Imaging Maya Pyramids with Cosmic Ray Muons

An Application of the Tools of High Energy Physics
The Maya: Extraordinary American Culture
Some Background

- **1839-ff**: John Lloyd Stephens with Frederick Catherwood, artist
  - *Incidents of Travel in Central America, Chiapas, and Yucatan* (1841)
  - *Incidents of Travel in Yucatan* (1843)

- **Linda Schele** (1942 - 1998) UT Austin
What is the internal structure?

Measure Spatial Distribution of Material *Inside* by Muon Tomography
This is Proven Technology

- Luis Alvarez* invented muon tomography in 1960’s to study the 2\textsuperscript{nd} Pyramid of Chephren
- Spark chambers used to track muons from Belzoni Chamber
- System worked well—could see structures of caps
- Main discovery: No other chambers exist

Cosmic Rays

- Very high energy “primary” cosmic rays - typically protons - interact in upper atmosphere
- Shower of unstable sub-nuclear particles created: typically pions, kaons
- Muons and neutrinos are decay products of pions and kaons
Muon Interactions in Matter

- Energy loss: predominately by ionization

\[ \frac{dE}{dx} \approx 2.3 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m in rock} \]

- Multiple-Coulomb Scattering

\[ \delta \theta \approx \frac{13.6 \text{ MeV}}{\sqrt{E_i E_f}} \sqrt{\frac{L}{X_0}} \]

\[ E_i - E_f \approx L \frac{dE}{dx} \]

dirt, rock:
\[ X_0 \approx 27 \text{ gm/cm}^2 \]
Arrangement Involving Cylindrical Detectors

- Use 2 or more detectors
  - Compensates for “blind cone” inherent in cylindrical detectors
  - Improved stereo sampling of target volume
  - Symmetry of cylindrical detectors good for measuring “average” image

- Minimizes excavation
Detectors

- **Cylindrical structure**
  - 1.5 m diameter
  - 4.5 m long

- **Muon tracking**
  - 3 stereo layers
  - WLS-scintillator technology
  - PMT readout

- **Threshold energy selection**
  - Use inner volume as a Cherenkov radiator
  - PMT readout

- **Other systems**
  - Electronics
  - Mechanical
  - Power/communications
Frame

Completed frame during lay-up of scintillator strips

Aircraft construction techniques to reduce weight

PMTs and electronics will be mounted in end-rings
Tracking System Elements

“MINOS” scintillator
30 mm wide
10 mm thick

WLS fiber readout
2 helical layers
1 axial layer (center)
441 total strips
Scintillator Installation

1st end of strip secured with machine screw, temporary straps applied.

Strip attached along full length with double-sided adhesive tape.

Helical wrap applied with twist; temporary straps tensioned.

Secure 2nd end of strip.

WLS fibers epoxied into groove in scintillator, covered by Al tape.

Plug fiber into PMT cookie.
Detector Electronics Systems

- Data from detector
  - Tracking: 2X448 “hit” bits
  - Cherenkov: Analog out

- Trigger
  - Based on tracking information only
  - Programmable logic

- DAQ
  - All tracking bits
  - Cherenkov hits above pedestal

- Control
  - Trigger/DAQ control
  - Monitor all detector systems
Trigger Requirements

- Use only tracking information
- Require:
  - \( >\geq 2 \) Hit “Triplets”
  - Chord \( c > c_{\text{min}} \)
  - Direction ?
- Flexible definition of Triplet
  - Coincidence gate: 25–50 ns
  - Number/pattern of hits to balance:
    - Noise - singles rates
    - Inefficiencies
- Typical rates:
  - True events \( \sim 100 \) Hz
  - CR singles:
    - \( \sim 4 \) KHz full detector
    - \( \sim 25 \) Hz per strip
Imaging

- Have begun studies of imaging with a single detector
  - Stereo pairs of spherical projections
  - Radon transformations

- Collaboration expected with UT CS experts

- Extensive sets of tools available:
  - MATLAB
  - LabVIEW
This is Also Real

- Detector is complete and works!
- Singles rates on all strips <100 Hz
  - Consistent with cosmic rays and light-leaks in test setup
  - FEBs are all installed and working—no surprises
- Currently focused on DAQ and triggering firmware
People & Things

- UT Physics
  - Jared Bennatt, Mark Cartwright
  - Brian Drell, JJ Hermes
  - Becket Hui, Jeremy Johnson
  - K. Krishnakumar, Nicholas Raspino
  - Cesar Rodriguez, Anandi Salinas
  - Mark Selover, Derrick Tucker
  - Brad Wray, Eric Wright
  - H. Adam Stevens
  - Austin Gleeson, RFS

- UT Electrical & Computer Eng.
  - Bill Bard, Lisy John
  - Carlos Villarreal
  - Elizabeth Van Ruitenbeek
  - Daniel Garcia, Nakul Narayan

- Fermilab—Scintillator Production
  - Anna Pla-Dalmau

- Harvard HEPL—Front-end Electronics
  - John Oliver, Sarah Harder

- Other physicists who contributed in the early stages
  - Prof. Rich Muller, UC Berkeley
  - Dr. Dick Mischke, LANL

- UT Mesoamerican Archaeological Research Laboratory (MARL)
  - Prof. Fred Valdez, Director

- National Instruments
  - Hugo Andrade, Joe Peck
UT Mesoamerican Archaeological Research Laboratory
Potential Target Structure

- La Milpa site has relatively good access/infrastructure
- Developing simulation tools to optimize detector design and placement
- Plan excavations for deployment
Other Potential Applications

- Muon Tomography is good for monitoring large underground volumes (~100 m$^3$), provided:
  - You are interested in structures of scale 1 m - 10 m
  - You can afford to wait for weeks to months to acquire the data
  - The volume of interest is between your detector and the surface

- Geological studies of aquifers
  - Shapes of underground cavities
  - Time-dependence of water levels

- Monitoring of geology surrounding underground sites, e.g. underground nuclear waste storage
Summary

- Muon tomography is feasible
  - Proven in Alvarez experiment
  - New technologies enable simplified detector design
  - WLS/scintillator tracking well-developed/good match
  - Cherenkov threshold detector is indicated
    - New approach to problem of low-energy multiple-scattering
    - Well-understood physics/technology
    - Simplifies system design

- Excellent project for engaging students

- Other applications are possible

- Maybe we can help to learn more about the Maya!