

# Proposal for Production Testing of Photomultiplier Tubes for the Pierre-Auger Observatory

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## *Executive Summary*

We discuss a system whereby several thousand photomultiplier tubes (PMTs) can be tested for use in the Auger ground array. We consider the light source; electronics; data acquisition (DAQ), analysis and archiving; the physical infrastructure required; storage; and the light source. A CAMAC electronics and DAQ system, very similar to that required for Auger PMT testing, is already running for another experiment at UCLA. The UCLA group has permission from the Dean to use space in the Science and Technology Research Building. Several types of light source have been built at UCLA and it is proposed to use two of them for production testing: There is a fast, but low-intensity laser that is ideal for studying the timing resolution of the phototubes. There is also a pulsed LED system that can generate short (<30 ns) pulses over a wide range of intensities. Current data suggest the LED system is sufficiently stable to test the linearity of the PMTs.

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## **1 Physics Requirements**

The Pierre-Auger Observatory is designed to measure cosmic rays with energies of up to  $10^{21}$  eV. The ground array for the observatory will consist of water-Cherenkov tanks on a grid with a spacing of 1500 m. The PMTs and read-out electronics must be able to handle a wide dynamic range of signal. The PMT signals will be readout by flash ADCs with a sampling rate of 40 MHz (25 ns between samples). The ADCs will have 15-bit resolution; this is accomplished using two 10-bit with different gains on the input such that there is an overlap of 5 bits between the two ADCs. A single-photoelectron (spe) PMT signal will correspond to approximately 1 ADC count.

- Therefore, the phototubes must be able to measure reliably a signal of approximately 32000 photoelectrons in a period of 25 ns. This corresponds to a peak current of 20 to 30 mA at a gain of  $10^5$ .

Given other constraints in the electronics and read-out, the PMTs will be operated at a gain of approximately  $10^5$ . These data define the requirements of the PMT testing. The output pulse of the PMTs must be measured as a function of the incident number of photoelectrons to ensure that the response of the PMT is linear.

- The maximum non-linearity is specified to be 3%.

Efficiency is important because the amount of Cherenkov light produced in the water tanks is proportional to the amount of energy deposited by electrons and gamma rays.

- Therefore, we require PMTs to have well understood and closely matched quantum efficiencies to measure accurately the energy profile of the cosmic-ray induced shower.
- The timing resolution should be measured.

But, given that most 8-inch phototubes have a timing resolution of approximately 2 ns (at a gain of  $10^7$ ) the timing resolution is not as critical as other factors.

- The gain of the PMT as a function of voltage must be understood.

The dark rate is the number of anode pulse above threshold per second with no external light source on the photocathode. Contributions to the dark rate come from three main sources: thermal emission of electrons from the photocathode, photoelectrons produced by Cherenkov light caused by radioactive decay in the PMT glass, and electrical instability in the PMT. For the Auger experiment, the first two sources are not important.

- It is necessary to understand the behavior of dark-noise rate as a function of high voltage to ensure that the PMT will be stable and that high-voltage breakdown, over the lifetime of the observatory, is unlikely.

## 2 Summary of Requirements for PMT Testing

To test the 10000 PMTs required for the southern and northern Pierre-Auger Observatories, it is necessary to have one or more automated systems capable of testing many PMTs at once. Such a system requires a large darkroom with a light source, independent high-voltage control for the PMTs, electronics to measure the charge and arrival time of each PMT signal, and DAQ software capable of reading out the PMT data and controlling the light source.

The testing we foresee doing at UCLA will be composed of several stages. First, the PMTs will be installed in a dark room and have bases attached. Of the 48 PMTs in the dark room for one testing cycle, over 40 will be PMTs for testing and the remainder will be standards for calibration purposes.

Second, high voltage will be applied to the PMTs and the dark current will be allowed to decrease with time. During this "cool-down" period we will measure dark-noise rate as a function of time. To do this, the high voltage will have to be such that the PMT gain is sufficiently high to make single-photoelectron (spe) counting possible without amplification. Because the gain will not yet have been measured, we will use the manufacturer's recommended voltage for a gain of  $10^7$ . This stage of the test ensures that the PMT will not be so noisy as to prohibit further testing and that the subsequent dark-noise measurements are not made while the PMT is still changing with time. This stage will take several hours.

Third, the system will automatically turn on a dim light source and then adjust the high voltage to set the gain of the PMTs at  $10^7$  using the mean charge for spe pulses. When this point is found, the timing resolution for spe signals will be measured.

Fourth, a bright light source will be used to measure the gain of the PMTs as a function of voltage. We will map out a gain versus voltage curve for a gain of  $10^5$  to  $10^7$ . During this process, we will measure the dark pulse as a function of voltage. However, as the gain of The PMT is lowered, the ability to measure spe pulses quickly drops. However we will measure the dark pulse rate at a few where possible to ensure that the PMT is stable with respect to high-voltage breakdown.

Fifth, with the gain versus voltage curve understood, we will proceed to set the gain of the PMTs at  $10^5$ , the operating gain of the PMTs in the Pierre-Auger Observatory. This process will take approximately two hours as well. At the operating gain, two important PMT characteristics will be measured: the relative efficiency of the PMTs and the linearity. In order to measure the relative efficiency, the dark room will be calibrated to measure the relative light intensity at each location.

The data taken during these tests will be analyzed automatically and summary tables and plots will be made as well as diagnostics describing the suitability of the PMTs for use in the observatory. The system operator will then examine these summary data.

### **a. The Dark Rooms**

The dark room must be large enough to hold the PMTs. The proposed room can hold 49 PMTs on a 7 by 7 grid. The PMTs are to be mounted on a table made from an aluminum frame with a plastic top. The top will have holes cut into it into which the PMTs are placed. The table must be a square with side 70 inches (6 feet 10 inches or 1.78 m). In order to make work around the PMTs possible the room should allow approximately 2 feet (60 cm) between the table and the walls. Thus the total internal size of the dark room should be 11 feet square. We are currently not considering installing magnetic-field compensation coils.

It is also imperative that the likelihood of accidental entry of light into the dark rooms be small to avoid irreparably damaging 49 PMTs. The walls of the darkroom must be made of a rigid material attached securely to a solid frame. The doors must seal tightly and there must be an interlock on a lock on the door to ramp down the high voltage if the door is unlocked. (It is too late to ramp down the voltage when the door is opened.)

The dark rooms must be carefully checked to ensure that they are light tight, especially in areas such as joints in the building materials and cable feed-throughs. The table also has several requirements. It must be made of a non-magnetic material and hold the PMTs rigidly so the testing is done under constant conditions for all PMTs. Also, each PMT must be given a shroud so that light does not reflect from one PMT and strike another. The table should also be sufficiently tall that it is easy to connect cables to the PMTs underneath the table. The requirement for the height of the room is determined by the light source.

### **b. Electronics and DAQ**

The requirements for the electronics are straightforward. Commercial off-the-shelf CAMAC ADCs to measure the charge and TDCs to measure the timing resolution are sufficient. There is one important issue with the charge measurement. Most ADC have 10 or 11 bits in the digitized output, which corresponds to 1024 or 2048 channels. This is insufficient for making measurements from 1 to 20000 pe. Thus we need to split the input signal into two: one line having about 98% of the initial charge and

the other line having about 2%. Both the high- and low-charge line for each PMT will be passed to an ADC which doubles the required number of ADCs. Amplifiers will not be needed. Even if the PMTs are tested at a gain of  $10^5$ , the total anode charge for a spe pulse will be 1.6 pC. This must be divided into three parts: a small fraction of the pulse will be diverted to ADCs for the high-intensity measurements and the remainder will be split between the signal required for the timing and charge measurement. Thus the charge ADC will receive about 0.8 pC. Sensitivity of the ADCs is 0.25 pC/channel. Therefore, the spe spectrum can be studied, admittedly with coarse granularity. It will also be possible to test the spe spectrum at higher gain.

The timing resolution measurements will require either constant-fraction discriminators or leading edge discriminators. If leading edge discriminators are used, it will be necessary to measure the "walk", the change in measured arrival time of the signal with signal amplitude. We will require scalars for counting dark pulses. A schematic for the electronics is shown in figure 1.

Another group in the UCLA physics department working on the Endcap Muon Detector for the CMS experiment are using a CAMAC system to instrument 48 PMTs in a set of cosmic-ray muon detectors. This system also has computer-controlled independent high-voltage for each PMT. We propose to imitate this system as much as possible.

The other requirement of the DAQ is that it control the light source and allow the process to be fully automated. There are members of our group with experience in these matters and we see the software to run the DAQ as a time-consuming, but not fundamentally difficult job.

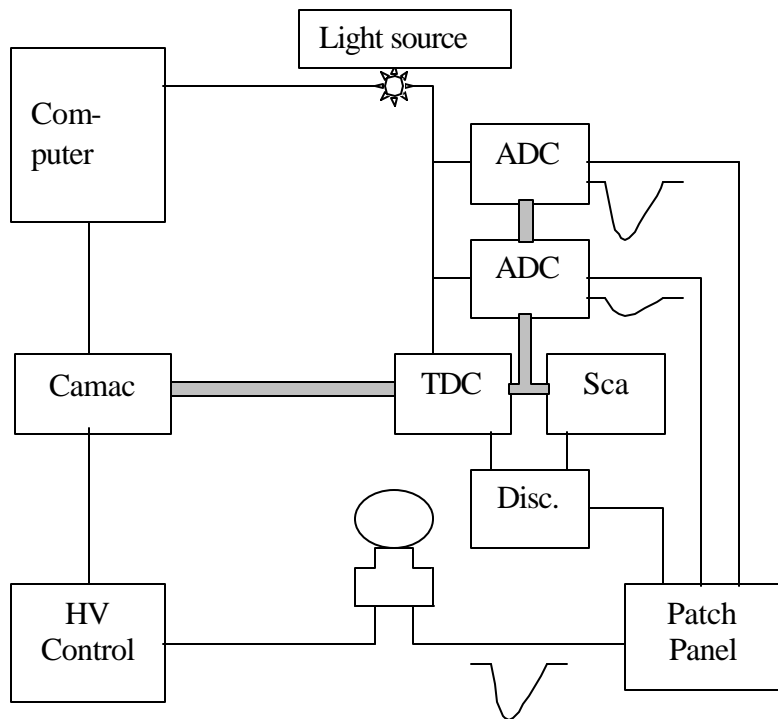
Once the data is collected however, it must be analyzed and the PMTs evaluated. PMTs which meet all standards will be flagged as passing the tests and the others will be flagged for human inspection of the data. The data must be archived so that in future it is possible to easily extract information. Relevant histograms for each PMT will be stored in a format commonly used in high-energy physics (probably ROOT). Tools such as root have graphical browsers allowing the user to navigate through files to find the histograms of interest as well as simple ways of extracting the histograms with C++ code. As well as storing archival histograms, we propose to have the DAQ generate a web page for each PMT with the measured parameters in tables and histograms of interest shown. These web pages would be available under password protection to all members of the Pierre Auger collaboration. The code for these tasks must be written. Again, this is a straightforward but time-consuming task.

### **c. Storage**

It will be necessary to store large numbers of PMTs at UCLA. We estimated the required space using the packaging for the Hamamatsu 8-inch PMT, which comes in a cardboard box 10.75 inches square by 17 inches high. This is a volume of 1.14 cubic feet. To store 1000 PMTs then requires 1140 cubic feet. If the storage is 8.5 feet high (tall enough to hold 6 boxes) then the required area for the storage is slightly less than 12 feet by 12 feet.

In addition to bulk storage we will require storage for PMTs that require retesting or are standards for calibration purposes. One hundred and fifty feet of shelving should be sufficient.

**Figure 1: A schematic of the electronics for production PMT testing. The shaded band connecting the CAMAC components represents the backplane of the crate. The lines to and from the light source represent electrical control lines rather than an optical path.**



#### **d. The Light Source**

Designing and building the light source is the most difficult job. The testing for the PMTs requires that several PMT properties be measured: the spe timing resolution, the efficiency, the linearity, and after-pulsing rates. These jobs require that the light source have a sub-nanosecond intrinsic time width and have stable light output over 5 orders of magnitude of output intensity. This is a serious challenge for a single light source and it is likely that more than one source will be necessary for production testing.

We have worked on several light sources at UCLA for detailed testing of individual PMTs. Two of those, and a light source used extensively by one of us at Queen's University are under serious scrutiny for use in production testing.

To test timing resolution there are a few choices. A pulsed nitrogen laser can off sub-nanosecond pulse widths. The primary beam (337 nm) can be used or organic dyes can be used to shift the wavelength. Nitrogen lasers supply lots of power and attenuation would be needed to reach spe levels. There are three drawbacks to nitrogen lasers. They are finicky. Experience with nitrogen lasers with the SNO project suggests that maintenance will be required frequently. The pulse-to-pulse stability in

laser output is not sufficient for linearity testing. Also the repetition rate of nitrogen lasers is typically 40 Hz. This implies that the time for testing PMTs would be dominated by the time required to measure the timing resolution.

The UCLA group currently uses a fast solid-state laser (Hamamatsu PLP-01) which produces light at a wavelength of 470 nm. This laser produces low-intensity output at high rates (typically kHz). Thus spe timing histograms can be accumulated quickly with this laser.

One other possibility is the use of a Cherenkov light source. One source used for small-scale testing for the SNO project was made from  $^{90}\text{Sr}$  in a piece of UV-transmitting plastic mounted on a small (3/8-inch) PMT. The source has the benefit that it can be used for quantum efficiency measurements for Cherenkov light because the light emitted is Cherenkov light. The small PMT acts as a trigger the electronics and gives sub-nanosecond timing accuracy.

To test the linearity of the PMTs (i.e. anode charge vs. total light intensity) the source must be able to produce light with an intensity that varies by more than 4 orders of magnitude from an average of 1 pe per pulse to  $2 \times 10^4$  pe. This is, without question, the most difficult task in this proposal.

We propose to use a fast blue ( $\lambda = 450$  nm) LED as this light source. We have a system currently that produces a pulse approximately 40 ns long. The circuit to drive the LED works. It can operate in a mode where the pulses are generated internally at a programmable rate or it can be triggered externally. Tests of the stability of the light source are underway and early results suggest that we will be able to reach our goal of stability to better than one percent.

However, this LED emits only 500 mCd (milli Candle) of light and may be insufficiently bright. We can use an LED that emits a longer wavelength,  $\lambda = 470$  nm, but with a power of 1500 mCd. It is also not necessary to use a single light source. It is possible to separate the room into several sections with each section having its own light source.

Once a light source has been chosen it will be necessary to control its intensity for testing linearity of the PMTs. There are two methods to do this with an LED. First it is possible to change the current through the LED; second, neutral density (ND) filters can be used to attenuate different amounts of light. To have an automated system the ND filters must be put on a wheel whose position is controlled by a stepper motor.

(Note that the absolute power output of the LED does not need to be known a priori. The linear testing can be performed using two LEDs, "A" and "B". On the first flash, only A emits a pulse. On the second pulse, only B. On the third pulse, both A and B. If the size of the PMT anode signal when both LEDs fire is the same as the sum of the signal when A fires alone and when B fires alone, then the PMT is linear.)

Distributing the light from the photodiode onto an array of 49 PMTs will require can be accomplished in a few ways. The PMTs can be divided up into smaller sections, separated by black curtains, with each section having its own LED and filter-wheel assembly. The table for testing the PMTs could also be built such that the PMTs are held at an angle so they point straight at the light source.

## **e. Human Resources**

During construction and commissioning of this system there will be several tasks that will require both scientific and technical work. The scientific work will be mainly in two areas: design, construction, and testing of the light source, and developing the DAQ and data analysis/archiving system. Both of these tasks will require the full-time attention of two people for 4 months.

The technical tasks include machining work for the light source and test system. This work is not yet well defined and an R-and-D effort on the light source is required. It will as a minimum require the machining of a filter-wheel assembly. Physicists will perform most of the development work of the light source.

During the production testing, the work will be carried out by undergraduate students at UCLA with supervision from the professors and post-doctoral scientists at UCLA.

## **f. Detailed Testing of a Subset of PMTs**

The large-scale system is necessary to process the thousands of required PMTs. However, some fraction of those PMTs will be tested in the small-scale testing system already in place at UCLA. At UCLA, we are currently able to test gain and dark *current* as a function of voltage, linearity at an arbitrary gain, absolute quantum efficiency as a function of wavelength. Timing resolution measurements and relative sensitivity as a function of position on the photocathode will be implemented shortly.

These PMTs serve several useful purposes. First, they allow a cross-check of the calibration of the dark rooms and the relative efficiency measurements. Second, these PMTs can be stored at UCLA and ensure that the production light source is not changing with time. Third, the detailed data obtained may well be useful in checking the calibration of the Auger ground array itself.

# **3 Required Equipment and Space**

## **a. Equipment and Human Resources**

The following table lists the required equipment. This electronics is expensive but standard nuclear and particle physics equipment. Because scientists FNAL are working on the Pierre-Auger Observatory, we ask to borrow the required hardware from PREP at Fermilab.

Many cables will be required. Note that most of these will be relatively short 50  $\Omega$  coaxial cables whose price is dominated by the cost of the connectors. All cables, except where noted require a LEMO connector on each end. This list of cables does not include cables necessary to run the light source.

The light source is under development at time of writing but it is understood now that some important items will be needed. Because the computer will control the light source, an I/O card will be needed. These typically cost about 1000 USD. We will require a series of optical filters on a motorized wheel. We expect development and production of the light source to require \$10,000 for hardware.

During testing, we propose to hire 3 undergraduates for 20 hours a week each. These students will perform the bulk of the production testing and maintenance work. These students will be required for several months. The salary cost of the students is approximately \$10 an hour, giving a total cost of \$600.00 a week. If we are able to test PMTs at an average rate of 160 a week, then labour will be required for 16 weeks which. This will have a total cost of \$9600.

This equipment falls under section 2.2.1.1.2 of the revised WBS, “Phototube Test Stand” and section 2.2.1.2.3, “Phototube Test Stands for Production”. All prices are rounded to the nearest United States dollar.

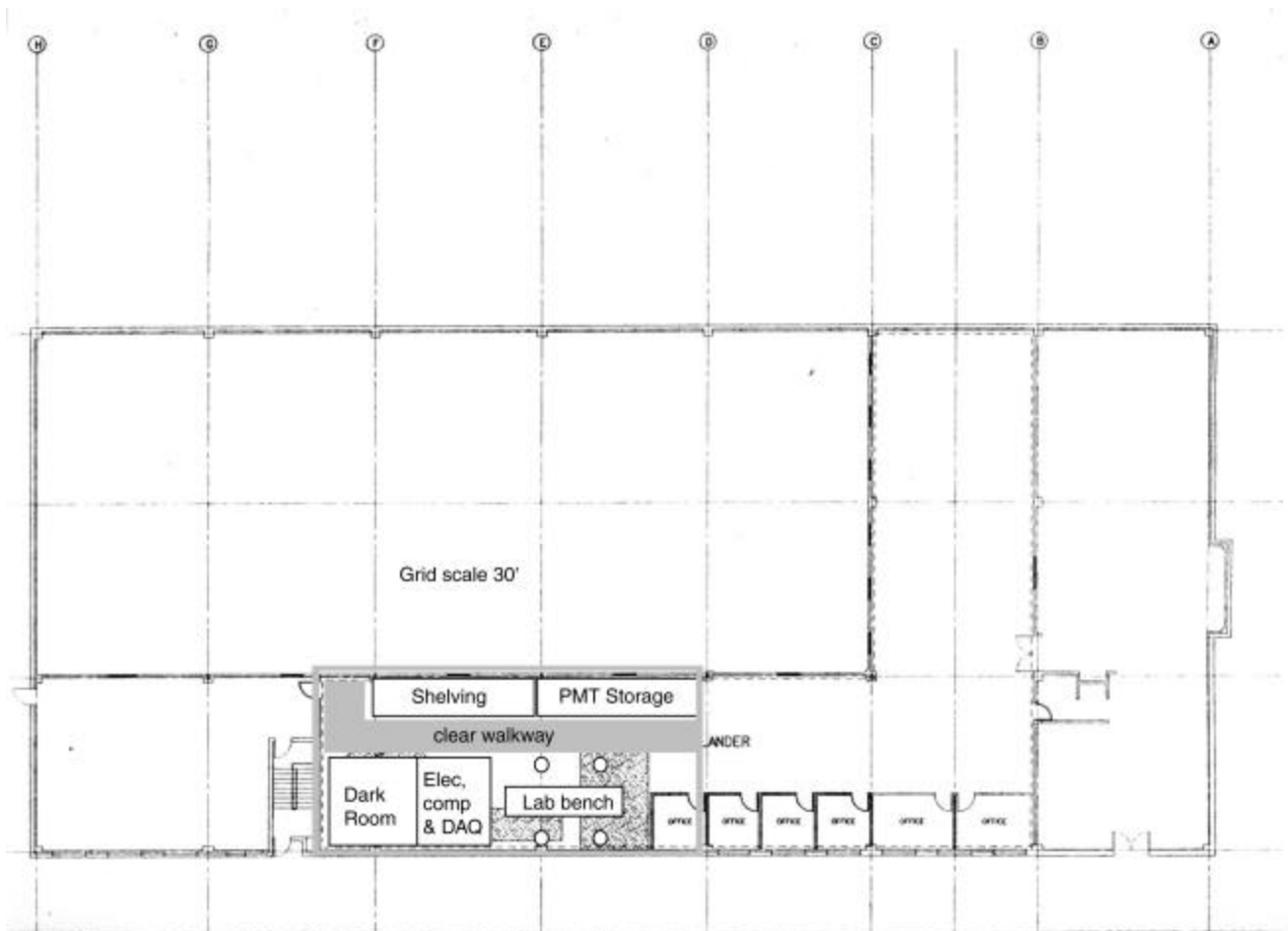
WBS	Purpose	Description	No.	Cost/ Unit	Cost (USD)
2.2.1.2.3.1	Elec: Timing	LeCroy 2228A TDC	8	2890	23,120
2.2.1.2.3.1	Elec: Timing	Phillips Scientific NIM Model 715 CFD	11	1650	18,150
2.2.1.2.3.1	Elec: Dark Noise	Phillips Scientific CAMAC Model 7132 Scaler	2	3295	6,590
2.2.1.2.3.1	Elec: Gain/linearity	LeCroy 2249A ADC <i>or</i>	9	2890	26,010
		Phillips Scientific 7166 ADC	7	2750	19,250
2.2.1.2.3.1	Elec: High Voltage	CAEN Model SY2527 Universal Power Supply	64	351	22,520
2.2.1.2.3.1	Elec: Hardware	1 rack, CAMAC Crate, NIM bin	1	?	?
			<b>Sub</b>	<b>Total</b>	<b>89,630</b>
2.2.1.2.3.1	DAQ	Computer	1	1	3500
2.2.1.2.3.1	DAQ	CAMAC Crate Controller	1	1	2500
			<b>Sub</b>	<b>Total</b>	<b>6000</b>
2.2.1.2.3.1	Cables	High Voltage Cable (1000 feet)	1	150	150
2.2.1.2.3.1	Cables	SHV connectors	100	10	1000
2.2.1.2.3.1	Cables	50 $\Omega$ signal cable RG-58 (1000 feet)	1	150	150
2.2.1.2.3.1	Cables	BNC connectors	100	5	500
2.2.1.2.3.1	Cables	Patch panel connectors (1 BNC, 3 LEMO bulkhead)	50	20	1000
2.2.1.2.3.1	Cables	Delay for CFD: length = 4 ns	50	10	500
2.2.1.2.3.1	Cables	Patch panel to ADCs: length = 4 feet	100	10	1000
2.2.1.2.3.1	Cables	Discriminators to TDCs: length = 4 feet	50	10	500
2.2.1.2.3.1	Cables	Discriminators to Scalers: length = 4 feet	50	10	500
			<b>Sub</b>	<b>Total</b>	<b>5,300</b>
2.2.1.1.2.1	Light source	Development and testing	n/a		2000
2.2.1.1.2.2	Light source	Purchase of parts (motors, filter wheels)			7000
2.2.1.1.2.4	Light source	Machining and construction			1000
			<b>Sub</b>	<b>Total</b>	<b>10,000</b>
2.2.1.2.3.3	Dark room	Construction	N/a		8,000
2.2.1.1.2.4	Dark room	Hardware for dark room development.			2,000
			<b>Sub</b>	<b>Total</b>	<b>10,000</b>
2.2.1.2.2.3	Human Resources	Testing of PMTs and maintenance of test stand based on estimated cost per PMT	5000 PMTs	4	19,200
2.2.1.2.2.3	Human Resources	Detailed testing of PMTs			9,600
			<b>Sub</b>	<b>Total</b>	<b>28,800</b>
			<b>Grand</b>	<b>Total</b>	<b>149,730</b>

## ***b. Facilities at the STRB at UCLA***

We request the following space in the Science and Technology Research Building (STRB). The desired space is part of the area previously used by the Mars Lander Project. We request an area of floor space 30 feet by 75 feet (2250 square feet). This space will be required to contain

- the dark rooms (external size 12 feet by 12 feet by approximately 8 feet high),
- a storage volume (6 feet by 24 feet by 9 feet high),
- 150 feet of shelving,
- an electronics rack, small desk, and computer,
- two lab benches for construction/repair of light source and electronics,
- a small office with a desk and filing cabinets

At time of writing the cost estimates for these facilities were being obtained. Facilities Management at UCLA will be able to build the darkroom and storage. We estimate now construction and materials costs of approximately \$8000 for the darkroom, storage and shelving.



**Figure 2: The proposed layout for the STRB. The area we wish to use is highlighted in gray. Note that a clear walkway has been left to reach the exit. The diagram of our proposed usage has been drawn over the layout of the previous use: the Mars Polar Lander.**

## 4 Conclusions

We have outlined a system whereby all PMTs for the Pierre-Auger Observatory can be tested. The electronics and DAQ system proposed is based on standard off-the-shelf components and can be assembled in a straight-forward way, albeit with some effort in the computer-control and data archiving effort. The largest scientific effort will be in building and characterizing the light source. We have several possible sources in hand at UCLA and current data suggests they will be adequate. We have confidence that a system can be constructed in 6 to 8 months. Once the system is constructed, it will be capable of processing more than 40 PMTs a day.