Version 3.0
January 22, 2021

Exploring the Great Pyramid: Detector Technical Design Report

Omar Shohoud, Tabitha Welch

Abstract

Cosmic-ray muon imaging has been used to non-destructively examine the Pyramids of Khufu and Khafre on the Giza Plateau; the EGP project will continue this line of research by undertaking a full tomographic scan of the former and by doing so will increase the sensitivity of the technique by upwards of two orders of magnitude. For this purpose, we propose a muon telescope composed of triangular (vernier) scintillator cells. This detector design yields a positional resolution for a back-projection to the center of the pyramid of less than 20 cm, ensuring that a feature large enough to be of significance will be seen by the telescope. This method is able to accurately and precisely reconstruct tracks of muons that pass through the King's Chamber, Queen's Chamber, and Grand Gallery.

Contents

1 Introduction **1**
1.1 Possibility of a Second King's Chamber 2

2 Requirements **2**

3 Detector Design **2**

4 Simulation Results **5**
4.1 Coordinate System 5
4.2 Reconstruction Algorithm 6
4.3 Angular RMS 7
4.4 Positional RMS 7
4.5 Back-projection to Significant Features 9

5 Conclusion **12**

6 Acknowledgments **12**

1 Introduction

The construction of the Great Pyramid, the oldest of the Seven Wonders of the ancient world and the only one left standing, still stirs debate among archaeologists. There is no universal consensus regarding the details of how the pyramid was built, which brings up the question: does the inside of the pyramid contain something of interest, something that could explain how the ancient Egyptians created these marvels?

Such a question has been difficult to answer, as excavating the pyramids would have dramatic economic and cultural consequences for Egypt. However, the invention of muon tomography by Alvarez et al.—using cosmic-ray muons to scan the inside of the pyramid—may be the solution [3]. This paper describes the use of physics simulation engines to optimize the detectors to be used by the Exploring the Great Pyramid (EGP) Mission, a collaboration between Fermilab, the University of Chicago, the University of Virginia, and the Oriental Institute.

1.1 Possibility of a Second King's Chamber

Micro-gravity imaging has revealed curious density variations near the pyramid's peak [10]. These variations might suggest the existence of another King's Chamber (henceforth referred to as the Phantom Chamber). Its existence was simulated in our Monte Carlo to test the detectors capability to spot this unknown.

2 Requirements

The detector must have an RMS pointing error that is negligible compared to scattering within the pyramid, and in cases where this is not possible (near the surface), it must be precise enough to identify key features. Generally, a pointing resolution of approximately 20 cm, corresponding to about 1.7 milliradian angular resolution, would be sufficient.

The cosmic ray muon flux at the Great Pyramid (sea level) is approximately 10^4 m ^{2} min ^{1}. The surface area of each detector plane is 92 m; therefore, to distinguish separate muon tracks, each detector would need a resolution of approximately 60 microseconds or better. The detectors will likely be on the order of nanoseconds.

The Hamamatsu silicon photomultipliers (SiPMs) used in the detector read out noise hits generated by dark-current pulses. These dark pulses hardly ever surpass 2 PE (at 2 V and room temperature), so the detector must have a sufficiently low pointing error with a signal threshold of 2.5 PE or higher [1]. Muons are expected to produce signals of 50 PE/cm in the detector; the signal in particular cases can range from 0 to 140 PE, depending on the angle through and position along the detector cell.

Finally, the detector system must be capable of weathering a 1-2 year viewing time on the Giza Plateau. Therefore, our chosen telescopes must be very sturdy, and they will ideally also be climate-controlled to protect important components from the hot Egyptian summers.

3 Detector Design

The detectors will be constructed using triangular scintillator extrusions with a base of 40 mm and a height of 20 mm, as shown in Fig. 1. Each extrusion will be fitted with a wavelength-shifting fiber located 10 mm above the base that will be read out on both ends with a silicon photomultiplier. The cells will be arranged as shown in Figure 2 to form a vernier plane (module). Vertical modules will have cells of 2.4 m length, while horizontal modules will have cells of 4.8 m length. Two banks will be arranged in a temperature-controlled cargo container as shown in Figure 3, with 3 horizontal modules and 6 vertical modules per array, and 2 arrays per bank. The banks will be separated by 2 m. The full

detector unit will consist of a 2 x 2 stacking of these cargo containers. The detector units will be placed as shown in Figure 4.

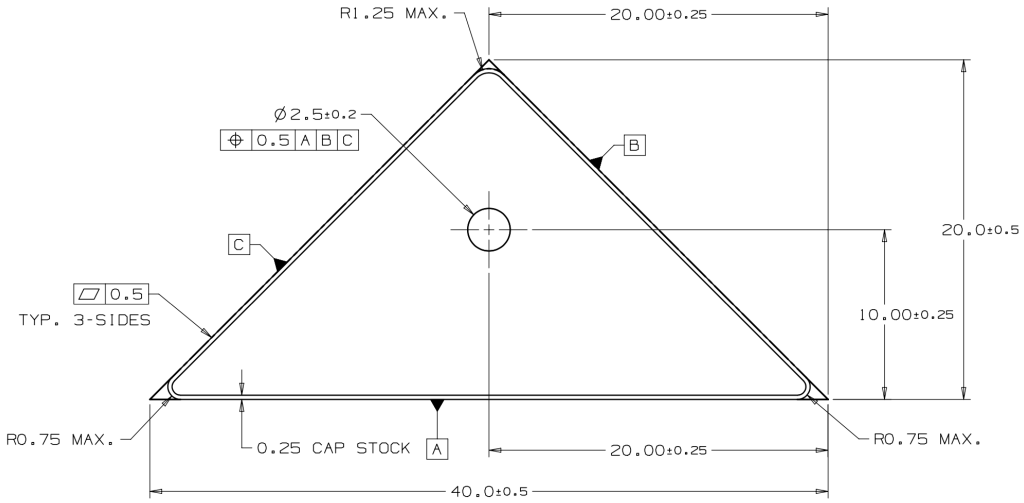

Figure 1: Schematic of triangular scintillator extrusion. Measurements are in millimeters.

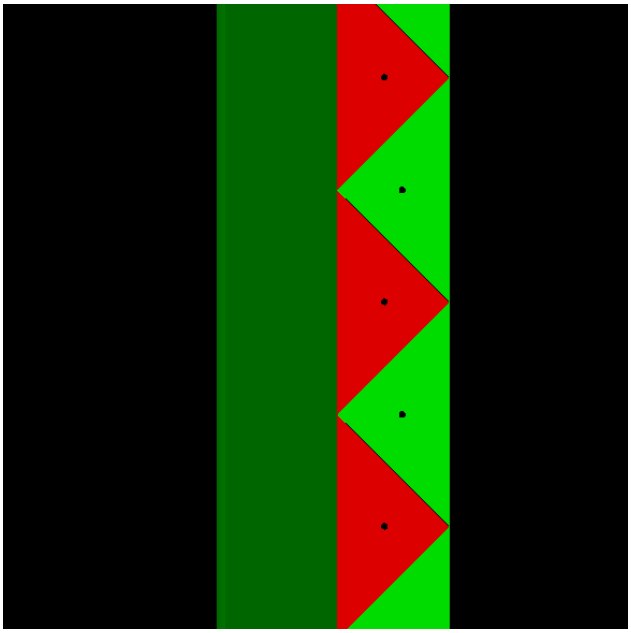

Figure 2: Plan view of triangular cells arranged to form a vernier plane.