilled through would be used.
- With all major questions answered, the final pinhole camera design began to take shape.

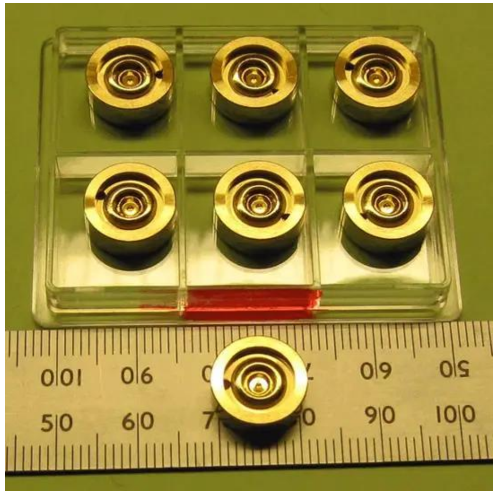


Figure 6: Experimental gamma ray lenses made from gold. (Habs et al., 2012)

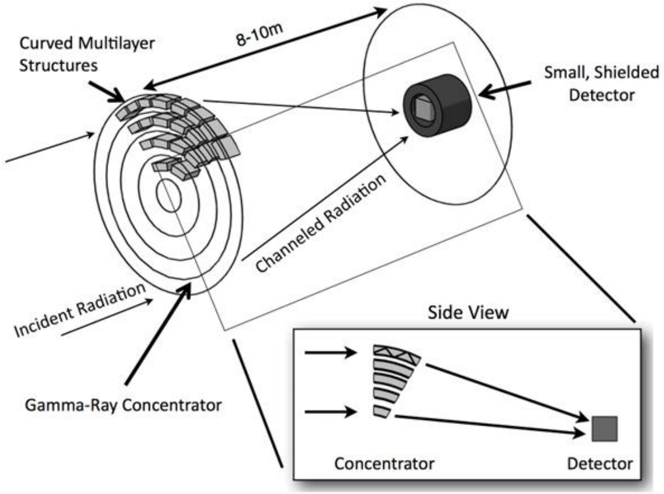


Figure 7: Experimental gamma ray concentrator proposed at Los Alamos. (Shirazi et al., 2020)

Candidate Designs

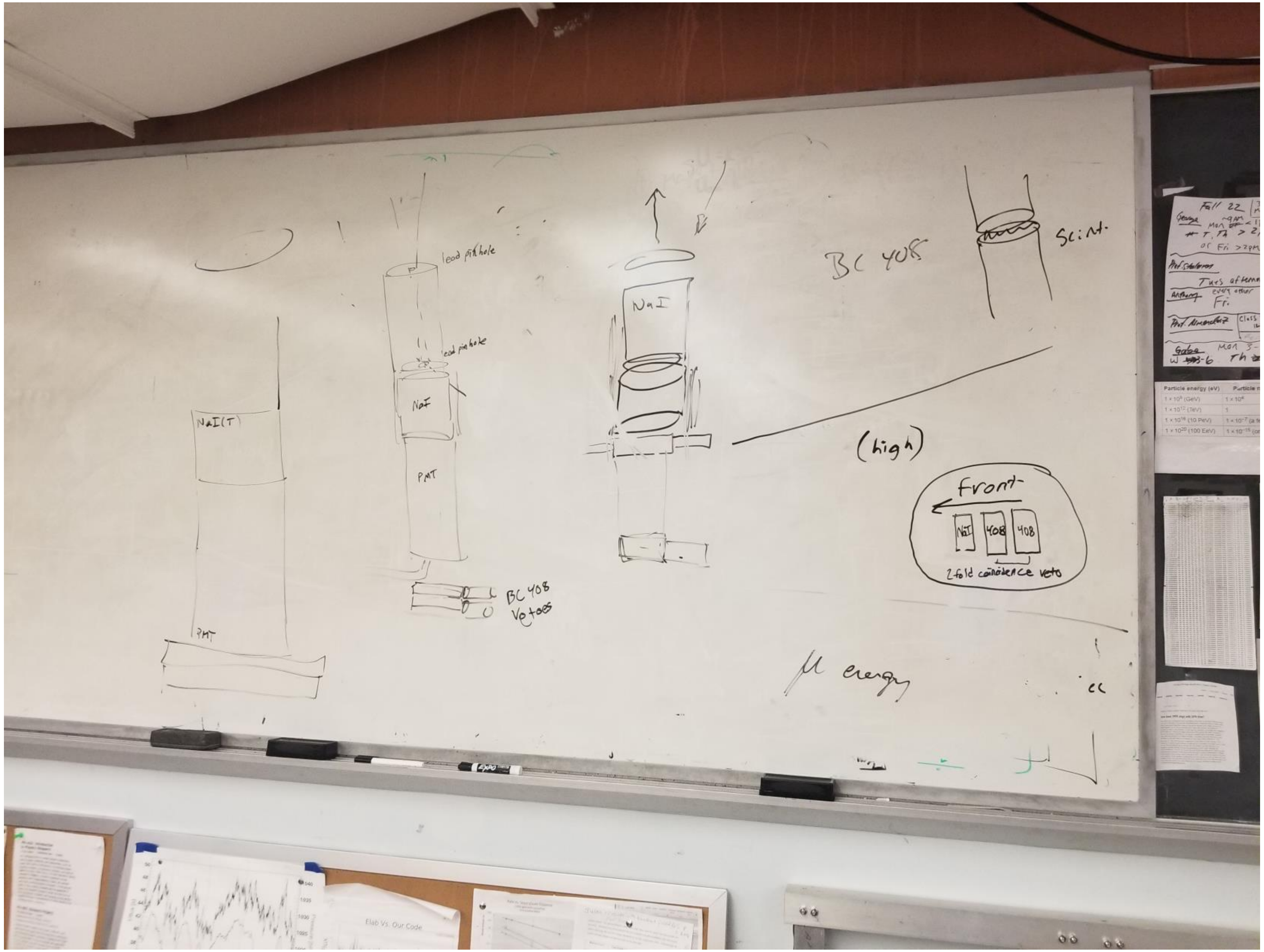


Figure 8: First rough sketches and design concepts

Candidate Designs(cont.)

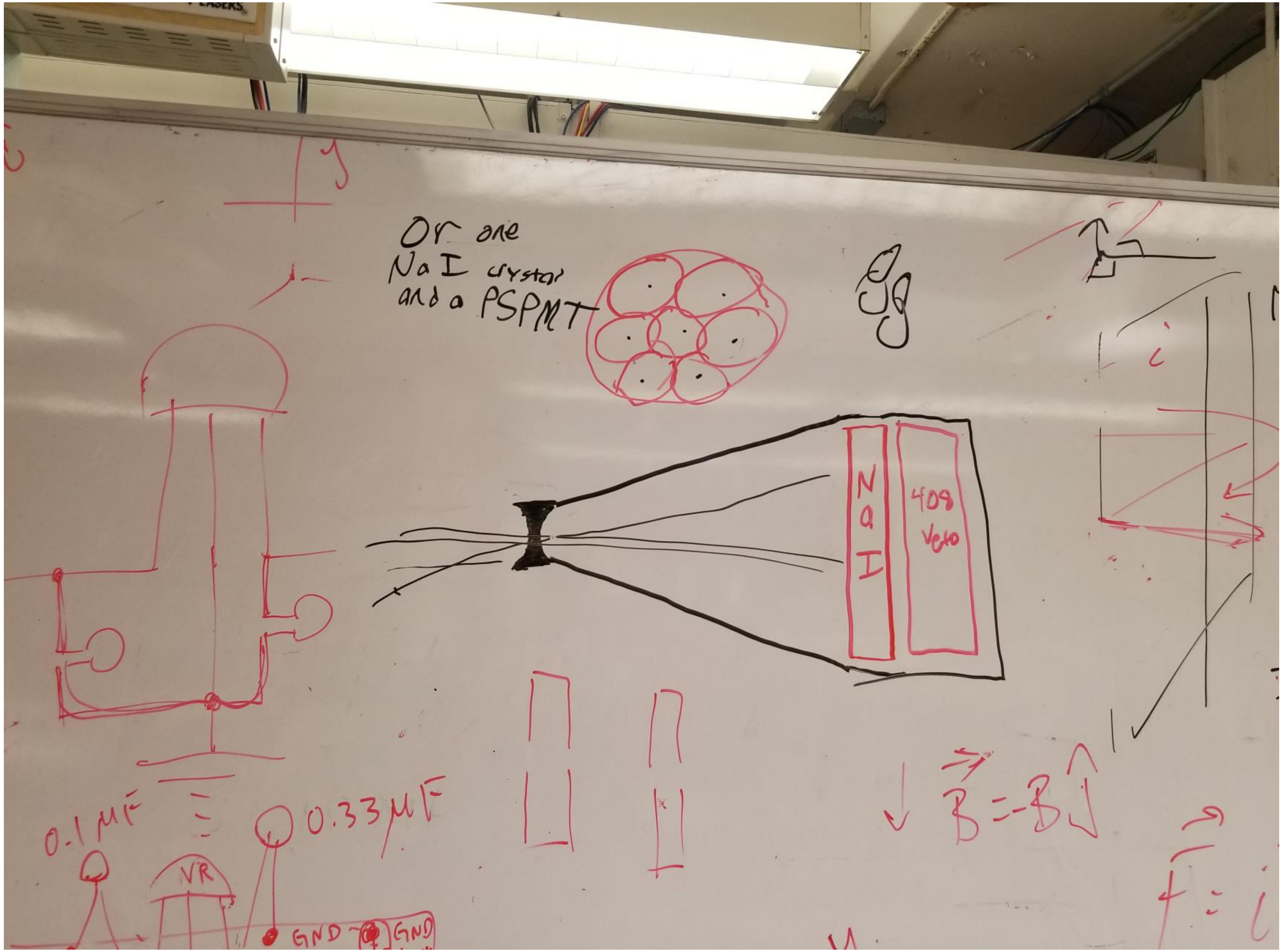
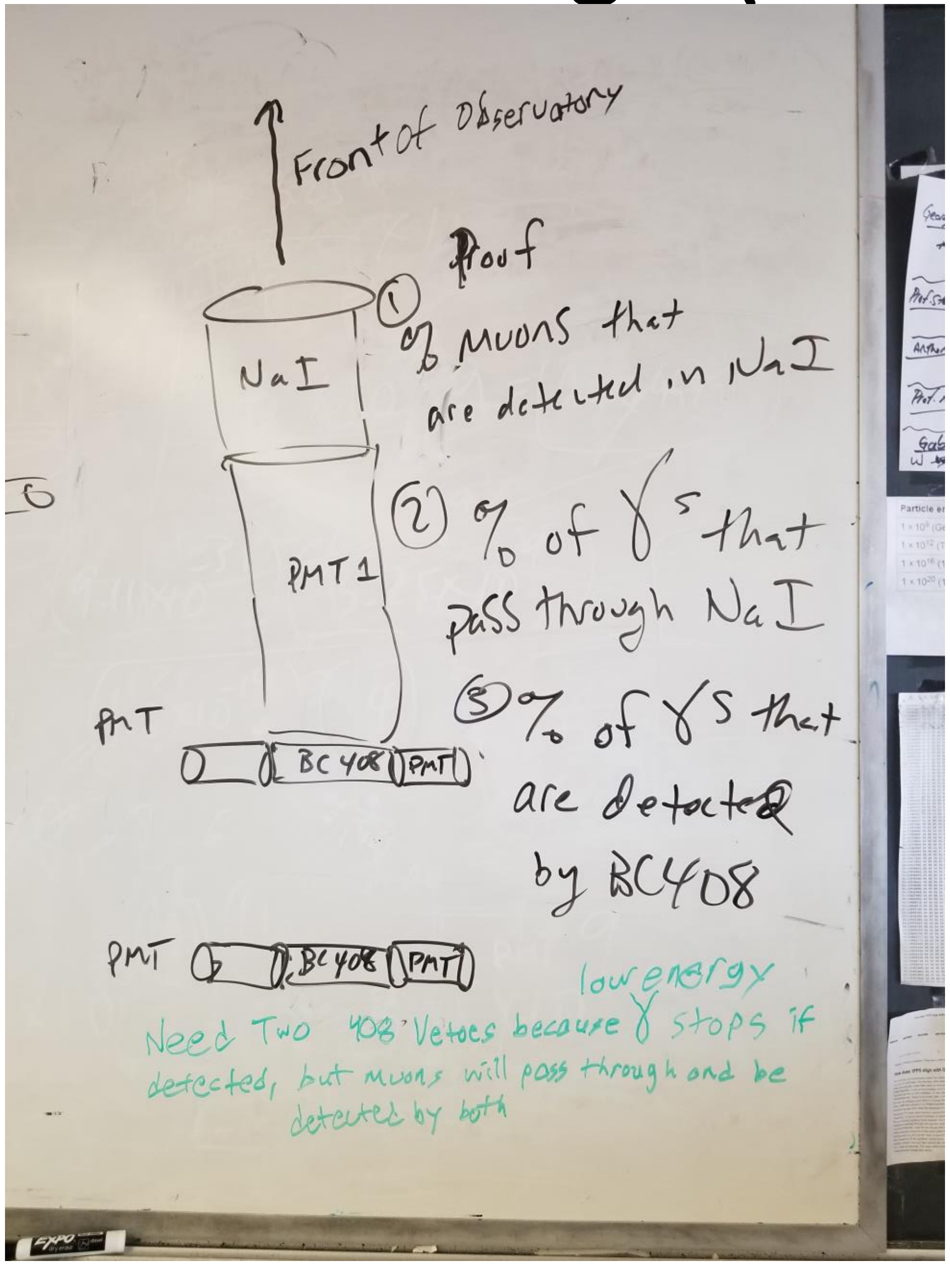


Figure 9: a design that would have used experimental lenses.

Candidate Designs(cont.)



① % muons that are detected in NaI

② % of γs that pass through NaI

③ % of γs that are detected by BC408

Need Two 408 Vetoes because low energy γ stops if detected, but muons will pass through and be detected by both

Figure 10: Early candidate for design utilizing a NaI(Tl) and BC-408 veto setup.

Candidate Designs(cont.)

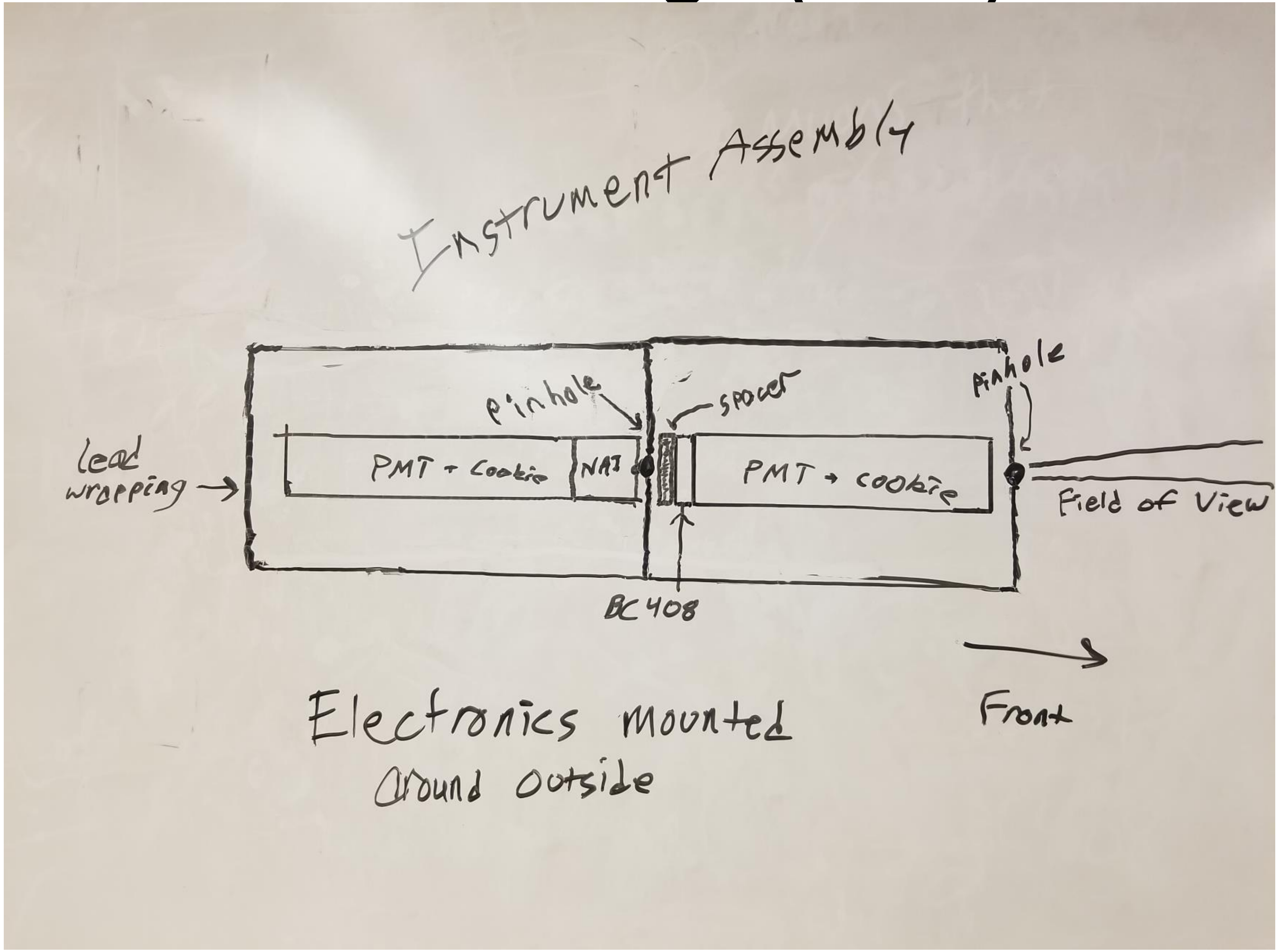


Figure 11: Final design concept, to be refined and prototyped.

Prototype 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
    - Various electrical components
    - GPS components

Prototype Construction (cont.)

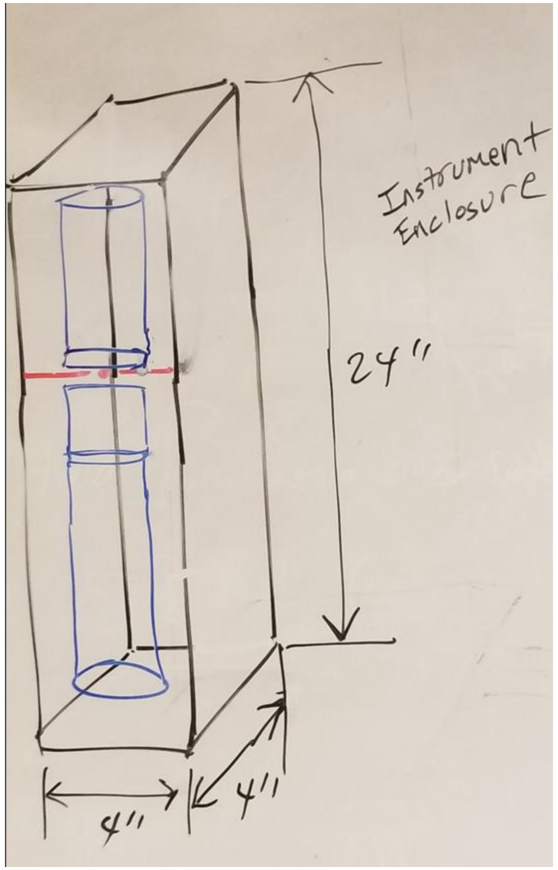


Figure 12: Sorting out dimensions for the prototype enclosure.

Figure 13: Top left to bottom right: 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.

Initial Testing and Further Construction

- Both detectors were individually powered up and tested with radioactive test sources once installed into the housing to confirm operation and expected sensitivities.
- Work is currently focused on constructing the lead sheeting to go around the housing; lead pinhole panels to restrict observatory FoV.
- Data acquisition board is currently being designed and built, originally as part of another project.
  - Only minor modifications needed to make DAQ compatible with this project.

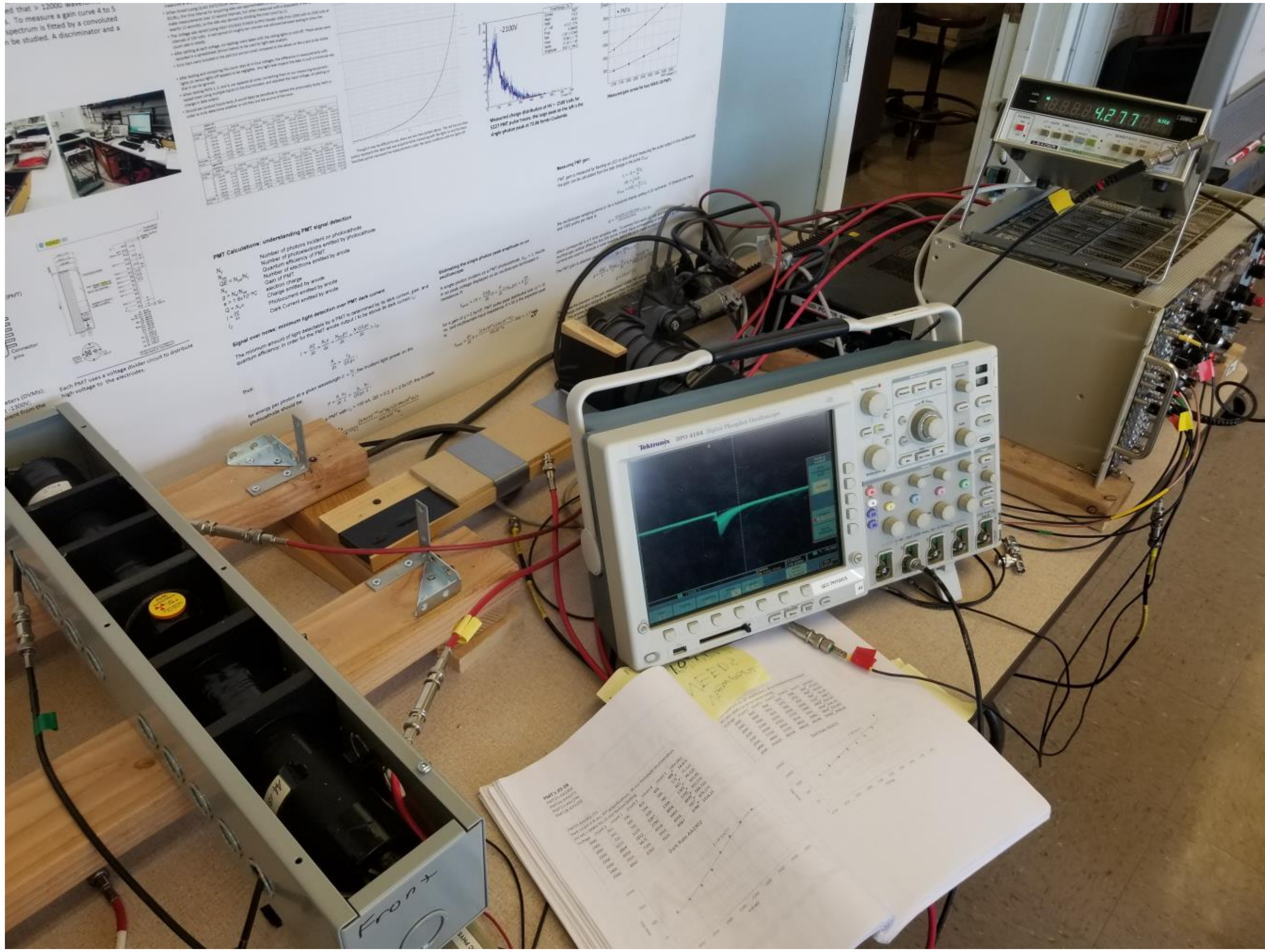


Figure 14: NaI(Tl) radiation detector powered up and exposed to Co-60 test source to confirm operation.

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.
- Full results page will not be available until construction is further along and more testing has been conducted with a completed prototype.

Limitations

- Celestial gamma rays do not reach ground, cannot test prototype using them.
- Issues with ancient NIM crate electronics.
- Supplier/cost issues while acquiring NaI(Tl) crystal.
- Reworking data acquisition board to accommodate 408 veto functionality.
- Current 408 veto only works in line with FoV, need to redesign to cover 360 degrees to block muons.
- Lead sheeting requires special care to be worked safely, may not be thick enough as-is.
- Greater-than-expected distance falloff for gamma-ray detection, potentially due to atmospheric attenuation.
- Prototype currently works off external power, needs to be made self-sufficient.

Ongoing & Future Work

Ongoing:

- Lead sheeting being worked and installed.
- DAQ 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.

Figure(s) 15: Lead foil being worked into shielding panels and installed.

Conclusion

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.

Acknowledgments

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References

- L3Harris Geospatial. (2014, August 25). *Atmospheric windows and optical sensors*. L3Harris Geospatial. Retrieved April 3, 2023, from https://www.l3harrisgeospatial.com/Support/Maintenance-Detail/ArtMID/13350/ArticleID/17333/Atmospheric-Windows-and-Optical-Sensors

- Richmond, M. (n.d.). *Highest-energy gamma rays: ground based telescopes, sources*. Highest-energy gamma rays: Ground based telescopes, sources. Retrieved April 3, 2023, from http://spiff.rit.edu/classes/ast613/lectures/gamma_high/gamma_high.html

- VERITAS. (n.d.). *VERITAS (Very Energetic Radiation Imaging Telescope Array System)*. VERITAS. Retrieved April 3, 2023, from https://veritas.sao.arizona.edu/

- Dooling, D. (2019, February 21). Fermi Gamma-ray Space Telescope. Encyclopedia Britannica. https://www.britannica.com/topic/Fermi-Gamma-ray-Space-Telescope

- Stark, G. (2021, October 22). *gamma ray*. *Encyclopedia Britannica*. https://www.britannica.com/science/gamma-ray

- Luxium Solutions. (2021). *Efficiency Calculations for Selected Scintillators*. Luxium Solutions. Retrieved April 9, 2023, from https://www.crystals.saint-gobain.com/sites/hps-mac3-cma-crystals/files/2021-09/Efficiency-Calculations-Brochure.pdf

- Habs, D., Günther, M. M., Jentschel, M., & Urban, W. (2012, May 1). *Refractive index of silicon at y-ray energies*. Physical Review Letters. Retrieved April 9, 2023, from https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.184802

- Shirazi, Farzane, Bloser, Peter Forbes, Legere, Jason S., & McConnell, Mark L. *Performance simulation of the soft gamma-ray concentrator.* United States. https://doi.org/10.1117/1.jatis.6.2.024001