Warren J. Baker Endowment *for Excellence in Project-Based Learning*
Robert D. Koob Endowment *for Student Success*

Towards Radio Frequency Detection of High-Energy Neutrinos & Cosmic Rays

I. Abstract

High-energy cosmic rays and neutrinos traveling from the distant universe interact with the earth's atmosphere and magnetic field, producing detectable signals at radio frequencies. This principle was experimentally proven by the SLAC National Accelerator Laboratory in 2014 [1], and the data was used to validate and calibrate ANITA (ANtarctic Impulsive Transient Antenna), an experiment searching for cosmic rays and neutrinos over Antarctica [2]. Two biconical antennas used in these experiments were brought to Cal Poly by Dr. Stephanie Wissel, physics professor and member of the ANITA team. Under her guidance, as well as that of Dr. Dean Arakaki, Cal Poly EE professor and antenna expert, I will be characterizing the two biconical antennas by taking radiation patterns, S-parameters, and impulse response tests, both in an anechoic chamber and in a specially designed outdoor setup. These tests will provide the antenna parameters that will allow me to analyze the data collected by ANITA for evidence of ultra-high-energy neutrinos and cosmic rays.

II. Introduction

Neutrinos are elementary particles that interact very weakly with other particles of matter. Owing to the weak interaction, high-energy neutrinos produced by extremely distant sources can reach Earth unimpeded, carrying with them information about cosmic events far off in our universe. However, because they interact so rarely, direct detection of these particles is difficult. This project focuses on one of the most promising neutrino detection techniques, radio detection. When high-energy cosmic rays and neutrinos reach the atmosphere, they produce a cascade of charged particles. Currents created within this particle shower generate coherent radio-frequency radiation [3], and the strength and polarization of this radiation is influenced both by the total charge of the shower and the Earth's magnetic field. These impulses can be picked up by specialized antennas, the characterization of which is the goal of this project.

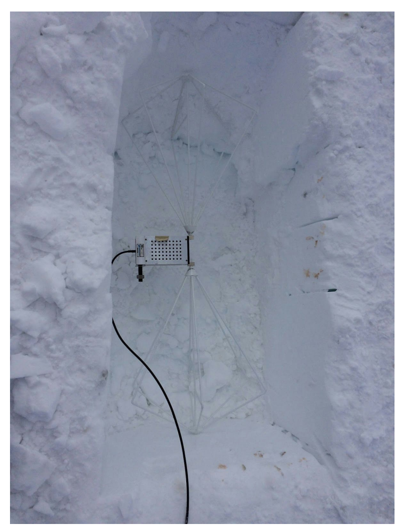

Fig. 1: Bicone antenna embedded in Antarctic ice for testing of ANITA III

The bicone antennas to be characterized have been used in two experiments related to neutrino detection. The SLAC T-510 Experiment measured magnetically-induced particle showers in a high-density polyurethane. This simulated high-energy cosmic rays inducing particle showers in the atmosphere [1]. ANITA, the second experiment, uses a balloon carrying an array of horn antennas to detect these showers over Antarctica [2]. The bicone antennas used in this project were used in 2014 to calibrate ANITA III from the ground when the instrument was in flight.

However, the bicone antennas have not yet been characterized independently. Both experiments used simulated models of the antennas, but it is common at these frequencies for antennas to vary significantly from simulation results. Without an established baseline of the antennas' response, it is impossible to conclusively analyze the data from the two experiments.

III. Objective(s)

1. Measure the bicone antennas radiation patterns, S-parameters, and impulse response.
2. Use the measurements to find the effective height, gain, and electric field of the antennas.
3. Use the measured antenna parameters, analyze the data from the SLAC T-510 and ANITA experiments.
4. Present results at the October 2016 Annual Meeting of the Far West Section of the American Physics Society

IV. Methodology

1. Establish antenna test set-up

The bicone antenna frequencies range from 30 MHz to 1 GHz. The Cal Poly ElectroMagnetic Compatibility (EMC) Chamber Lab is rated to a minimum radio frequency of about 100 MHz, making it useful only for frequencies above that limit. To accommodate for this, I will be setting up an additional, outdoor antenna test system to measure frequencies from 30 MHz to 100 MHz.

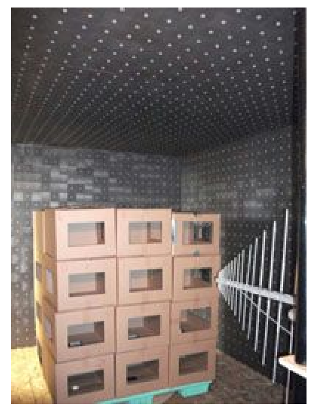

Figure 2: Cal Poly ElectroMagnetic Compatibility (EMC) Chamber Lab

2. Acquire antennas characterization data

Antennas can be characterized in a variety of ways, because their response is dependent on their design as well as the frequency and direction of the signal. In order to fully understand the performance of these antennas, I will be running tests on multiple parameters. These tests will include:

- S-parameters – measure the amount of signal loss present in the antennas
- Radiation Patterns – measure the antennas' response as a function of the direction of the incoming signal
- Impulse responses – measure the antennas' response to a short signal pulse

Much of the necessary equipment (pulsars and Vector Network Analyzers) are available from Dr. Wissel's Physics Lab and Dr. Arakaki's EE Lab. However, I will need to rent an oscilloscope suitable for these tests' frequencies.

3. Analyze data to establish baseline antenna characteristics

The data collected in the above tests can be analyzed to find important characteristics, including gain and effective height, and will result in a complete electric field plot of the bicone antennas. After this experiment, their response will be fully characterized over their entire frequency range.

4. Use the biconical antenna parameters to analyze SLAC T-510 data

Previously, experimental data analysis relied on simulated characterization. By comparing data measured in T-510 to model predictions, we can verify previous conclusions, as well as establish a better basis of what to look for in terms of neutrino and cosmic ray air showers.

V. Timeline

Feb. 29 – Begin ordering test equipment
By March 11 – Finish setup of new equipment and positioning systems and begin taking data
March 14 - April 4 – Measure and graph antenna S-parameters, radiation patterns, and impulse response from 100 MHz-1GHz in the anechoic chamber
April 4-11 – Establish and test an outdoor setup for antenna measurements below 100 MHz.
April 11-25 – Repeat tests from 30 MHz-100 MHz.
April 25 - May 9 – Analyze data, establish antenna performance, and compare data to that of simulated antenna models used in SLAC T-510 and ANITA experiments.
May 9 - June 11 – Use the measured antenna characterizations, collaborating with SLAC T-510 and ANITA teams, to analyze the VHF T-510 data and characterize the observed radio emission from particle showers in a magnetic field.
Sept. 22 - Oct. 27 – Finalize results and prepare presentation.
Oct. 28-29 – Present work at APS Conference.

VI. Final Products and Dissemination

The final project will be a presentation of the work at the 2016 Annual Meeting of the Far West Section of the American Physics Society (APS). The conference will be held on October 28-29th, at University of California Davis.

VII. Budget Justification

- **<u>Travel - In-state:</u>** To APS Conference at UC Davis
  $300 - 2 days in Davis, CA, including hotel room for 2 nights
  $56 - Amtrak ticket
- **<u>Operating Expenses:</u>**
  $799.96 - 5300-11 Seco Hardwood/Fiberglass Tripod from Tiger Supplies to mount antennas for accurate positioning during outdoor tests (2 at $399.98 each)
  $274.95 - G450A Antenna Rotator from Ham City to accurately measure positioning angle
  $102.58 - 1,000 ft of RG-58/AU Coaxial cable from Cable Wholesale to be used as a trigger cable during outdoor tests
  $50 - Mounting supplies to attach antennas on tripods
  $50 - RF cables and adapters from Mini-Circuits and RF Depot
  $92.31 - Shipping Costs: $9.31 for cables, $23 for tripods, $35 for oscilloscope, $25 misc. for mounting supplies
- **<u>Contractual Services -</u>**
  $772.50- 1 Month Rental of a Tektronix MSO5204 Mixed Signal Oscilloscope from Microlease. The 2 GHz, 5 GSPS Oscilloscope is ideal for the bicone antennas, and is essential to receiving and analyzing signals transmitted to the antennas.

Student Applicant: Caroline Paciaroni	**Project Title: "Towards Radio Frequency Detection of High-Energy Neutrinos & Cosmic Rays"**
Faculty Advisor: Dr. Stephanie Wissel	**Requested Endowment Funding:** **$2,483.30**
Travel	**$356**
In-state: APS Conference, UC Davis	**$356**
Operating Expenses	**$1354.80**
Non-computer Supplies & Materials	**$1277.49**
Shipping Costs	**$77.31**
Contractual Services	**$772.50**
Equipment Rental	**$772.50**

VIII. References

[1] K. Belov, K. Mulrey, A. Romero-Wolf, S. A. Wissel, and A. Zilles, et al (The T-510 Collaboration) "Accelerator measurements of magnetically induced radio emission from particle cascades with applications to cosmic-ray air showers", Phys. Rev. Letters, in press, Jan 2016.
[2] P. Miočinovič, *et al.* (ANITA Collaboration), "Tuning into UHE Neutrinos in Antarctica - The ANITA Experiment" in 22nd Texas Symposium on Relativistic Astrophysics at Stanford University, 13-17 December 2004.
[3] G. A. Askaryan, "Coherent Radio Emission from Cosmic Showers in Air and in Dense Media. Soviet Journal of Experimental and Theoretical Physics, 21:658, September 1965.

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January 31, 2016

Michael D. Miller
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To Michael Miller and Members of the Baker / Koob Endowments Committee,

I write to you in support of Caroline Paciaroni's proposal. While I have not been on the faculty here long, Caroline Paciaroni embodies for me the "Learn by Doing" spirit, being a creative and independent researcher. I whole-heartedly endorse this project.

The measurement Caroline proposes to make will likely lead to a publication (in *Physical Review D* or a similar journal), as it will be the first measurement of its kind. She proposes to first calibrate of a pair of VHF antennas that were used in an experiment (called T-510) at the Stanford Linear Accelerator Center (SLAC). She will use that calibration to analyze data from the T-510 experiment. Her analysis will be the first direct, laboratory measurement at VHF frequencies of radio emission relevant for the detection of the highest energy cosmic rays and neutrinos. The spectral information and sky maps produced by detecting such high-energy particles have implications for the most extreme astrophysical environments in the universe.

Caroline has a clear vision of her plan. This is reflective of her qualities as a researcher: she first ensures that she understands all aspects of a problem and then formulates a plan to address the problem. One of the primary challenges of her proposed project is that none of the three anechoic chambers here on campus are rated for VHF (<100 MHz) measurements. Faced with this challenge, Caroline suggested a two-pronged approach: start by making measurements in the higher frequency portion of the band (100-1000 MHz), while identifying places for outdoor antenna ranging on campus. Few early-career graduate students are capable of such careful planning. Based on the work she has done in the past, I expect that she will use her superior judgement and lab skills to perform this important study.

Sincerely,

Stephanie Wissel
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