Remote Monitoring and Data versus Monte Carlo Comparison for the HAWC Experiment

Jennifer H. Ranta
Michigan State University - Physics REU Program 2014
August 7, 2014

Introduction

The High Altitude Water Cherenkov, or HAWC, experiment is designed to detect and measure high-energy gamma rays (i.e. 100 GeV to 100 TeV) that have entered Earth's atmosphere. The HAWC detector is still under construction, but when finished it will be an array of 300 tanks, each containing a light-tight bladder filled with water and 4 photomultiplier tubes (PMTs) situated at the bottom of this bladder. These PMTs capture the Cherenkov radiation emitted from high-energy particles passing through the water. The HAWC detector has been constructed at such a high altitude (at approximately 4100 meters above sea level) because the incoming cosmic particles it is trying to detect will have less atmosphere to traverse through before making contact with Earth's surface. This allows the HAWC detector to measure more events than it would at lower altitudes as well as measure more events from particles with lower energies.

When high-energy gamma rays (i.e. high-energy photons) enter the atmosphere, they interact and collide with the atmospheric particles. These collisions produce showers of other high-energy particles that will continue to plummet towards Earth's surface, colliding with other particles and thus causing more showers along the way. Eventually, the shower of particles, resulting from the original photon that entered the Earth's atmosphere, will reach Earth's surface. Showers resulting from incoming photons are comprised of electrons and positrons; these are the end particles that reach the HAWC detector. By measuring the Cherenkov radiation emitted by these end particles in the water of the tanks and using the timing of the observed radiation, the HAWC detector can measure the energy and direction of the original incoming photon. Knowing these pieces of information, one can then point to where in the sky a high-energy emitting object is and, based on the energy of the incoming photon, what kind of object it may be. Complicated reconstruction code is being written to calculate direction, energy, and angle of the original incoming photon to determine what and where high-energy photon sources might just be in our own galactic neighborhood and beyond.

Cherenkov radiation is produced when a particle passing through a medium (in the case of the HAWC detector, the medium is water) is moving faster than the speed of light in that medium. When this occurs, photons are emitted, similar to a sonic boom when an object moves faster than the speed of sound. These emitted photons are known as Cherenkov radiation, and they are what the PMTs in each of HAWC's tanks are measuring.

The HAWC detector is being built in a Mexican national park: Parque Nacional Pico de Orizaba. Specifically, it sits in the valley between Pico de Orizaba, a dormant volcano and the highest point in Mexico, and Sierra Negra, an extinct volcano. As one could imagine, this site is not an easy one to reach, nor is it close to any of the American universities that are in collaboration on this project. As a result, remote monitoring is currently a major priority for the HAWC experiment; this requires a detailed system through which those on shift can easily and accurately check the status of the detector and its instruments. In addition to this, the equipment must be documented such that one can find where and to what each piece is connected to for error diagnosis as well as testing and repair. Therefore, the work that I did this summer to benefit the HAWC experiment dealt with adding features and information to the preexisting, though still a work in progress, remote monitoring system.

Remote Monitoring of the HAWC Detector

<u>Shift Wizard</u>

The ability to monitor the detector remotely was one of the primary focuses of the HAWC group here at MSU when I began on this project. Before I could begin working on a specific assignment though, familiarity with the detector, its instruments, and the physics behind it was necessary. Thus, after reading several papers (including the *Construction of the HAWC Gamma-Ray Observatory* [4] proposal as well as *Sensitivity of the High Altitude Water Cherenkov Detector to Sources of Multi-TeV Gamma Rays* [2]), many web pages (including all pages on the MSU HAWC website and the HAWC public wiki), and going through multiple HAWC PowerPoint lectures with my advisor, Dr. Tollefson, I acquired adequate background knowledge regarding this experiment. Not only did I have to be familiar with this experiment, but also with the predecessor to the HAWC experiment, Milagro (also a water Cherenkov detector, yet it utilized a single large pond instead of an array of tanks). The Milagro experiment had a remote monitoring and shift system similar to what the HAWC experiment is hoping to have. Consequently, the first task was to review all of the questions, plots, and data (ascertained from the Milagro Monitoring Web Page and the Milagro Shift Log web page) that the individuals on remote shift (i.e. the shifters) for the Milagro experiment were asked to answer, investigate, and record, respectively. Every Milagro question or displayed data that pertained to a counterpart question or important data type, respectively, for the HAWC experiment was recorded as a starting point for questions to be included in the HAWC Shift Wizard. This Shift Wizard is a series of questions and plots that the shifters will run through to check the status and health of the experiment remotely. As the HAWC experiment already has a monitoring web page, this is where the Shift Wizard is located. This website is named HAWCmon, and it displays a multitude of measurements regarding the HAWC detector's status and that of its instruments; however, the University of Maryland (UMD) also has an additional monitoring page with some varying as well as overlapping types of measurements. Therefore, this second web page was also examined to look for which data are not yet given in HAWCmon, and of those data, which are important enough, rather than too technical and detailed, to be reviewed by each and every shifter, instead of only by experts when fixing or finding errors.

From the Milagro and UMD sites, I created a six-page document which contained a first-draft list of questions for the HAWC Shift Wizard. For each of these questions that required the shifter to look at certain plots or data, a link to the relevant plot or data display page was included underneath the question. Also, I included in this document a list of all Milagro shift questions and measurements relevant to HAWC, all UMD measurements that were not yet on HAWCmon but were significant enough to be added, as well as general comments and types of measurements that members of the HAWC collaboration had expressed the need for in the HAWC Shift Wizard. This list was then refined and edited through a series of meetings with my project's group, consisting of advisors Dr. Kirsten Tollefson and Dr. Jim Linnemann, postdoc Tilan Ukwatta, graduate student Sam Marinelli, and fellow REU student Krista Smith. In these group meetings, the important questions and measurements that each shifter should address were determined, which questions should be asked first (and how), as well as making sure there were the proper links to the necessary plots and data. As a result of these group meetings (receiving feedback and suggestions to refine the list), the list was now a series of questions ready to be implemented as a starting draft in the Shift Wizard itself, with links to relevant measurement pages and plots for each question. Thus, the next action to take was to write these questions into the HAWC Shift Wizard, worded coherently and listed in an appropriate order. The screen shot below (Figure 1) will display the page for editing the Shift Wizard questions, as it appeared after all the Shift Wizard questions had been added and thoroughly reviewed.

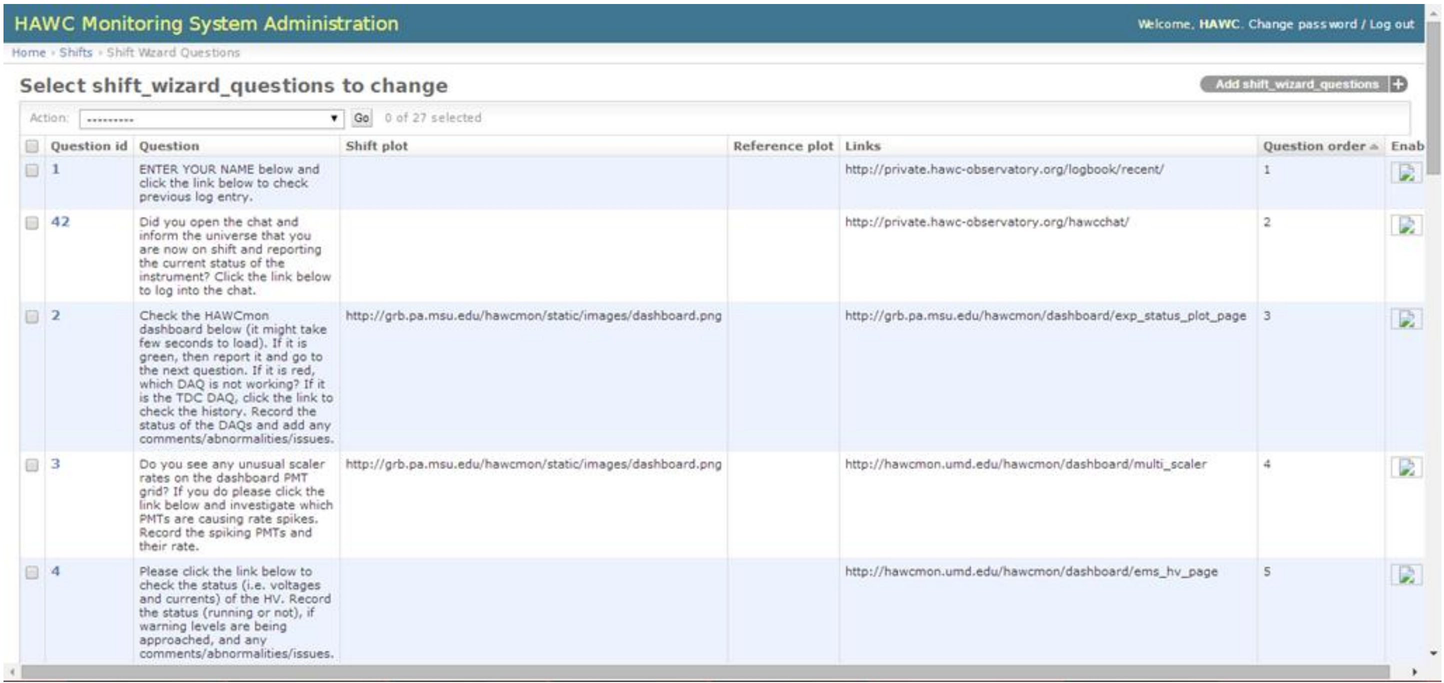


Figure 1: HAWCmon Shift Wizard Questions page where one can add or edit questions

After all this, the Shift Wizard now had twenty-seven significant questions (whereas before it only had two), most of which had links to needed or helpful data for the shifters to utilize. The screen shots below (Figures 2.1 – 2.2) display examples of a couple of the shift questions, including plots and links.

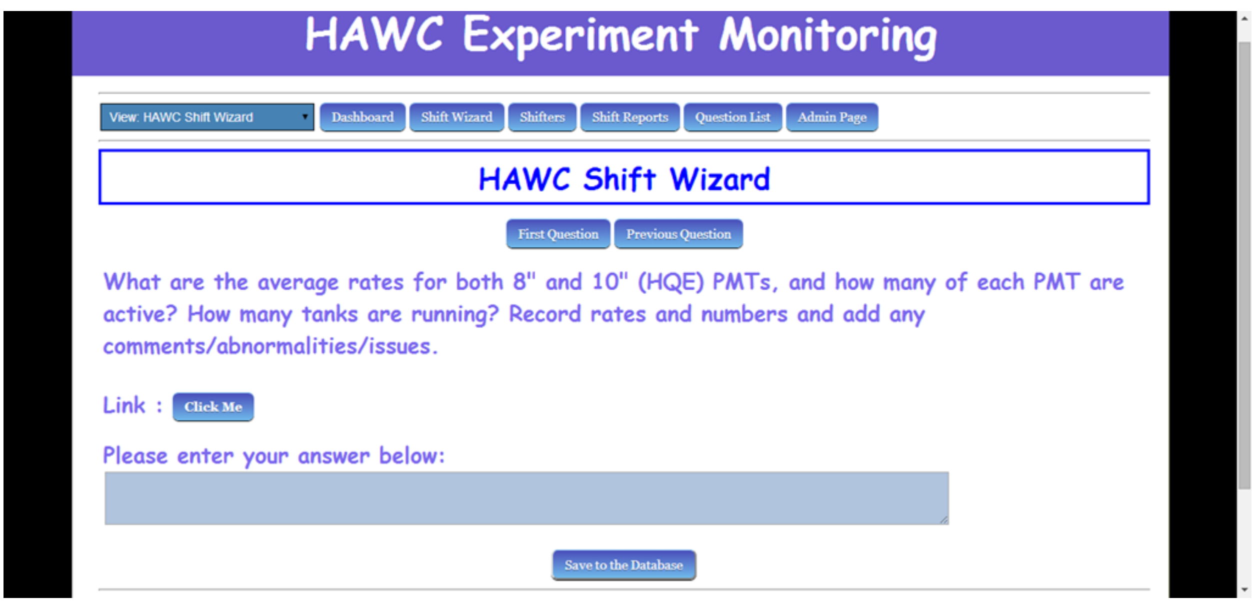


Figure 2.1: Shift Wizard Question with link to information for shifter to check and record

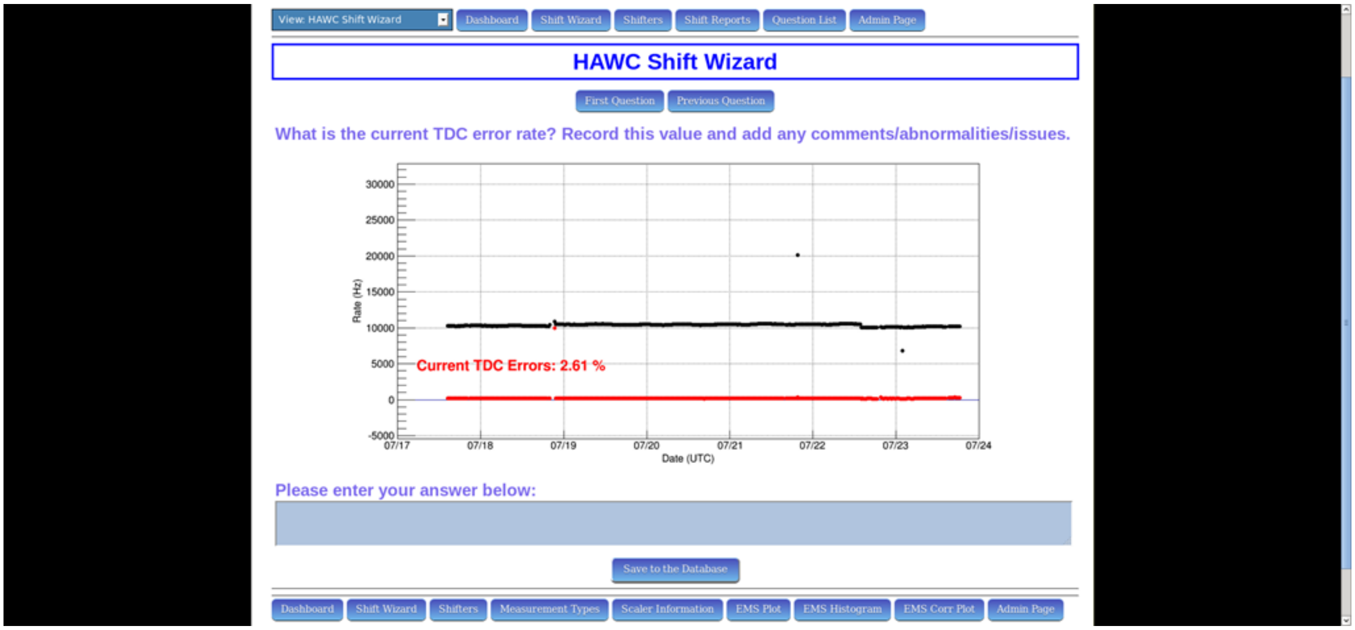


Figure 2.2: Shift Wizard Question with a plot for shifters to check and record status

This was an important accomplishment because HAWCmon now had a testable Shift Wizard that could begin undergoing use and experimentation by HAWC collaboration members, which was an essential step towards having a finalized remote monitoring system. My advisor Dr. Tollefson, while on site at HAWC for two weeks in July, actually tested out the Shift Wizard to see what changes might need to be made to it before it is to be officially implemented. She also was the remote shifter while Dr. Linnemann and grad student Sam were on site for the week or two after she was. In addition to actually being testable now, the Shift Wizard completion was also significant in that it helped display which types of measurements did not have data currently available (i.e. via questions whose links go to pages where the respective data will eventually be displayed but are blank instead), a pointer to what work still must be completed for a successful and fully operational remote monitoring system. The newly updated and long-awaited Shift Wizard was presented at the HAWC Collaboration Meeting at UMD in June of 2014 to all the rest of the HAWC experiment team.

Renaming of Data Measurement Types

Another monitoring project I worked on that was also presented at this Collaboration Meeting was renaming a series of high voltage measurements. Measurements for the high voltage had been waited on for some time, yet when it finally was implemented, the titles and labels for the plots were unhelpful, at least to all not associated with creating this technical naming scheme. Using both (for verification of correctness) the Electronics Configuration on the private HAWC wiki and another web page that was developed by the HAWC member that named the high voltage measurements, the "Type" names for the high voltage measurements were able to be replaced with the following information: the name of the channel each one referred to, and which tanks were connected to that channel. Also, the lower thresholds for the warning and alarm levels were changed; although the values entered for these levels were not yet confirmed, they were indeed more accurate than the values originally in place. There were sixty-four high voltage measurements (i.e. channels) that were renamed, resulting in 128 entries that were renamed since each channel had separate entries for both voltage and current. These entries were renamed such that the measurement type description would now give adequate and helpful information to individuals looking at these measurements and their plots. Figure 3 displays some of the 128 high voltage measurements that were renamed. The second column from the left is the technical name of each measurement, and the column just to the right of that is the new measurement type name that was given to these measurements to make it obvious to all viewers what each measurement actually was. The columns second and fourth from the right are the alarm and warning lower levels, respectively.

421	hv-1_u0_c	W1, Tanks N11, O11	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
422	hv-1_u1_v	W2, Tanks N12, O12	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1605.0	2000.0	0.0	1800.0
423	hv-1_u1_c	W2, Tanks N12, O12	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
424	hv-1_u2_v	W3, Tanks N13, O13	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1565.0	2000.0	0.0	1800.0
425	hv-1_u2_c	W3, Tanks N13, O13	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
426	hv-1_u3_v	W4, Tanks N14, O14	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1640.0	2000.0	0.0	1800.0
427	hv-1_u3_c	W4, Tanks N14, O14	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
428	hv-1_u4_v	W5, Tanks N15, O15	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1665.0	2000.0	0.0	1800.0
429	hv-1_u4_c	W5, Tanks N15, O15	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
430	hv-1_u5_v	W6, Tanks N16, O16	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1715.0	2000.0	0.0	1800.0
431	hv-1_u5_c	W6, Tanks N16, O16	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
432	hv-1_u6_v	W7, Tanks N17, O17	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1790.0	2000.0	0.0	1800.0
433	hv-1_u6_c	W7, Tanks N17, O17	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
434	hv-1_u7_v	W8, Tanks N18, O18	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1555.0	2000.0	0.0	1800.0
435	hv-1_u7_c	W8, Tanks N18, O18	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
436	hv-1_u8_v	W9, Tanks N19, O19	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1585.0	2000.0	0.0	1800.0
437	hv-1_u8_c	W9, Tanks N19, O19	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
438	hv-1_u9_v	W10, Tanks P11, Q11	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1650.0	2000.0	0.0	1800.0
439	hv-1_u9_c	W10, Tanks P11, Q11	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0
440	hv-1_u10_v	W11, Tanks P12, Q12	V	Wiener_HV_Unit_1: Wiener High Voltage Unit	1680.0	2000.0	0.0	1800.0
441	hv-1_u10_c	W11, Tanks P12, Q12	A	Wiener_HV_Unit_1: Wiener High Voltage Unit	0.0	1.0	0.0	1.0

Figure 3: Sample of renamed HV measurements as seen from the HAWCmon Measurement editing page. This picture shows only 20 of the 128 renamed HV measurements

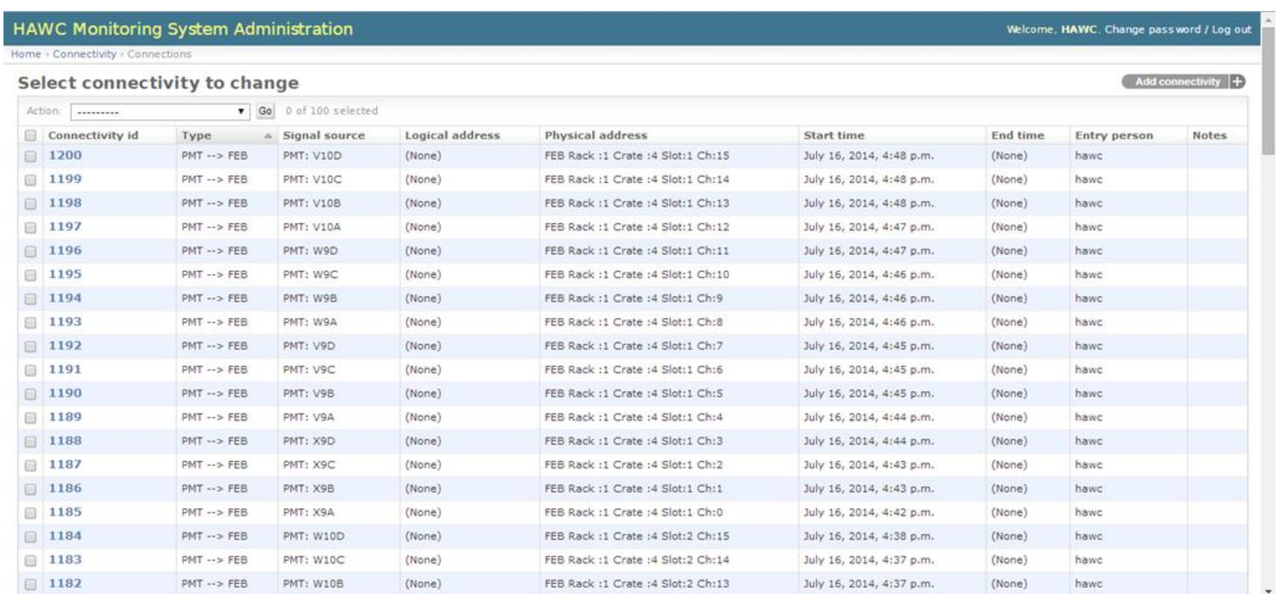
Later in the summer, I also added high voltage values to several PMTs and tanks that previous had not had a value in place because it had not yet been measured. Once Dr. Tollefson spent her two weeks on site, she had acquired these previously missing high voltage measurements. I then proceeded to add these newly measured voltages directly to the official Electronics Configuration page.

Connectivity Database

Having the ability to check which piece of equipment is connected to which channels, front end boards, crates, etc. was an integral part of remote monitoring and error diagnosis for HAWC. Thus, the next task that I completed was entering a total of 1,200 connections into the new Connectivity Database created by the project's postdoc Tilan. These connections were between each of the twelve hundred photomultiplier tubes (PMTs) and its respective front end board (FEB) crate number, slot number, and channel number. That is, each of the PMTs is connected to a specific channel within a particular slot within a certain FEB crate. There are currently four FEB crates for the HAWC detector, and each crate has twenty slots. Then, each slot has sixteen channels, each corresponding to a single PMT. Entered by hand, the information for these connections was retrieved from the Electronics Configuration web page previously mentioned. Even though this web page displayed the same information that was to be entered into the database, due to the format and layout of the tables, the desired information was not immediately obvious to one looking for the connectivity of a PMT.

Each entry to the connectivity database required the selection of correct options from several drop-down menus. First, the type of connection had to be selected, in this particular case, the connection type as PMT --> FEB (i.e. the connection source was a PMT and the destination was a FEB). Then, the particular PMT had to be selected, out of a drop-down list of 1,200 PMTs (four in each of the 300 tanks labeled as the tank number followed by A, B, C, or D). Following that, the destination for each connection had to be selected. This drop-down menu contained far more selections than are actually existent in the HAWC instrumentation at present, as it included slots and channel numbers for more than four crates, thus finding the proper destination could prove tedious after having to sift through the several thousand options for the accurate one. Since connections may change over the course of operation of the HAWC experiment, a start and end date and time for each connection also had to be input. For each connection the start time was set simply as the time that this connection was entered into the database, and the end time was left blank since each connection is still currently in use. Lastly, the name of the individual entering each connection had to be selected, so that HAWC members can see who updated or changed which connections should problems arise. For now, since the HAWC personnel database is not yet linked up to the connectivity database, the only two options for “entry person” are “hawc” and “tilan”, thus the option “hawc” was selected for each connection entry. Eventually though, each member of the HAWC team will have their own name as an option. The screen shots shown below display the format of each entry upon being entered into the database (Figure 4) as well as one of the twelve pages that now constitute the list of these 1,200 PMT connections (Figure 5).

Figure 4: Example of information that goes into entering each PMT → FEB connection



Connectivity id	Type	Signal source	Logical address	Physical address	Start time	End time	Entry person	Notes
1200	PMT --> FEB	PMT: V10D	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:15	July 16, 2014, 4:48 p.m.	(None)	hawc	
1199	PMT --> FEB	PMT: V10C	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:14	July 16, 2014, 4:48 p.m.	(None)	hawc	
1198	PMT --> FEB	PMT: V10B	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:13	July 16, 2014, 4:48 p.m.	(None)	hawc	
1197	PMT --> FEB	PMT: V10A	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:12	July 16, 2014, 4:47 p.m.	(None)	hawc	
1196	PMT --> FEB	PMT: W9D	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:11	July 16, 2014, 4:47 p.m.	(None)	hawc	
1195	PMT --> FEB	PMT: W9C	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:10	July 16, 2014, 4:46 p.m.	(None)	hawc	
1194	PMT --> FEB	PMT: W9B	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:9	July 16, 2014, 4:46 p.m.	(None)	hawc	
1193	PMT --> FEB	PMT: W9A	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:8	July 16, 2014, 4:46 p.m.	(None)	hawc	
1192	PMT --> FEB	PMT: V9D	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:7	July 16, 2014, 4:45 p.m.	(None)	hawc	
1191	PMT --> FEB	PMT: V9C	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:6	July 16, 2014, 4:45 p.m.	(None)	hawc	
1190	PMT --> FEB	PMT: V9B	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:5	July 16, 2014, 4:45 p.m.	(None)	hawc	
1189	PMT --> FEB	PMT: V9A	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:4	July 16, 2014, 4:44 p.m.	(None)	hawc	
1188	PMT --> FEB	PMT: X9D	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:3	July 16, 2014, 4:44 p.m.	(None)	hawc	
1187	PMT --> FEB	PMT: X9C	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:2	July 16, 2014, 4:43 p.m.	(None)	hawc	
1186	PMT --> FEB	PMT: X9B	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:1	July 16, 2014, 4:43 p.m.	(None)	hawc	
1185	PMT --> FEB	PMT: X9A	(None)	FEB Rack :1 Crate :4 Slot:1 Ch:0	July 16, 2014, 4:42 p.m.	(None)	hawc	
1184	PMT --> FEB	PMT: W10D	(None)	FEB Rack :1 Crate :4 Slot:2 Ch:15	July 16, 2014, 4:38 p.m.	(None)	hawc	
1183	PMT --> FEB	PMT: W10C	(None)	FEB Rack :1 Crate :4 Slot:2 Ch:14	July 16, 2014, 4:37 p.m.	(None)	hawc	
1182	PMT --> FEB	PMT: W10B	(None)	FEB Rack :1 Crate :4 Slot:2 Ch:13	July 16, 2014, 4:37 p.m.	(None)	hawc	

Figure 5: Shown here are only 18 of 1,200 PMT → FEB connections entered into the database

While entering these PMTs, I found multiple errors within the Electronics Configuration page. I was able to entirely solve and fix one of them myself, and the other I alerted my advisors so that they could contact the proper individuals. The spokesperson for the entire HAWC Collaboration even thanked me for finding these issues.

Primordial Black Holes Mass Accretion versus Loss Rates

Throughout the course of my time on this project, the MSU HAWC group had been focusing on trying to publish a paper regarding HAWC's sensitivity to primordial black holes (PBHs), as well as what they are and how they may be detected. In this paper, titled *Milagro Limits and HAWC Sensitivity for the Rate-Density of Evaporating Primordial Black Holes* [**1**], the effect of Hawking radiation is extensively discussed, which is the emission of particles from black holes as proposed by Stephen Hawking. As a result of this radiation, these PBHs will lose mass and "evaporate" over time, and based on the mass of a PBH and the rate of mass loss, it can be estimated when a PBH should be detonating. The detonation of a PBH is an event that would look similar to a gamma ray burst (GRB), which should be able to be observed by the HAWC detector as long as the emitted photons are in the 100 GeV to 100 TeV range that HAWC is sensitive to. So far, no GRBs have been observed which emit photons in the TeV range.

The aforementioned paper's calculations however, do not take into effect the mass accretion by these PBHs as they move through space. Thus, my advisor Dr. Linnemann pointed me to several references regarding Bondi accretion, i.e. the accretion of mass onto black holes, neutron stars, or other compact objects as they traverse through the interstellar medium (ISM) [**3**], to calculate the mass accretion rate and compare this to the rate of mass lost due to Hawking radiation [**5**, **7**]. This calculation was important because it would definitively show whether or not the effect of mass accretion was significant compared with the mass loss, thus whether it was a calculation that was essential enough to be added into the paper or not. Using the Bondi accretion rate formula [3] for the mass accretion, the only additional pieces of information necessary were estimates for the density of the ISM, velocity of dark matter through the ISM, and mass of a typical PBH. Dr. Linnemann gave the suggested values of 10^{13}g to 10^{14}g for the mass of a PBH, 30 km/s to 300 km/s for the speed of dark mater through the ISM, and one proton per cubic centimeter, or 10^{-24}g/cm³. Using these values and, mass accretion could then be calculated and was determined to be around the order of 10^{-32}grams per second. For the mass loss rate, the Stefan-Boltzmann-Schwarzschild-Hawking power law [5] was used (in addition to using $E = mc^2$and several conversion factors to get power into units of mass per second), which only required the mass of the PBH, and the calculation resulted in a rate around the order of 10^{-2}grams per second. Seeing that for each second, the mass lost was thirty or so orders of magnitudes greater than the mass gained, I concluded that the PBH paper was in fact justified in excluding the calculations associated with Bondi mass accretion (as was the expected result). Upon showing my results to Dr. Linnemann, he confirmed that the thirty orders of magnitude difference certainly constitutes the mass accretion as being a negligible effect.

Data versus Monte Carlo Comparisons

While acquisition of data is extremely important for the HAWC experiment, in order to draw any conclusions regarding the raw data for the events that HAWC captures, complicated reconstruction code must be written to analyze what type of particle hit the detector (hadron vs. photon), what direction it came from (pointing to the source object's location in the universe), as well as what the energy of the original incoming particle was. All of these are characteristics that can help describe the type of object the source of the particle was as well as provide important information about these types of sources. While the writing of the code to perform these calculations is being worked on by several HAWC members across the various involved universities, the various versions of code are being tested on Monte Carlo simulated data. In order for the final reconstruction code to be of any significant use to the experiment though, the simulated data must be comparable to the actual data, otherwise the reconstruction code will not be calibrated properly. This comparison of the Monte Carlo data and actual data was the final aspect of this project that I worked on this summer.

For comparison of actual data to Monte Carlo simulated data, the sample of actual data that is to be used should be data that is well understood. In order to have well understood data, the cosmic source that provided these data should also be well understood. The Crab Nebula is precisely that; it has been observed by numerous experiments around the world, and thus its characteristics, including location and signal strength (i.e. flux), are very well known and can be used as a standard calibration source for other detectors, such as HAWC. Because the Crab is so well studied, the Monte Carlo simulated data can be parameterized to simulate the Crab specifically. HAWC data can then be carefully selected to correspond to when the Crab was in the sky, and HAWC's field of view, and where in the sky the Crab appeared. In this way, the data I used in my actual versus Monte Carlo data analysis were able to be compared specifically as actual versus simulated Crab data. The next step however, was to now retrieve the code written to perform the aforementioned analysis.

After a long and tedious process of attempting to receive the desired code and related data necessary, finally this was accomplished and the comparison could commence (with significant help from both the postdoc and the grad student, Tilan and Sam, respectively). With code that Sam had written, implementing ROOT, I was able to create plots of the actual data and of the Monte Carlo data, plotting both for a certain variable on a single graph; this was done for several variables to compare the variables' values in each set of data.

After looking at each of the plots I created, it was clear that there is still a considerable amount of work left to do in getting the Monte Carlo data to resemble the actual data. I also compared my plots to those of a HAWC member who had previously run a (more elaborate) data versus Monte Carlo comparison [**6**]; his results were nearly identical to mine. In particular, the distributions of variables corresponding to the number of PMTs (rec.nHit), the number of tanks hit (rec.nTankHit), and the "y", and to a lesser extent, "x" coordinates of the reconstructed core (rec.coreY and rec.coreX, respectively) are all significantly different between the two types of data. Alternatively, the distributions of variables pertaining to the zenith angle (rec.zenithAngle) and the number of photoelectrons detected (rec.logNPE) are very closely related between the two types of data. Thus, the Monte Carlo code is not producing substantially inaccurate simulations of data; however, they are certainly not acceptably accurate results either.

The first type of plot that I made was plotting both the actual data and the Monte Carlo simulated data for a given variable on a single graph; this was done for several variables to compare the variables' values in each set of data. In the following two figures, I show plots that display examples of a variable that is strongly related (Figure 6) in the actual and Monte Carlo data and a variable that is poorly related (Figure 7).

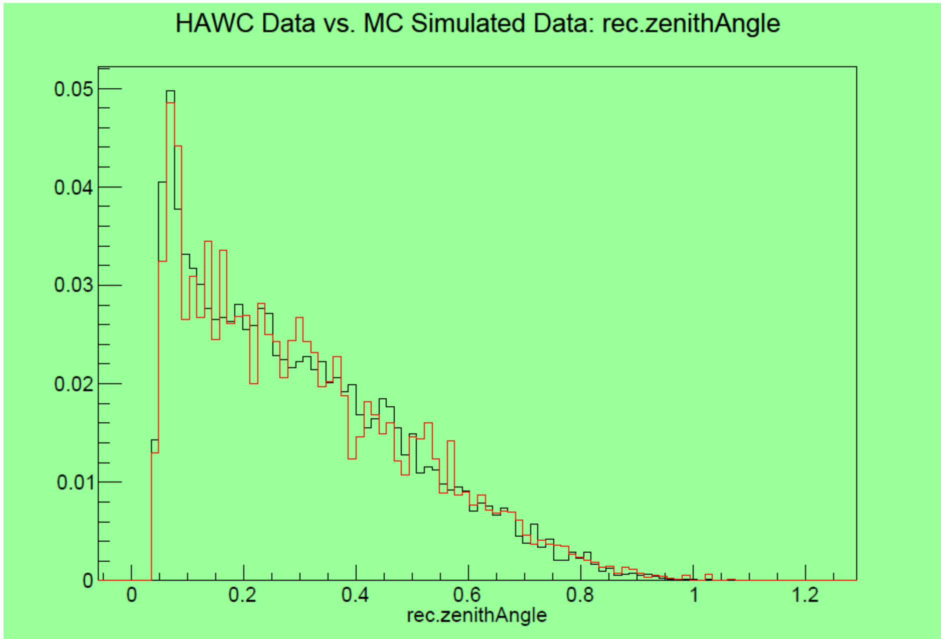


Figure 6: Comparison of zenith angle in actual vs. MC data (red = MC, black = actual)

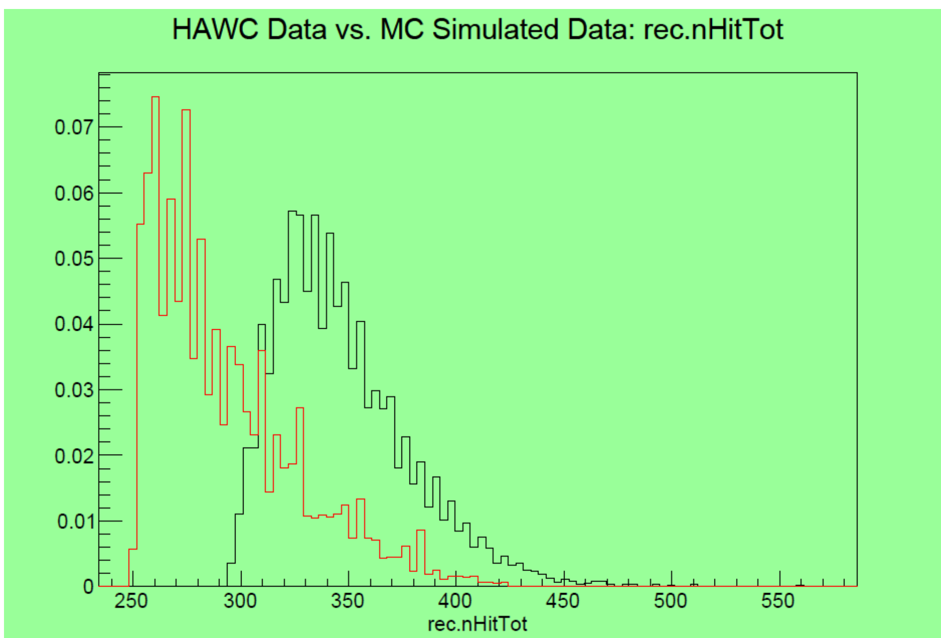


Figure 7: Comparison of total PMTs hit in actual vs. MC data (red = MC, black = actual)

Next, I was able to create two-dimensional plots, plotting one variable versus another, for both the actual and Monte Carlo data (on separate plots this time); these types of plots allowed me to look for correlations between variables as well as check for matching correlations between the data sets. An example of this type of plot is given below.

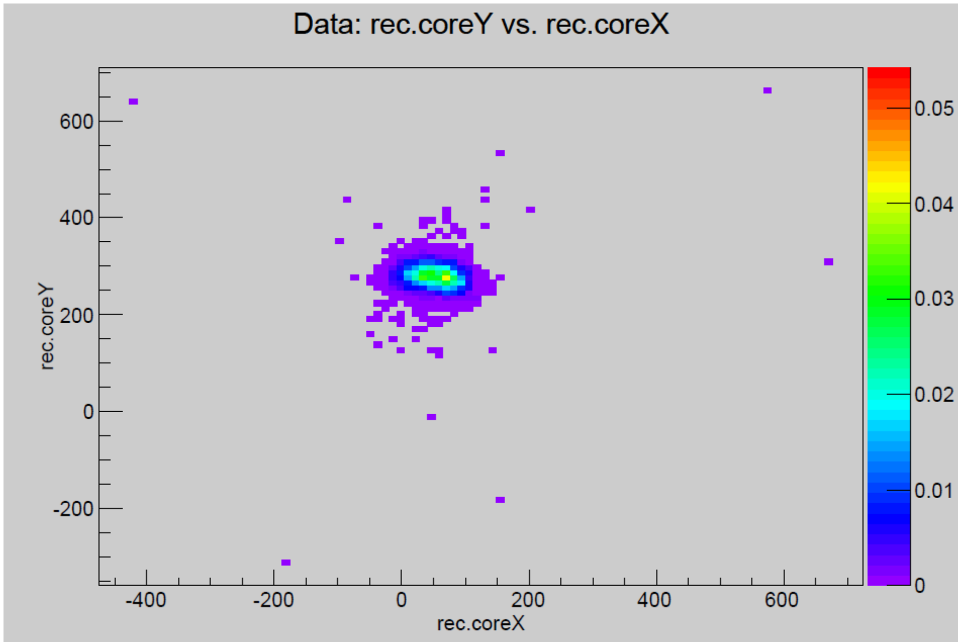


Figure 8: Plot of the reconstructed event core location in actual data

These plots represent the attempt to reconstruct the characteristics (such as energy, position, particle type, etc.) of an event (having a particle enter Earth's atmosphere and produce a shower of particles that HAWC then detects) using complex physics models and calculations. The variables that I analyzed are some of the means by which the physics of the experiment are captured and measured; they are how the physics can be applied to the raw data that are received from the HAWC detector. Nonetheless, these variables will need to be simulated properly if the physics conclusions drawn from the HAWC experiment are to be reliable and compelling. As for why these variables are not being simulated properly, one probable reason is that, since the HAWC detector is the first of its kind and is still under construction, it is not fully understood yet, thus the program that simulates the detector may simply not describe the detector as accurately as expected. My analysis of these variables was one of many important steps towards determining which variables and aspects of the Monte Carlo simulated data need to be improved upon in order for it to mirror the actual data that HAWC is detecting.

Summer Synopsis

All in all, this summer presented me with an amazing opportunity. I was able to not only work with incredible faculty and group members, but I was able to work on actual, current physics research that could be making new and important discoveries over the course of the next few years of operation. The contributions I made were significant mostly in getting the HAWC experiment's remote monitoring ability further along in the development process.

When I started on this project, the Shift Wizard was not much more than a goal, barely a work in progress. Yet, after several drafts, lots of research, and thorough reviews and edits, it is now a run through of twenty-seven questions that adequately assess the status of the HAWC detector (assuming the shifters answer the questions properly).

In addition to the Shift Wizard, there were several measurements on HAWCmon that, although they were displayed, were not descriptive of what exactly was being displayed. These were the high voltage measurements, and after careful evaluation, all 164 displayed measurements of the high voltage were renamed to provide accurate definitions of what each measurement pertained to.

Also, to have the information of which equipment was connected where is extremely useful in any complicated and large scale experiment such as this. Thus, after the Connectivity Database was created by the postdoc Tilan, I entered 1,200 PMT to FEB crate connections manually (using the Electronics Configuration page for deciphering each connection's information).

Lastly, the HAWC experiment not only needs to capture data, but also process it and be able to make several calculations to determine the energy and direction of the original incoming particle. The code to do this is still in the making, to optimize the accuracy and reliability of the calculations. However, in order to calibrate the code, the data being used is Monte Carlo simulated data rather than the real HAWC data. For the code to produce trustworthy results then, the Monte Carlo data must be similar to the actual data. As such, I worked on this analysis as my last task on this project, comparing several types of variables used in the data to check for similarities or discrepancies in order to help the HAWC experiment investigate the resemblance between the actual and simulated data. As a consequence of these comparisons, it seems that while some simulated variables coincide with the actual data quite nicely, there are still several others whose resemblances are not yet sufficient, thus the Monte Carlo simulation code is not, as of late, producing altogether satisfactory variable values.

The work that I completed this summer was an essential effort towards getting HAWC to be a successfully remotely monitored system. It was also a step towards deciphering which aspects of the simulated data code need to be improved upon (i.e. adjusted to match the actual data more closely) in order to ensure the reconstruction code, which will calculate all of the physical values from the raw event data, will be calibrated properly allowing the results of the HAWC experiment to be accurate and valid. Although I did not have a personal project in the same sense that I was expecting to have, the experience I gained this summer was invaluable, very enjoyable, and overall has been of unparalleled benefit in regards to assisting with my upcoming graduate school decisions. I am honored to have had this opportunity and would gladly have gone through this program again.

References

1. A. U. Abeysekara, et al. "Milagro Limits and HAWC Sensitivity for the Rate-Density of Evaporating Primordial Black Holes." *Milagro Limits and HAWC Sensitivity for the Rate-Density of Evaporating Primordial Black Holes.* arXiv, 7 July 2014. Web. <http://arxiv.org/abs/1407.1686>.

2. A. U. Abeysekara, et al. "Sensitivity of the High Altitude Water Cherenkov Detector to Sources of Multi-TeV Gamma Rays." *Astroparticle Physics* Vol. 50-52: 26-32. 2013. Web.

3. "Bondi Accretion." *Wikipedia.* Wikimedia Foundation, 26 May 2014. Web. <http://en.wikipedia.org/wiki/Bondi_accretion>.

4. HAWC et al. "Construction of the HAWC Gamma-Ray Observatory." 2 May 2011. Web.

5. "Hawking Radiation." *Wikipedia.* Wikimedia Foundation, 17 July 2014. Web. <http://en.wikipedia.org/wiki/Hawking_radiation>.

6. Riviere, Colas. "Data/MC.", 20 May 2014. Web. <http://private.hawc-observatory.org/wiki/images/7/74/2014-05-20_more-data-mc.pdf>.

7. Zimmerman Jones, Andrew. "Hawking Radiation - Radiation Emitted from Black Holes." *About.com Physics.* About.com Physics. Web. <http://physics.about.com/od/astronomy/f/hawkrad.htm>.