Exploring the Great Pyramid

Tomographing the Great Pyramid of Giza

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Unlocking Khufu's Secrets

Motivation

The pyramids of the Giza plateau have fascinated visitors since ancient times and are the last of the Seven Wonders of the ancient world still standing. They continue to stir debate among scholars, researchers and the public as to their origins and purpose and although they have been studied for centuries, many questions still remain.

It has been nearly half a century since Luiz Alvarez Alvarez et al. [1970] and his team used cosmic-ray muon tomography to look for hidden chambers in Khafre's Pyramid. Advances in instrumentation for High-Energy Physics (HEP) have now allowed a new survey, Scan Pyramids Morishima et al. [2017], to make important new discoveries at the Great Pyramid (Khufu) utilizing the same basic technique that the Alvarez team used, but now with modern instrumentation. Although there are other modern methodologies that can be used to "interrogate" the internal structure of Khufu, the Scan Pyramids team chose to use the same technique employed by Alvarez's team because cosmic-ray muon tomography presents a very powerful tool that can see deep into the core of the structure. However, as in Alvarez's case, they set out looking for "hidden" chambers or voids.

Although Egypt's two largest pyramids, the Great Pyramid of Khufu and the second Giza pyramid of Khafre, look much the same, the internal structure of these two pyramids differ remarkably. The known internal spaces of the Great Pyramid are far more complex, most notably demonstrated by its spectacular Grand Gallery, an 8-meter high passageway with corbelled masonry walls. In none of the pyramids that followed the Great Pyramid have passages or chambers been found built within the pyramid body high above grade. *Why is this? And what might still be missing in our understanding of this structure?* Our approach will attempt to answer theses two fundamental questions by taking the technology beyond what has been accomplished to date. Instead of just looking for chambers (voids) in the structure, we can begin a study of the very fabric of the core of the Great Pyramid itself.

Our Solution is to field a very-large muon telescope system that will be transformational with respect to the field of cosmic-ray muon tomography. Using techniques developed and perfected in our laboratories, we plan to field a telescope system that has upwards of 100 times the sensitivity of the equipment that has recently been used at Khufu. This increased sensitivity will allow us to apply the technique not only to look for voids in the structure, but will permit a detailed analysis of the core fabric, the basic construction techniques used throughout the entirety of the pyramid itself. The system will be much larger compared to any comparable system used in archaeological or geophysical studies to date and it will have tremendously enhanced capabilities. The instrument we propose will, for the first time, offer the opportunity to make a detailed study of the entire interior of the Great Pyramid. The resolution that these large muon telescopes offer is ground-breaking and, if successful, will allow future scans to be done on other pyramids constructed both before and after the Great Pyramid. This will allow Egyptologists and Archaeologists to assemble a more complete history regarding the architectural techniques used to construct these large structures.

1 Muon Telescopes

The fundamental philosophy behind our approach is to follow the concepts using plastic scintillator arrays that were first developed for geophysical studies Marteau et al. [2012], but make them much larger and assemble them in oversea inter-modal containers. The basic unit is 40' long, by 8' wide, by 9.5' tall. The detector is designed to be modular, simple to transport, easy to fabricate, easy to operate and extremely robust. We propose that the containers be outfitted with two scintillator banks that are constructed from horizontal and vertical modules (see Figure 1) which will provide the two views (X-Y) of each bank. Matching a hit in a horizontal module with one in a vertical module produces a unique point in the bank. Connecting two points, one in the right bank and one in left bank, defines the trajectory of the cosmic-ray muon. Collecting muon trajectories in this way allows us to build the tomographic image.

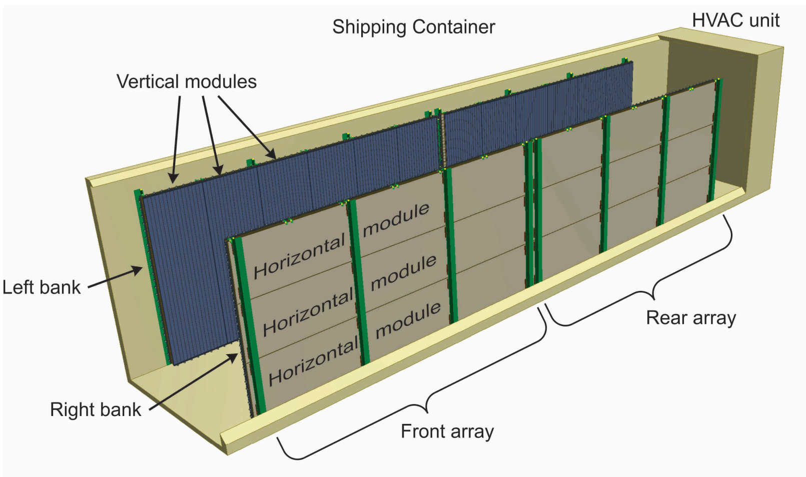

Figure 1: Shipping container with side and top removed showing the detector layout.

2 Test model

We have started to explore the capabilities of the telescope system on the computer using existing tools in HEP and medical imaging. Although analytical calculations indicate that our idea will produce unprecedented image quality, the largest risk associated with this work is that systematic effects will limit the ultimate resolution of the device. These can be accurately evaluated on the computer given our knowledge of the muon flux, how the detectors have operated in HEP experiments and using existing software tools. We now have a comprehensive computer model of a pyramid and the detectors. A basic pyramid structure with a 3-dimensional phantom array has been implemented. Figure 2 shows our current computer model of the pyramid with one telescope system shown in red. The images in grey represent moving the telescope around the pyramid to detect muons penetrating the pyramid from all angles. In this study, the effective viewing time was approximately 2 years. Figure 2 (right) shows the phantoms placed in the model and Figure 2 (left) shows a 2D reconstruction from the muon data. Voids as small a 4m are clearly visible.

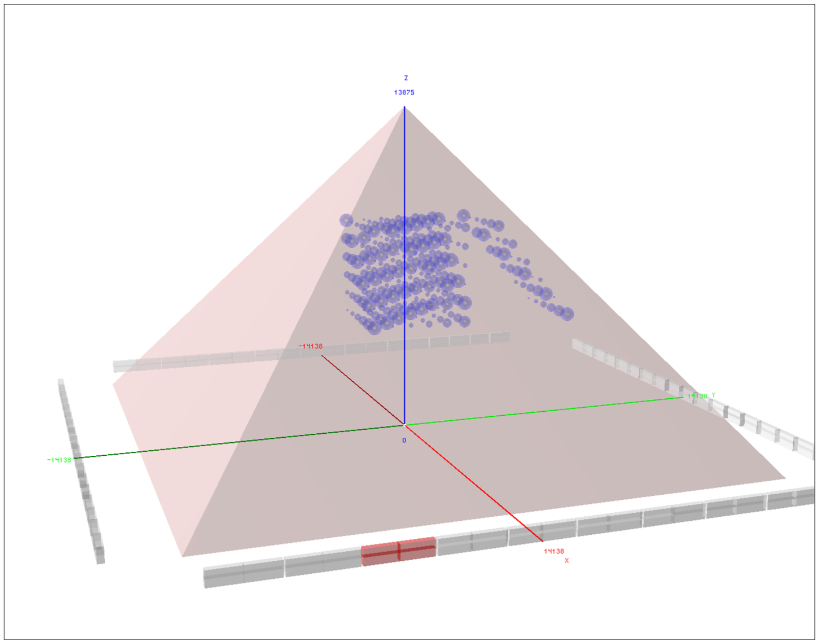

Figure 2: Left: Model of the pyramid showing telescopes on two faces. Right Phantoms (voids) placed in the model

Results

We have simulated data with an effective viewing time of approximately 2 years. Figure 3 (right) shows the phantoms placed in the model and Figure 3 (left) shows a 2D reconstruction from the muon data. Voids as small a 4m are clearly visible. As a point of reference, the large new void that the Scan Pyramids team discovered after roughly 2 years of viewing was $\simeq$ 30m long $\times$ by 8m in diameter. The image of the 4m void in our study represents an increase in sensitivity of approximately 50. **We anticipate reaching an ultimate sensitivity of 1-2 m^3 which would represent an increase in sensitivity of 100 to 300.**

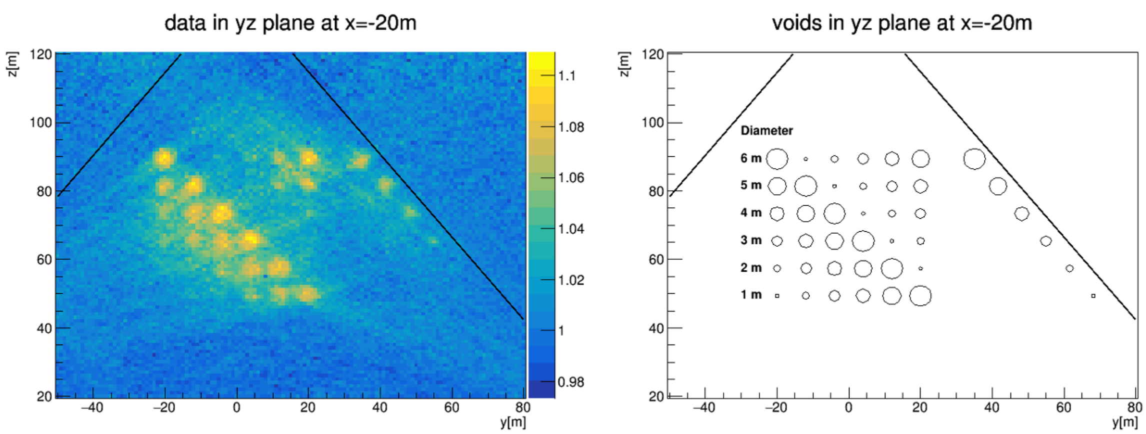

Figure 3: Preliminary simulation results

3 Outlook and Funding request

We have made good progress on our simulation to date. Our next step is to test different models of the Great Pyramid and to start developing detailed 3D image reconstruction algorithms. Test models of the unknown parts of the Great Pyramid will be based on archaeological data from other pyramids and extrapolations from those data, so should be representative of what we may eventually find in the field. The output of these studies will demonstrate the ultimate precision of our technique and will predict with great accuracy how well the final system will perform. We believe that the results from this in-depth simulation study will make a strong case needed to fund the full project.

We are seeking funds to expand our team in order to facilitate the simulation work and to begin prototyping of the muon detector components.

The Collaboration

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