A Nanosat Payload for Space Weather Research

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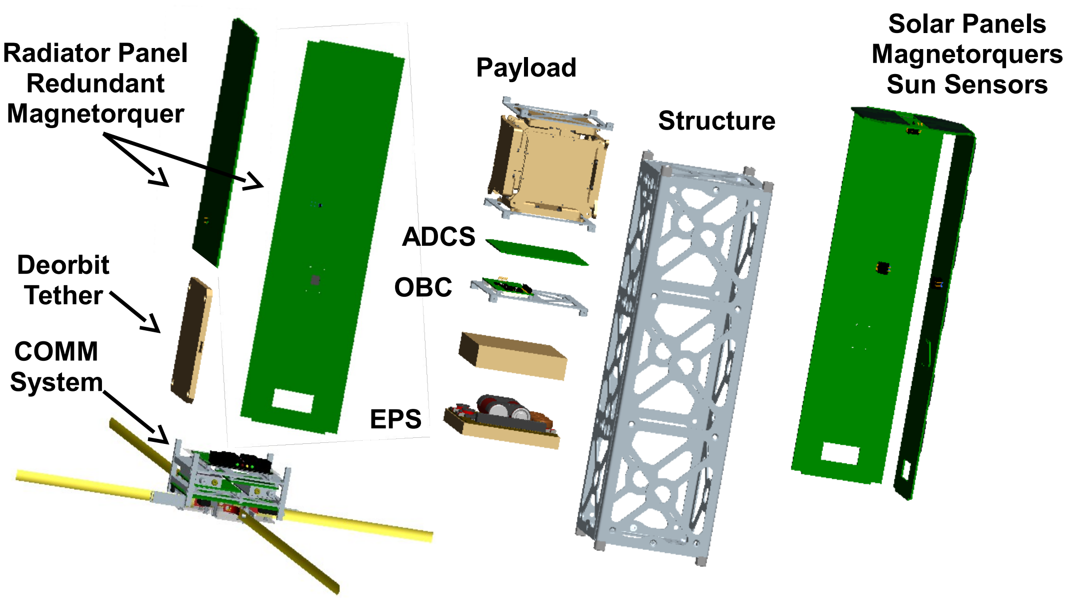
History: Canadian Satellite Design Challenge

- Students at Carleton participated in the first CSDC to design and test a 3U CubeSAT nanosatellite (CDR 2012). We didn't win... ☹
- Was general enthusiasm about the mission and proposed scientific payload design

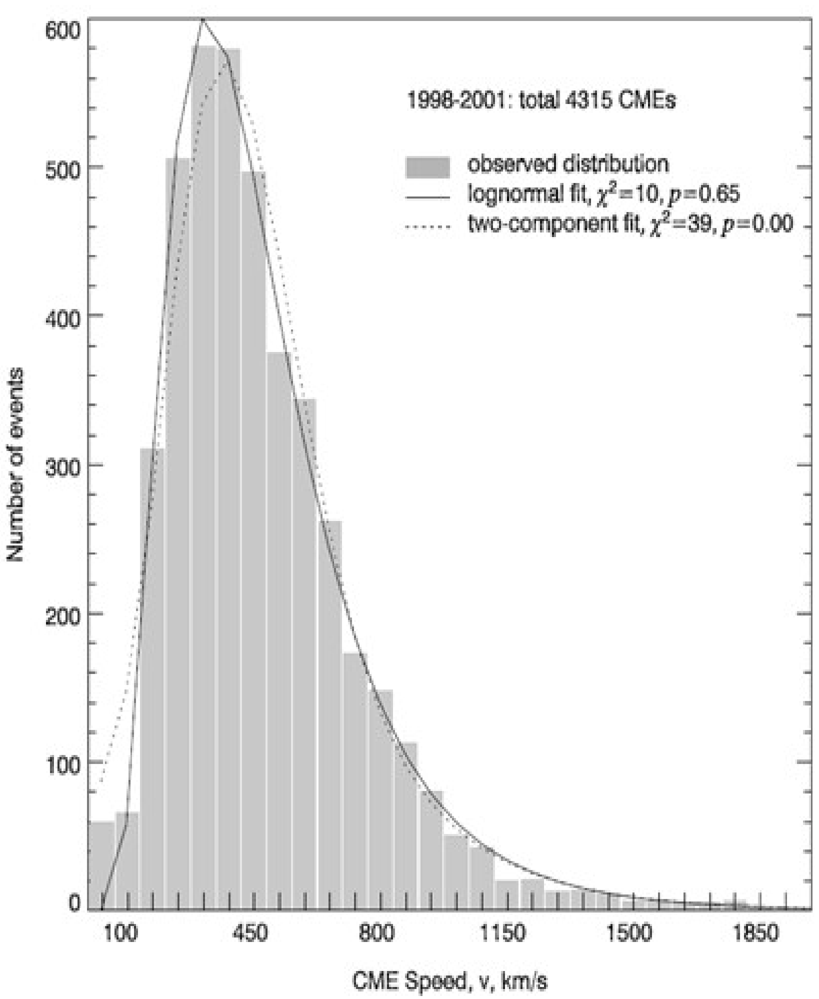


Satellite Scientific Mission Objective

"To employ a space-based detector in low-Earth orbit to monitor the intensity and anisotropic modulation of the galactic *primary* cosmic ray (CR) particle flux – as caused by the supersonic shock fronts of approaching solar Coronal Mass Ejections (CMEs). This data, along with *secondary* CR data from the ground-based Global Muon Detector Network and others data sources, will be used as part of ongoing research into methods of providing 18 to 72 hour advance notice of major geomagnetic storms."

Coronal Mass Ejections (CMEs)

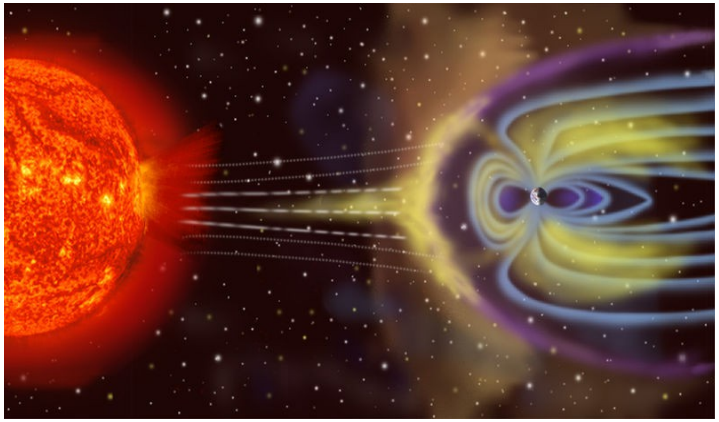
- CMEs are large ejections of plasma from the sun, some of which travel towards the Earth
- High velocity plasma creates a shock front as it overtakes solar wind already en-route
- Between 1 and 4 days travel
- Shock front has large chaotic magnetic and electric fields that interact with the inter-planetary environment and ultimately with Earth's magnetosphere if it hits



Source: "Statistical Distributions of Speeds of Coronal Mass Ejections", Yurchyshyn, V., et al., The Astrophysical Journal, 619:599–603, 2005 January 20

Terrestrial Geomagnetic Storms

- If a CME hits the Earth, the magnetosphere becomes compressed in the direction of Sun and its tail is elongated away from Sun
- Creates large currents in magnetosphere and the Earth itself
- In the event of extreme CMEs, critical infrastructure can be disrupted:
  - Power grid disruption or collapse, possible permanent transformer damage
  - Spacecraft: extensive surface charging, transient and permanent systems failures
  - High radiation hazard to astronauts, radiation risk to those flying in aircraft
  - Pipeline currents to hundreds of Amps
  - HF radio and GPS navigation could be degraded or non-functional for days



Source: NASA Heliophysics Resources – Image Gallery, http://sec.gsfc.nasa.gov/sec_resources_imagegallery.htm

- Governments are realizing enormous security threat of large solar storms and are funding scientific research and engineering projects

Predicting CMEs With Cosmic Ray Detectors

- CME supersonic shock front has complex and strong magnetic fields that can capture, alter the path of, or accelerate galactic and solar cosmic rays
- Accelerates en-route solar wind, resulting in directional increase in lower energy particles from solar cosmic ray flux
- Alters path of galactic cosmic rays and causes a detectable decrease in the flux as well as various detectable anisotropies, called the "Forbush Effect"
- Can be used as probe into the nature of approaching CMEs as cosmic rays only take minutes to reach the Earth (versus days for the actual CME)

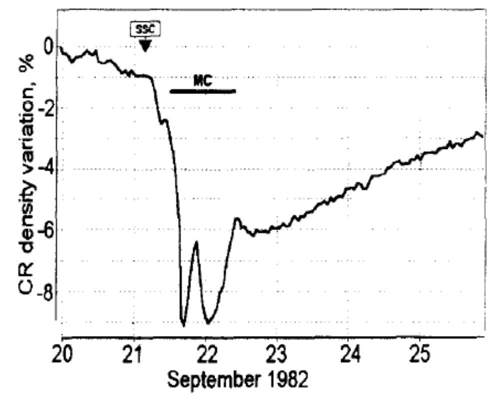


Fig. 1. Variation of 10 GV cosmic ray flux during the large Forbush-effect in September 1982.

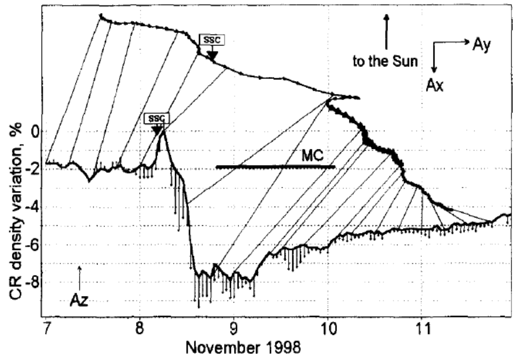
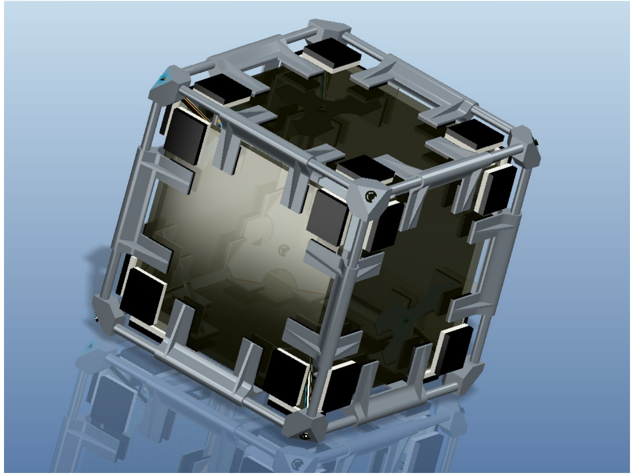


Fig. 4. Variation of 10 GV cosmic ray density and first-order anisotropy during a Forbush-decrease in November 1998. Labeling is like Figure 3. "MC" denotes ejecta passage.

Source: "Cosmic Ray Anisotropy Before and During the Passage of Major Solar Wind Disturbances", Belov, A.V., et al., Adv. Space Res. Vol. 31, No. 4, pp. 919-924, 2003

Proposed Cosmic Ray Detector Payload

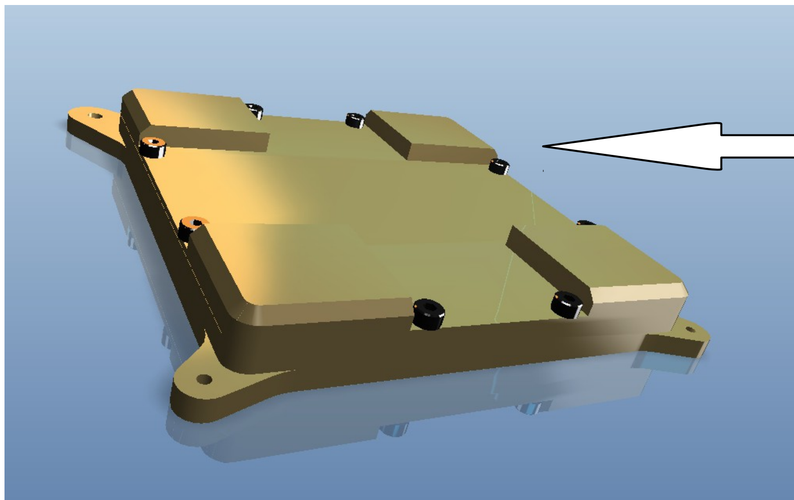
- Six CsI(Tl) scintillator panels, each with four large area photodiodes, are used to track the path of high energy primary cosmic rays through the satellite in three axes
- Cube 97.46mm outer dim.; mass 900g (incl. panel electronics); power: 1W max. avg.; each detector panel is 62x62x3mm plus 4 photodiodes w. integrated pre-amps
- CRs through exactly two panels are "events"– all other triggers are accumulated several times per orbit; event coverage is ~3π steradians = ~200 CRs/s (same detector on Earth would only see ~1 μ/s as secondary CRs)



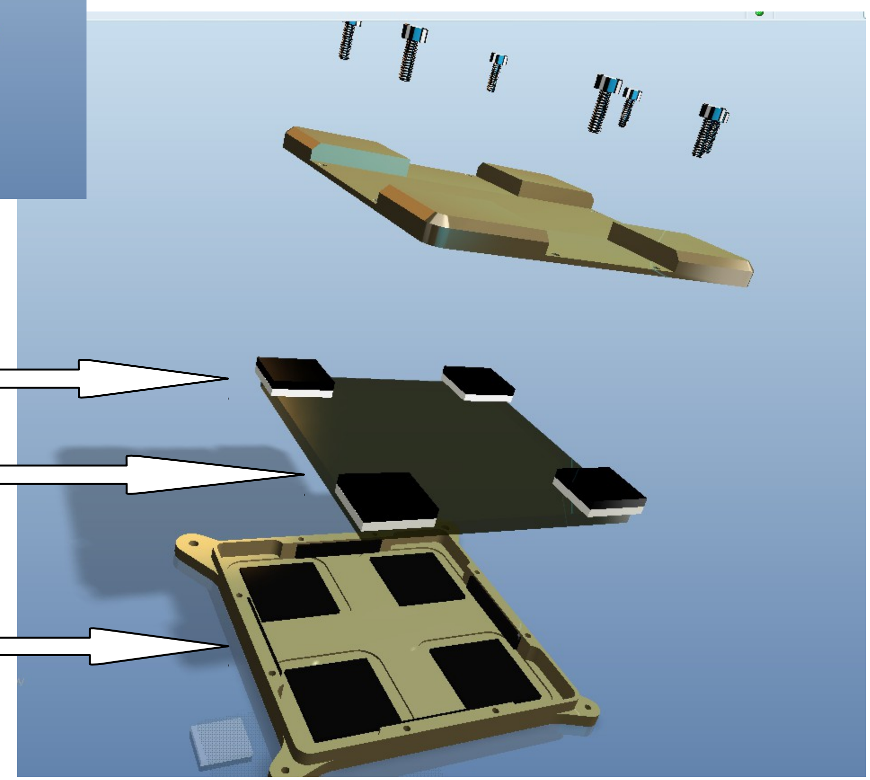
Note: Image is of old "cube" design for illustrative purposes only... see next page for current panel design

- ~2MB/day (scalable) presuming a single 9600bps downlink station, roughly 350,000 of 17.25 million events/day can be sent (~2%); aggressive selection performed using onboard CPU; additional events will be statistically discarded from queue; data collection rate and queue depth can be modified dynamically with a telecommand if a CME is expected
- Symmetric payload design relaxes attitude control and orbit determination requirements, data is post-correlated on ground with Sun vector and real-time magnetometer meta-data
- Integrated signal injection (optical and electrical) circuitry provides full testing, calibration, and fault coverage capability on ground and in orbit

Final Detector Panel Design



Light tight package and sensor electronics shielded against RF interference



4 Si PIN Photodiodes with Integrated Pre-Amplifiers

CsI(Tl) Scintillator Panel

Integrated shock/vibration damping and fully sealed for debris control in case of panel break during launch or in orbit

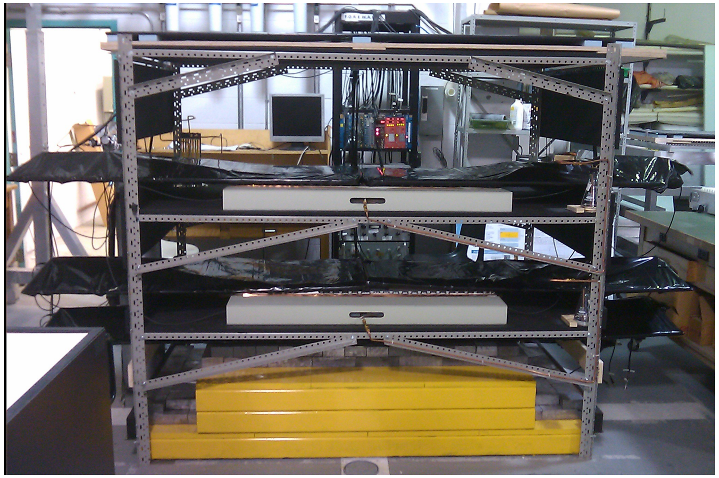
Outstanding Questions/Ongoing Research?

- Because the Carleton CSDC team did not win, the project was ended and the participants went their own ways, but there were many outstanding questions about the performance and implementation of the proposed detector design that demanded answers
- Specific questions include: what sort of X-Y resolution is possible using a single pane of scintillator (versus cutting it and instrumenting each piece separately), what sort of electronics would give the best performance with the severe power and weight restrictions imposed (esp. with regard to noise and speed), what specific features need to be extracted from the photodiode signals (and how best to make those measurements)?
- The lack of CSDC deadlines and access to materials, equipment, and world-class detector design expertise (e.g. OPAL, SNOlab, ATLAS, EXO) at Carleton has allowed me to pursue answers to these and other questions (e.g. can we use vacuum metal deposition to implement the pre-amp circuits directly on the ceramic backs of the photodiodes?)

Scavenging A Proof-Of-Concept!

My long term involvement as an undergraduate research assistant with the CRIPT (http://www.physics.carleton.ca/cript) passive cosmic ray tomography project and FOREWARN cosmic ray telescope (http://www.physics.carleton.ca/forewarn) project, and support and encouragement from Dr. John Armitage, provided me with the expertise, materials (mostly scrap and leftovers), and borrowed equipment needed to implement a near zero-cost functioning proof-of-concept analogue to the satellite detector design!

CRIPT Project



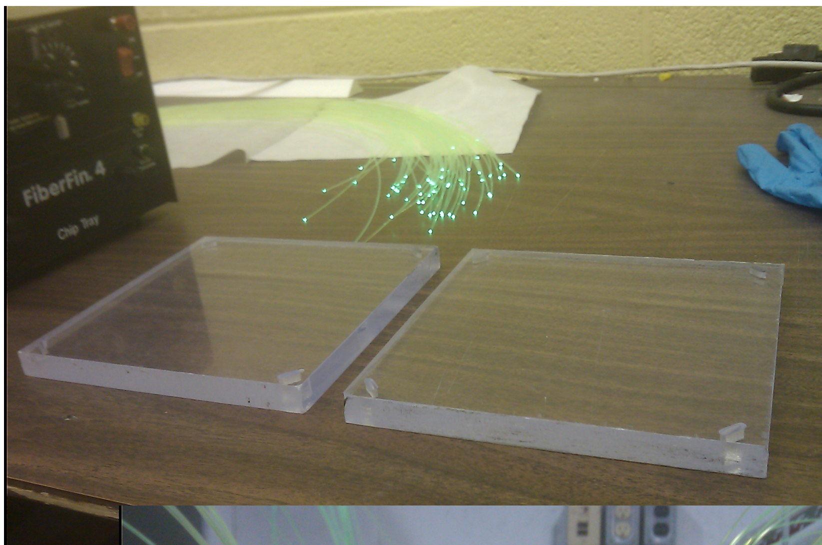
FOREWARN Project

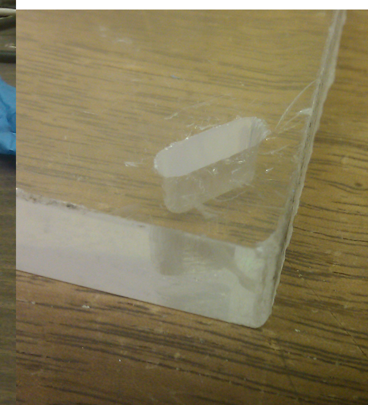
A Benchtop Analogue Detector

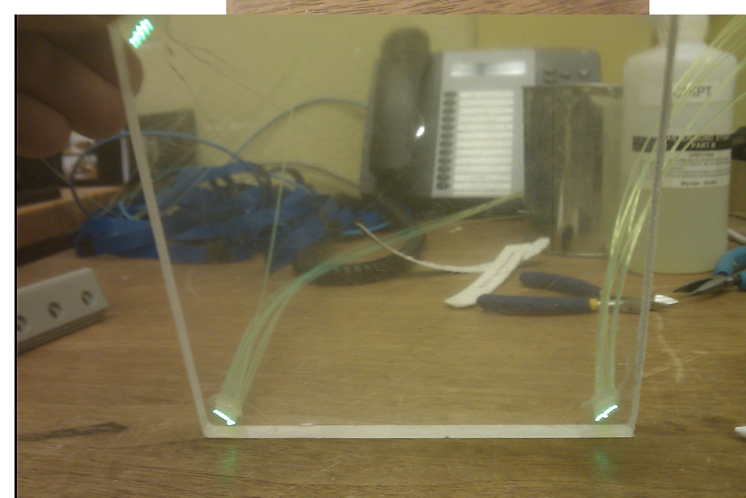
- *Satellite:* CsI(Tl) crystals: high efficiency vs. weight, long wave-length, can be measured with lightweight photodiodes – expensive and exotic and requiring precise custom-made electronics
- *Analogue:* plastic scintillator: low cost and rugged, requires wave-length shifting optical fibers to convert light to longer wavelength, uses a 64-channel photomultiplier tube (lower noise than photodiode) and two single channel PMTs for coincident trigger signal – scrap material and borrowed equipment
- Both have optical coupling area between scintillator and sensor of about 10x10mm (direct to photodiode for satellite design, via wavelength-shifting fibers to PMT for analogue detector)
- Analogue detector only has two panels while full solution has six
- Will be used to refine design and simulations before paying for high cost of building first CsI(Tl) based detector panels

Tilting At Windmills or Admirable Dedication?

Began work in Sept. 2012, completed in Nov. 2013 (yes, just recently). Had to learn new skills and come up with innovative implementation techniques at each point in the design and construction process.

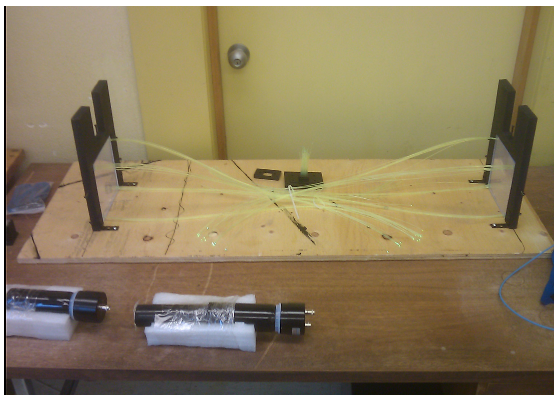
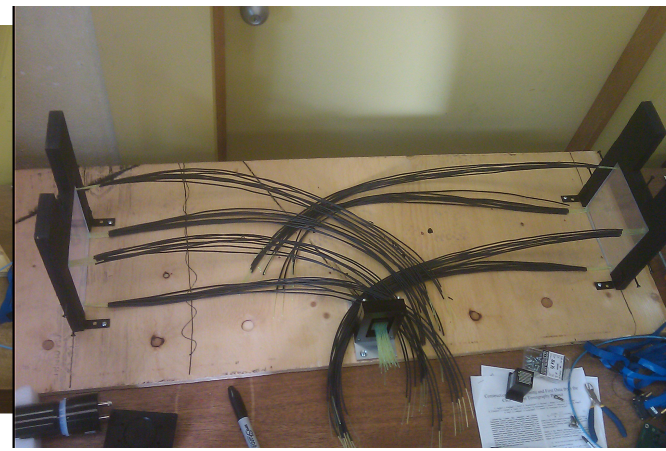
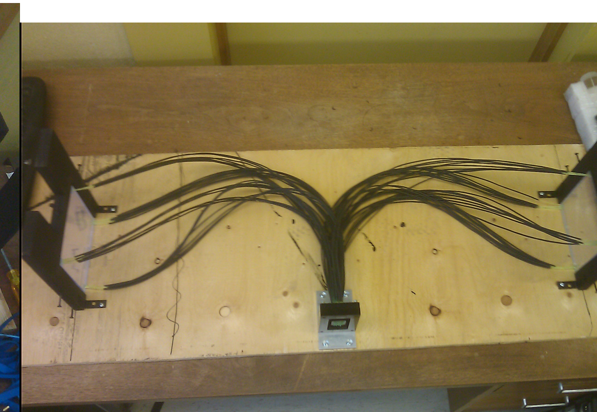


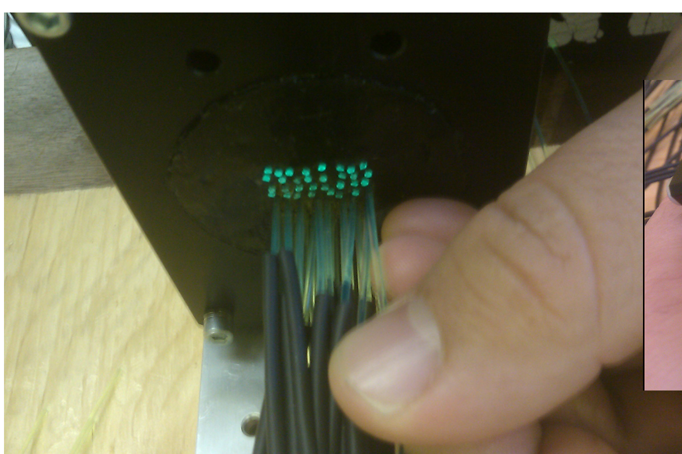
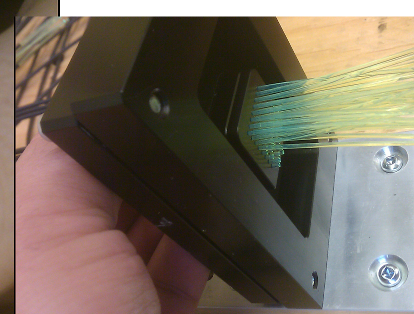




Low-Tech Methods, High-Tech Components...

Many of the components, such as the wavelength shifting fibers, photomultiplier tubes, and signal electronics are leading-edge technologies, but the zero-budget necessitated lo-fi solutions

The Impossible Only Takes A Little Longer...

The enclosure had to house the scintillator panels and PMTs, but also 60kg of lead shielding in the middle, be light-tightable (no visible photons at all), and serviceable

And it all finally starts to come together...

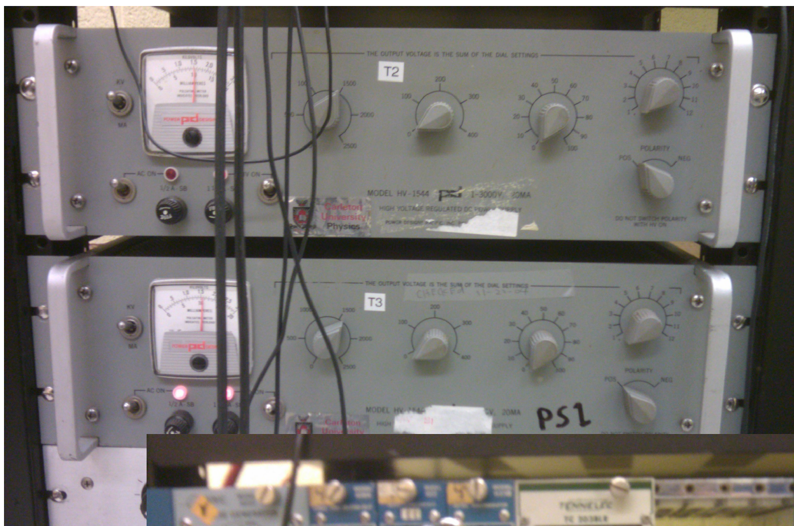
Once the enclosure was mostly finished and the fibers were run (May 2013), integration could finally begin (but would take until August 2013 to complete)

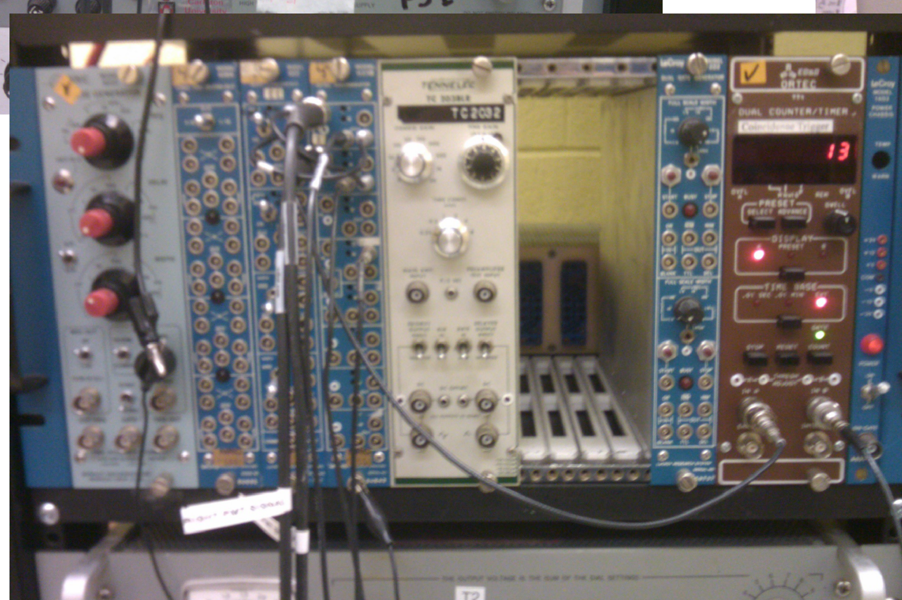
Last Step: Light-Tighting and Sealing The Box!

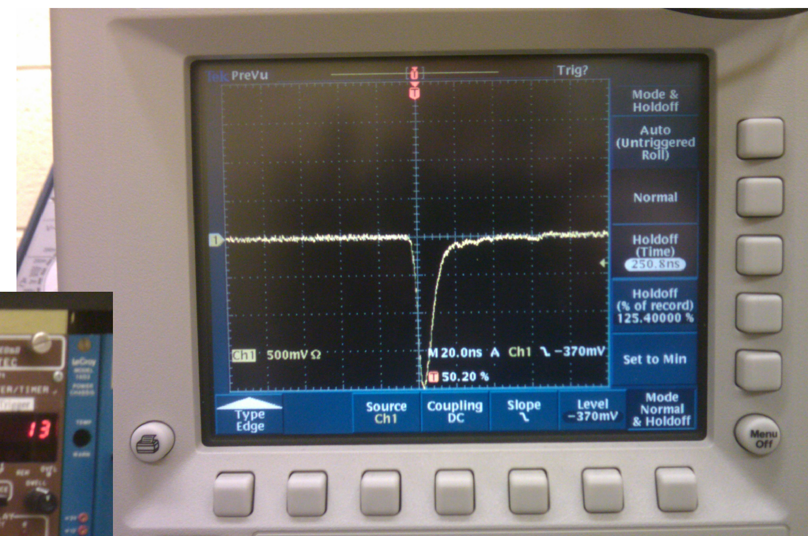
Techniques developed for the CRIPT project were employed to seal up the enclosure, but even then innovative solutions had to be found for challenges such as how to get the cables out without letting photons in

But Is It Art? Or Science?

Light-leaks can take weeks of effort to find and remedy, and so many other things could have gone undetected in building the detector system – Nov. 2013: high voltage is applied and the PMTs are read out… success!!!







No light leaks, functioning PMTs, and coincident triggers from both scintillators at expected rate indicates cosmic rays are being observed… ☺

And Now, the Physics Begins...

- Now that the detector system appears to have demonstrated basic soundness of operation, it must now be calibrated by taking many weeks of cosmic ray data and normalizing the response curves of all 64 channels of the "sensor" PMT output (to compensate for variations in optical coupling between the scintillator and each fiber, and in the varying channel response of the PMT itself)
- Once the calibration is done, the ability of the scintillator panel/edge sensors design to determine X-Y positioning of particles passing through the detector will be tested. Initial simplistic Monte-Carlo simulations indicated that the basic notion was sound, but it remains to be seen whether or not the real-world photonics and electronics are up to the challenge. This test is the primary reason for having built the analogue detector and will determine the next steps
- The next area of investigation will be with regards to analyzing the PMT output signals to determine whether particle type or momentum can be determined, or at least "energy deposited", and to what precision if so
- If all goes well, the following major step is to raise the funds to build a real prototype of the sensor using CsI(Tl) crystals and large area photodiodes

Questions?