Preliminary analysis of ice Cherenkov detector operation during a latitude survey

Y Tangjai¹,²,³, A Pagwhan¹,²,³, W Nuntiyakul²,⁴,*, D Ruffolo⁵, J W Bieber⁵, J Clem⁶, P S Mangeard⁶, R Pyle⁷, A Sáiz⁵ and IceCube Collaboration⁸

¹ Graduate School, Chiang Mai University, Chiang Mai 50200, Thailand
² Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
³ National Astronomical Research Institute of Thailand (NARIT), Chiang Mai 50180, Thailand
⁴ Research Center in Physics and Astronomy, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
⁵ Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand
⁶ Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
⁷ Pyle Consulting Group, Inc., St. Charles, IL 60174, USA
⁸ https://icecube.wisc.edu/collaboration/institutions
*E-mail: waraporn.n@cmu.ac.th

Abstract. IceTop, the surface component of IceCube Neutrino Observatory at the South Pole, studies cosmic ray air showers with an array of ice Cherenkov detectors typically referred to as “IceTop Tanks.” In November 2009, collaborators from the University of Delaware, UW River Falls, and Uppsala University loaded an insulated shipping container containing an IceTop Tank on the icebreaker Oden which traversed the Atlantic Ocean from Helsingborg, Sweden to McMurdo, Antarctica, and return. Over an approximately 6-month interval, Oden carried the IceTop Tank through a wide range of geomagnetic cut-offs. The data obtained will allow the energy dependent effective area (yield function) to be determined using the Earth as a magnet spectrometer. The ultimate goal of the project is to calibrate the IceTop Tanks to study cosmic rays in the GeV primary energy range. We will report preliminary results for determining the yield functions.

1. Introduction
Cosmic rays are high energy particles coming from outer space. There are two main sources of origin, inside and outside the solar system. The energy of primary cosmic rays originating from the sun, i.e., from the solar wind or solar flare, typically has less than GeV energy. In contrast, cosmic rays originating from outside the solar system possibly from supernovae have energy above the GeV energy range. When primary cosmic rays enter the Earth’s atmosphere, they collide with the air nuclei and produce sub-atomic particles such as muons, protons, neutrons, electrons, positrons, etc. The cascade of such secondary particles produces “air showers.”

Cosmic rays can be measured both directly and indirectly. The IceCube Neutrino Observatory also detects very high energy cosmic rays. Part of IceCube is IceTop, which studies indirect cosmic ray air showers with an array of ice Cherenkov detectors typically referred to as “IceTop Tanks.” There are 162 tanks located in the packed snow surface at the South Pole. Each tank comprises a block of transparent...
ice and two Digital Optical Modules (DOMs) embedded in the surface of the ice. DOMs contain a large photomultiplier and readout electronics. Particles striking the ice produce a light pulse that is electronically measured. These events are related to the flux of cosmic rays interacting with the Earth’s atmosphere, but the relationship is complex and depends on the spectrum and composition of the primary particles.

2. Observation

2.1. Instrumentation
The IceTop tank was loaded into a refrigerated shipping container, filled with water, and frozen into a solid block of clear ice (figure 1) using the same process employed at the South Pole. The only construction difference was the inclusion of four DOMs (named Warmbrau, Phoenix, Melophobia, and Boise) in the tank for redundancy.

![Figure 1](image-url). The IceTop tank in an insulated shipping container, filled with water and frozen using the same technique as at the South Pole. Four Digital Optical Modules (DOMs) are frozen into the clear ice. Two neutron detectors were also strapped on top the tank. This figure was created by Flair, which is an advanced user friendly interface for FLUKA (FLUktuierende KAskade) [1-3]. In this work, we analyze data from the DOM named “Phoenix” operated on the icebreaker Oden. We will not mention the analysis of the neutron counters and simulations.

2.2. The 2009 – 2010 latitude survey
To obtain experimental data to validate the calculation of the response of the IceTop tanks, a team of scientists from The University of Delaware and the University of Wisconsin River Falls in the USA, and Uppsala University in Sweden installed an IceTop Tank on the Swedish icebreaker “Oden” which carried them from Helsingborg, Sweden to McMurdo, Antarctica, and back in 2009-2010. The IceTop tanks at the South Pole are similar to the unit carried on the Oden except that they only contain two DOMs. The voyage traversed the route shown in figure 2.

In a latitude survey, a detector is carried through a wide range of geomagnetic cutoff rigidity. The cutoff rigidity is defined as momentum per charge in the units of Giga Volt (GV) that a particle requires to penetrate the geomagnetic field and reach the upper atmosphere. We applied geomagnetic field models to calculate both the vertical and apparent geomagnetic cutoff rigidity. The vertical cutoff rigidity is the minimum rigidity for a vertically incident particle to enter atmosphere at a particular location. Apparent cutoff rigidity is an estimate taking into account the details of geomagnetic penumbra in each possible direction of incidence. From [4], the apparent cutoff arranges transportable detector data better than the normally used vertical cutoff and can be significantly different. We calculated the apparent cutoff rigidity from the average cutoff rigidity measured at 30° zenith angle for eight different azimuth angles (0°, 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5°) plus the vertical cutoff rigidity.
at zero zenith angle as suggested from [4]. The cutoff rigidity varies with latitude, and also with time because the geomagnetic field is changing intrinsically and fluctuates due to the influence of the solar wind on the magnetosphere. From previous investigations, these phenomena are well-understood enough to allow the calculation of the cutoffs in different locations and time for a ship-borne detector [4-6]. The difference in a signal of a detector between one geomagnetic cutoff and another is precisely the response of the detector to the primary cosmic ray spectrum between two cutoffs.

Figure 2. Voyage of the 2009-2010 latitude survey, superimposed on contours of the 2010 vertical cutoff rigidity, calculated for April 08, 2010 at 12:00 UT. Numbers at each contour indicate the vertical cutoff rigidity in GV.

The objective of a latitude survey is to cover a large range of geomagnetic rigidity cutoff to measure the energy-dependent effective area (yield function). The derivative of the count rate with respect to the geomagnetic cutoff rigidity determines the so-called “response function” of the detector [5-6]. This way of using the geomagnetic field as a spectrometer has clear advantages compared with analyzing multiple fixed detectors. Since it uses a single detector there is no need for inter-calibration yet the data provide coverage of a wide range of cutoff rigidity. The latitude survey had the primary goal of calibrating an IceTop Tank [7].

3. Data reduction

3.1. Data processing
The primary data from each DOM consisted of the count rate from two major independent discriminators termed SPE (Single Photo Electron) and MPE (Multi Photo Electron). The data from each discriminator separate into 47 thresholds. In the analysis of this work, an overall 47 threshold settings from the SPE can be used whereas only 17 threshold settings from the MPE are usable because data from the other 30 settings are empty as they were set above the maximum possible signal. Note that at higher threshold settings, the measured count rate is lower and vice versa. An individual run for a DOM comprises the five minutes of data with the same discriminator setting. We analyze the data from one DOM named “Phoenix” because it remained stable for the entire voyage in spite of the rough weather encountered. The other DOMs showed gain changes ranging from minor to violent, so we focus on the most stable one. As noted above there were four DOMs for redundancy – which proved to be extremely valuable.

Figure 3 shows an example of various data as a function of time for one SPE threshold setting (level 890) from Phoenix. We refer to a day of year “DOY” starting at 1 for Jan., 2009. We can see clearly that the count rate before pressure correction (figure 3(a), red) is anti-correlation with the pressure (figure 3(b)). If we want data corrected for the pressure dependence, we need to understand the effects of Earth's atmosphere on the data. This can be quite complicated. We explain a technique to correct for pressure in section 3.2. After pressure correction has applied to the count rate, the variation with barometric pressure is no longer apparent. The ship was operating nearby the McMurdo neutron monitor station for 42 days in Antarctica from 3 January 2010-13 February 2010 (DOY 368.189-409.644), so
we think it may be useful to compare Oden IceTop Tank data with McMurdo data as these detectors have the same cutoff rigidity. Figure 3(c) shows the McMurdo count rate corrected for pressure. The short-term and long-term changes at McMurdo will be used to correct the tank data following the methods indicated in [5] and [8]. Figure 4(d) shows the geomagnetic cutoff rigidity for both the vertical cutoff rigidity and apparent cutoff rigidity. We can see that the pressure corrected count rate of the Oden IceTop tank changes inversely with the cutoff rigidity as expected. The ship’s orientation (pitch & roll) was recorded by the clinometers located in the electronics card cage.

3.2. Barometric pressure correction

When the particles pass through the Earth’s atmosphere, they interact with it in the atmosphere. This affects the count rate depending on environmental variables, primarily atmospheric pressure but also on atmospheric structure and composition. One clearly sees the anti-correlation when comparing the count rate from the Oden tank (red) in figure 3 (a) and the data of the barometric pressure in figure 3 (b).

Figure 3. Data from the 2009-2010 Oden IceTop tank latitude survey plotted from day of year (DOY). (a) An example signals at SPE discriminator setting 890 (condition code 19) uncorrected (red: \(C_{un}\)) and corrected (blue: \(C_{p}\)) for barometric pressure at sea level. (b) The barometric pressure in black. Note the inverse relationship with the uncorrected count rate for pressure. (c) McMurdo neutron monitor count rate corrected for pressure as a function of time. (d) Vertical cutoff (blue) and Apparent cutoff (red). (e) Standard deviation of ship pitch (green) and roll (blue) angles in arbitrary units (a.u.).
The corrected count rate can be obtained once we know a pressure coefficient \( \beta \) as a function of apparent cutoff rigidity \( (P_c) \) in GV. The pressure coefficient can in principle also vary with the discriminator setting, so we group a dataset according to the discriminator settings. For each setting, we also group the data for each \( P_c \) bin, i.e., 0-2 GV, 2-4 GV, …, 14-16 GV. We determined \( \beta \) from slope of fitted line of \( \Delta \ln C \) vs. \( \Delta p \) for each setting and cutoff rigidity bin. \( \Delta \ln C \) is the natural logarithm difference between the uncorrected count rate \( (\Delta \ln C) \) and a reference count rate. The pressure difference \( \Delta p \) is the change between the pressure in that time and a reference pressure. The reference data were analyzed for sub-blocks not more than 24 hours on the same day and \( P_c \) changes less than 0.5 GV. We show \( \beta \) determinations from all threshold settings as a function of \( P_c \) bin, as shown in figure 4.

Count rate was corrected to 760 mmHg using the empirical pressure coefficient \( \beta \) in units of percent per mmHg varying with \( P_c \) is apparent cutoff rigidity as determined from Oden latitude survey data:

\[
\beta = 0.2668 - 0.003524 P_c
\]

\[
C_p = C_{un} \exp \left[ \beta (p - 760) \right]
\]

where \( \beta \) is the pressure coefficient calculated from equation (1). \( C_{un} \) and \( C_p \) are mobile IceTop count rates that uncorrected and corrected for barometric pressure, respectively. Note, we apply this pressure correction technique to all thresholds.

![Figure 4](image.png)

**Figure 4.** Pressure coefficient \( \beta \) as a function of apparent cutoff rigidity, \( P_c \). Blue circles (with black error bars), the slopes of \( \Delta \ln C \) vs. \( \Delta p \) from pressure-correction analysis of the IceTop Tank putting together all SPE 47 thresholds and usable MPE 17 thresholds. Black triangle symbols and solid line: the result of standard neutron monitors, which are the ground-based detectors, from 13 latitude survey years of summed data [5].

3.3. **Latitude survey response function**

In this work, we define the response function as the relationship between the count rate of the detector and the apparent cutoff rigidity \( (P_c) \) in units of GV (figure 5).
4. Conclusion
During the survey year 2009-2010, we performed a latitude survey of an IceTop tank that detected secondary particles from GeV energy-range cosmic rays on board the Swedish icebreaker Oden. This study gives us a better understanding of the data that will lead to the improvement of techniques to correct data for barometric pressure. We can also clearly see that the count rate of the IceTop tank strongly depends on changes in latitude similar to those measured by the neutron monitors [5-6]. After pressure correction of the count rate (combination among blue, green, and black), we obtain a smoother response function as shown in figure 5.

Acknowledgements
In addition to the overall support for IceCube, the research is supported in part by Thailand Science Research and Innovation via Research Team Promotion Grant RTA6280002, Research Grant for New Scholar MRG6280155, and United States National Science Foundation Award OPP0838838. Support from the Swedish Polar Research Secretariat for the opportunity to use the icebreaker Oden and special funding from the Swedish Research Council for associated costs (Project Oden Southern Ocean 2009-2011) is gratefully acknowledged.

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Figure 5. Examples count rate as a function of $P_c$ for the four transitions between low and high cutoff rigidity. The grey is an uncorrected count rate recorded by the IceTop tank at specific discrimination setting 890 (condition code 19). The green and blue are the count rate after the pressure correction of the southbound and northbound trips while the black showed the count rate when the ship was located near McMurdo, Antarctica ($P_c = 0.1$ GV).