In-flight Performance of the Super-TIGER Cherenkov Counters

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Abstract: The Super-TIGER (Trans Iron Galactic Element Recorder) balloon payload completed its first flight from Antarctica (Dec 9, 2012-Feb 2, 2013). The instrument is designed to address the question of the sources of cosmic rays by precisely measuring the abundances of elements heavier than iron in the galactic cosmic radiation with high statistical accuracy and single charge resolution in the range 30$\leq Z \leq$ 42. In addition, it will provide exploratory charge measurements up to $Z = 56$. Super-TIGER has an effective geometrical acceptance that is 6.4 times larger than its predecessor TIGER. The first Super-TIGER flight recorded over 67.8 million CR events transmitted to the ground via TDRSS.
For the charge identification of incident cosmic rays, the Super-TIGER instrument employs three layers of plastic scintillator, which can also reject interacting events in the detector, and two light-diffusion Cherenkov counters, one with an acrylic radiator ($n = 1.49$) and the other with a silica-aerogel radiator ($n = 1.043$ and 1.025). Each Cherenkov counter has an aperture of 118 cm x 240 cm and is 20 cm tall, is lined with highly reflective Gore-Tex, and is viewed by 42 5-inch Hamamatsu R877-100 photomultiplier tubes. In addition to a Z^2 charge response, the Cherenkov counters also provide velocity information and allow for spectral information of the more abundant elements. A set of two orthogonal scintillating fiber hodoscope layers at the top and bottom of the stack provides position information allow for detector mapping and angle correction.
In this paper, we will discuss the design of the two Cherenkov counters for Super-TIGER and demonstrate their in-flight performance. A general overview of the Super-TIGER instrument, 2012 Antarctic flight, the scintillating fiber hodoscope, and the scintillator counter will be given elsewhere at this conference.

Keywords: Super-TIGER, Galactic Cosmic Rays, OB associations, Cherenkov, Cerenkov, Silica Aerogel

1 Introduction

The Super-TIGER (Trans-Iron Galactic Element Recorder) experiment is a long-duration balloon-borne instrument that launched on December 9, 2012 from Williams Field, near McMurdo Station, Antarctica, and flew for 55 days. The objective of Super-TIGER is to measure the abundances and energies of Galactic Cosmic-Ray nuclei with atomic number Z in the range $30 \leq Z \leq 42$, as well as obtaining preliminary measurements up to Z = 56. The precise measurement of the abundances of ultra-heavy elements ($Z \geq 30$) is a sensitive probe of the origin of Galactic Cosmic Rays.

Super-TIGER is comprised of two nearly-identical independent modules. Each module consists of three plastic scintillator planes that measure dE/dx for charge measurements; two scintillating fiber hodoscopes, to track the trajectories of particles; and two Cherenkov Counters for charge and energy measurements. The Cherenkov counters have radiators with different indices of refraction−an acrylic radiator ($n = 1.49$) for the bottom (C1) counter, and aerogel ($n = 1.043$ and 1.025) for the top (C0) counter. A detailed discussion of the Super-TIGER instrument [1], preliminary results [2], scintillator charge detectors [3], and scintillating fiber hodoscope [4] will be presented elsewhere at this conference.

The Super-TIGER Cherenkov counters are used for identifying the charge and energy of Cosmic-Ray particles that pass through the experiment. For events with energy below the C0 threshold (2.5 GeV/Nucleon or 3.3 GeV/Nucleon, depending on the index of refraction n of the aerogel), these are determined by a combination of C1 and the scintillator signals. Above the C0 threshold, C1 and C0 are used.

2 Description of the Cherenkov Counters

Each Cherenkov counter has an aperture of 118 cm × 240 cm and is 20 cm tall. For ease of handling during integration and recovery operations, each Cherenkov box can be split into two half-modules. Each Cherenkov counter uses 42 Hamamatsu R877-100 5-inch diameter photomultiplier tubes (PMTs). All inside surfaces of the counters are covered with a layer of 0.25 mm-thick high reflectance GORE^{TM} DRP material. This material has a reflectivity of

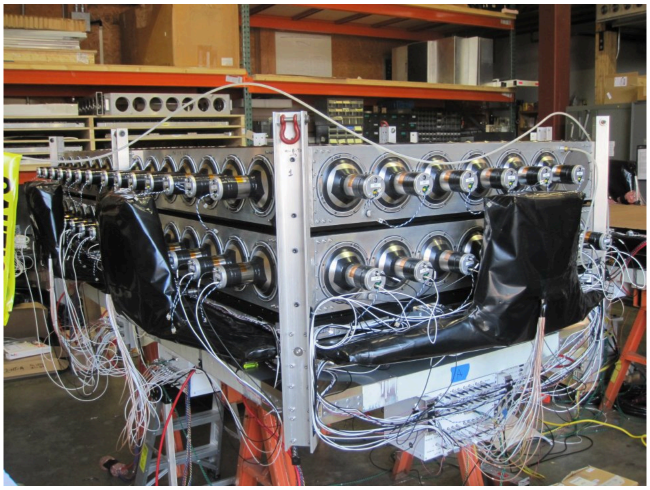

Figure 1: Super-TIGER Cherenkov Counters after installation in the detector stack. The Aerogel (C0) counter sits above the Acrylic (C1) counter

better than 93% and is a nearly Lambertian surface, which is isotropizing for directional Cherenkov light. The combination these two properties of the reflective lining maintains a uniform and position-independent detector response (¡25% for the acrylic C1) within this large-area counter. The Cherenkov radiators sit on a ultra-low-density composite closed-cell Polymethacrylimide (Rohacell 31 IG) substrate with 0.1mm Aluminum face sheets, chosen to reduce the probability of cosmic-ray particles interacting within the instrument. Figure 1 shows two Super-TIGER Cherenkov counters after being installed in one module of the detector stackup. The Super-TIGER Cherenkov counter design concept (light integration box and choice of radiators) was based on the Cherenkov counters successfully utilized in the TIGER experiment [5]. Each Super-TIGER module is approximately twice the size of the TIGER experiment.

The radiators for both the acrylic and aerogel counters are mounted on the lower support substrate. In the Aerogel (C0) counter, 4 blocks of aerogel with nominal dimensions of 55 cm $\times$ 55 cm, each 3 cm tall, are placed in a 2 $\times$ 2 array to form the radiator for each half-module. The Super-TIGER aerogel blocks were purchased in the early 1990s from Airglass AB in Sweden, and were maintained in a protective-dry nitrogen storage environment until installation in the experiment. To improve light yield, each aerogel block was baked at high temperature to eliminate any absorbed aerosol materials or remaining interstitial alcohol, using a technique originally developed for the IMAX experiment [6]. To protect the aerogel blocks from potential stresses due to deformation of the counter or shock during launch, landing, and recovery, each block was placed on a thin composite pallet covered in the same GORE^{TM} DRP used to line the inside of the counter. These blocks are held in place on the pallets by a layer of low-density UV-transparent polyethylene terephthalate, using a technique adapted from the BESS/BESS-Polar experiment [7] [8]. Three of the four half-modules used aerogel blocks with index of refraction $n = 1.043$ (12 blocks total), while the remaining half-module used blocks with index of refraction $n = 1.025$. The Cherenkov energy thresholds for the aerogel half-modules are 2.5 GeV/Nucleon and 3.3 GeV/Nucleon, respectively.

In the Acrylic (C1) counters, the radiators are 116 cm $\times$ 116 cm sheets of 1.28 cm-thick UV-transparent acrylic in each half module. These radiators which were cast by Spartech/Polycast, had a bis-MSB wavelength shifter dye added (25mg/L). This material has an index of refraction of $n = 1.49$, giving a Cherenkov energy threshold of 0.3 GeV/Nucleon. The wavelength shiter provided additional isotropization of the wavelength-shifted Cherenkov photos. Furthermore, the top and sides of the radiators were soda-blasted to eliminate total internal reflection on those surfaces and allow the Cherenkov photons to leave the radiator and be diffused in the light-integration box.

Figure 2: One Aerogel block being installed in the Super-TIGER C0 counter.

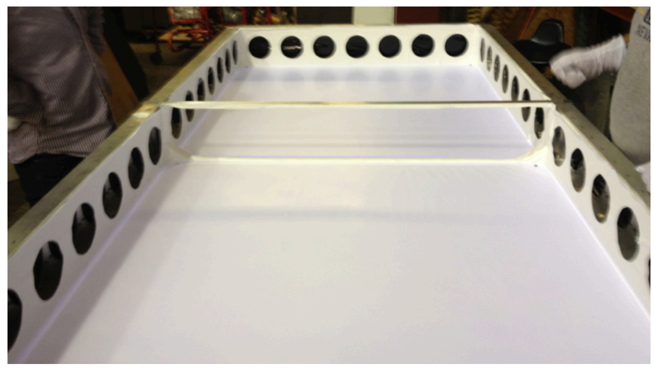

Figure 3: One of the Acrylic radiators installed in a Super-TIGER Cherenkov Counter.

Each counter uses a total of 42 5-inch Hamamatsu R877-100 high quantum-efficiency PMTs. To reduce the effects of the geomagnetic field on PMT gain, a light-weight μ-metal shield is wrapped around each PMT. These custom shells were hydro-formed out of 0.14" mu-metal by Amuneal. In addition, these shells also served mechanical mounting flange to the counter box and provided the ambient light seal to the counter volume. These PMTs are mounted from the outside into circular cutouts in the side walls, with 7 mounted on each short side and 14 mounted on each long side of each rectangular module. The gain of each PMT can be adjusted with the use of a High Voltage (HV) trim circuit. The nominal flight voltages of each PMT were set individually and chosen based on the results of gain-curve characterizations to normalize signals throughout the counter. During flight, these voltages ranged from 950V to 1200V. In the C1 counters, each PMT is attached to a 1250V EMCO CA12P HV supply. In the C0 counters, the

PMTs on the short sides of the rectangular box are attached to CA20P 2000V HV supplies.

On each C0 long side, from left to right the PMTs alternate between being attached to 1250V supplies and 2000V supplies. This distribution of PMTs was designed to ensure a graceful degradation of data quality in the event of a HV supply failure. Initially, all Cherenkov HV trim circuits used 2000V supplies, but HV board failures during a thermal-vacuum test at NASA's B-2 facility at Plum Brook Station prompted replacing 16 of the 24 2000V supplies with more reliable 1250V supplies. Each HV supply powers 7 PMTs.

The dynamic range requirement for the Super-TIGER Cherenkov PMTs was determined with the help of a Geant4 Monte Carlo computer simulation [**?**]. In order to meet Super-TIGER's science objectives, we require single-charge resolution over the range $10 \leq Z \leq 60$. Since the light produced in the Cherenkov counters scales as Z^2 and also varies with the energy of the particle, this required a large dynamic range. To meet these requirements and ensure a linear PMT response over the entire range, strongly tapered voltage dividers were developed. An integrated charge-sensitive preamplifier was included in the base of each PMT. These bases allowed the Super-TIGER PMTs to detect from 10 to 200,000 photoelectrons with only a 2% non-linearity over that range. In flight, for Fe ($Z = 26$) nuclei, the acrylic counters detected approximately 30,000 photoelectrons while the aerogel counters detected approximately 4300 photoelectrons. This is outstanding performance for such large-area detectors.

In addition, each PMT signal channel was read out using two separate readout circuits, one with a high-gain amplifier and one with a low-gain amplifier. Each of these signal channels was read out using a 16-bit analog-to-digital converter (ADC). However, data telemetered via the TDRSS network sent only one of the two signal channels for each PMT, and that signal was compressed to 15 bits of resolution with a single bit indicating whether the high or low gain channel was sent down. Due to the failure of the Intel 320 series Solid State Drives (SSDs) used to store Super-TIGER data events on board, this lower-resolution TDRSS data will be used for the bulk of the data analysis.

3 Charge and Energy Determination

Both of the Super-TIGER Cherenkov counters are used in the determination of the charge Z and energy of cosmic rays. For particles with energy below the C0 threshold, the C1 signal is combined with signals from the scintillation counters, described in [3]. Since the C1 signal scales as Z^2 while the scintillator (S1 + S2) signal scales as roughly $Z^{1.7}$ (due to saturation and other effects [3]), plotting the square root of the C1 signal against the 1.7th root of the scintillator (S1) signal gives well-defined charge bands showing a clear separation between elements. Figure 4 shows these charge bands for below-C0 events. In this range, the acrylic Cherenkov response also provides an energy measurement.

Above the C0 threshold, the charge and energy of cosmic-ray particles can be measured using only the C1 and C0 signals. Similar to the below-C0 events, plotting the two signals against each other gives well-defined charge bands, as shown in Figure 5. Above C0, the charge resolution is primarily governed by the C1 signal while the energy resolution is primarily governed by the C0 signal, but both are necessary for the measurements. The C1 vs. C0

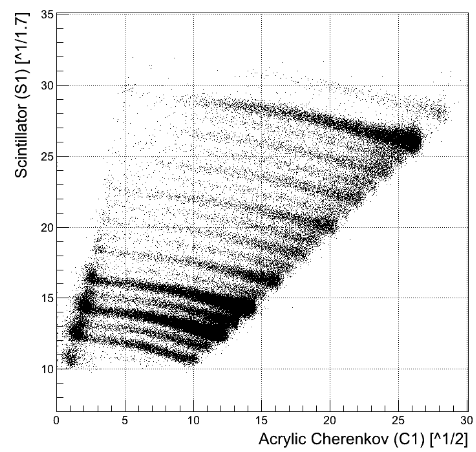

Figure 4: Charge identification method for events below the C0 energy threshold, plotting Scintillator signal vs C1 signal.

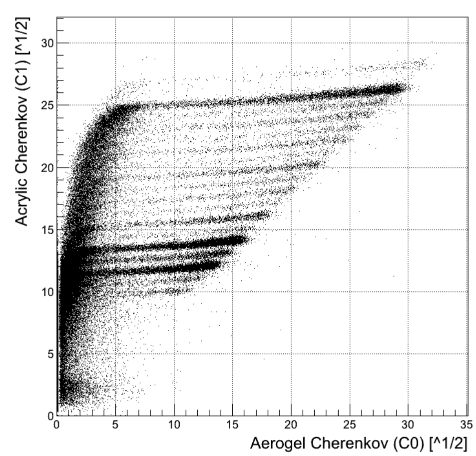

Figure 5: Charge identification method for events above C0 energy threshold, plotting C1 signal vs C0 signal.

technique provides better charge resolution than the (S1 + S2) vs. C1 technique because the Cherenkov signals have a pure Z^2 dependence. This charge resolution is discussed in [2].

4 Area Correction Maps

Area correction maps were generated to normalize the signals of PMTs for particles throughout the counter so that all events can be properly identified. These maps were generated using events determined to be Iron ($Z = 26$) at zenith angles of less than 0.8 radians. These particles provide sufficient information about the position-dependent responses of each PMT to be used as an effective map. Area correction maps were generated using a 2 cm $\times$ 2 cm grid, with positions determined by the scintillating fiber hodoscope (described by [4]). The spatial response maps generated with flight data are consistent with those generated in the Geant4 Monte Carlo simulation discussed in [**?**] when applying the same analysis techniques. Figure 6 shows an

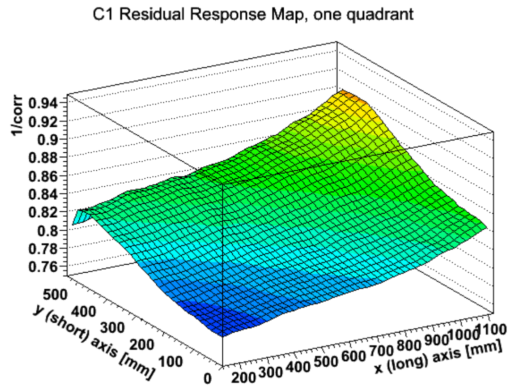

Figure 6: Sample area response map for one half-module of the C1 counter. The response maps derived from flight data are consistent with the maps generated by the Geant4 simulation discussed in [**?**]

example map for a half-module of the C1 counter. Overall, the Cherenkov counters worked very well and contributed to the excellent charge resolution discussed in [2], even at this preliminary stage of the data analysis.

5 Conclusions

The Super-TIGER Cherenkov counters performed successfully throughout the 55-day 2012-13 flight of Super-TIGER and will play an integral role in the data analysis.

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