Spring 4-28-2020

# Measurements of Radio Pulse Reception with Stations of the ARA Experiment based on the SpiceCore Pulser Data Set

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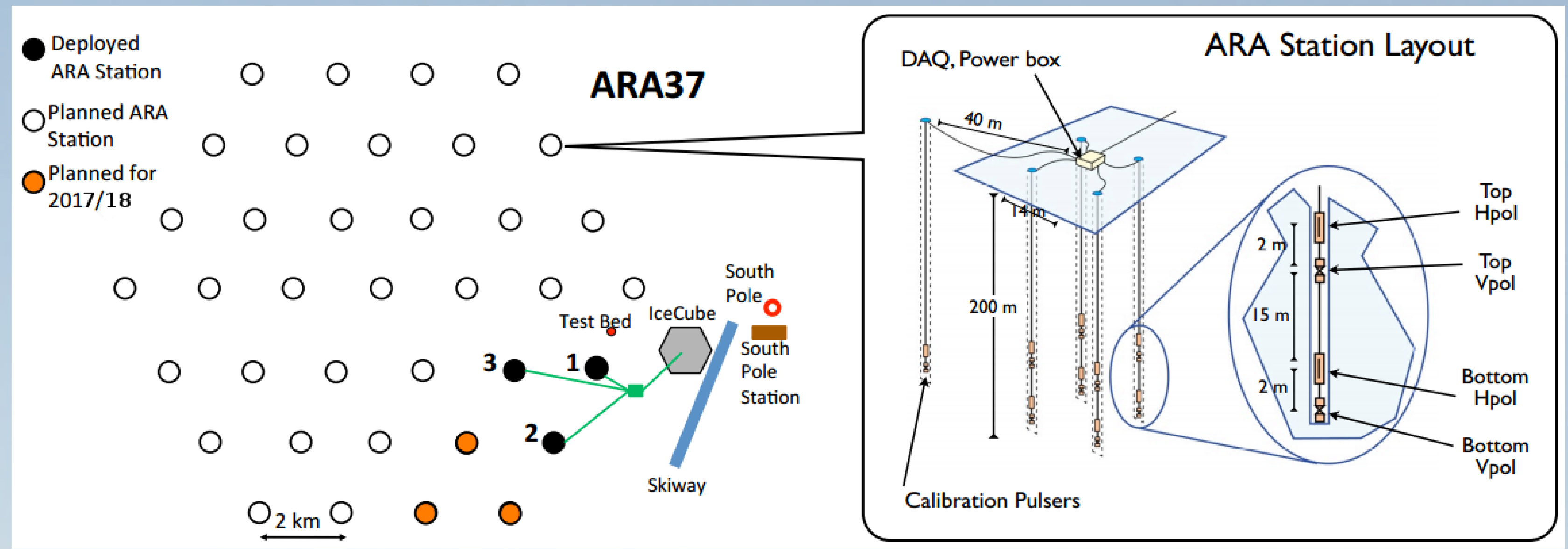
## Introduction

The Askaryan Radio Array (ARA) is a large-scale detector at the South Pole concerned with the measurement of ultra-high energy (UHE) neutrinos and their flux here on Earth through the Askaryan Effect. The ARA detector currently consists of 5 stations, each consisting of 16 radio antennas (or channels) submerged 200 meters in the Antarctic ice. Studying UHE neutrinos allows testing of various theories that cannot be tested in any other way and provides a means to studying processes occurring far beyond our solar system.

In Dec 2018, over eight days, a calibration data set was recorded by the ARA stations while a transmitter broadcasting narrow radio pulses was lowered into the polar icecap using a 1700 meter deep hole made by the SpiceCore project. This research focused on analysis of this SpiceCore data set.



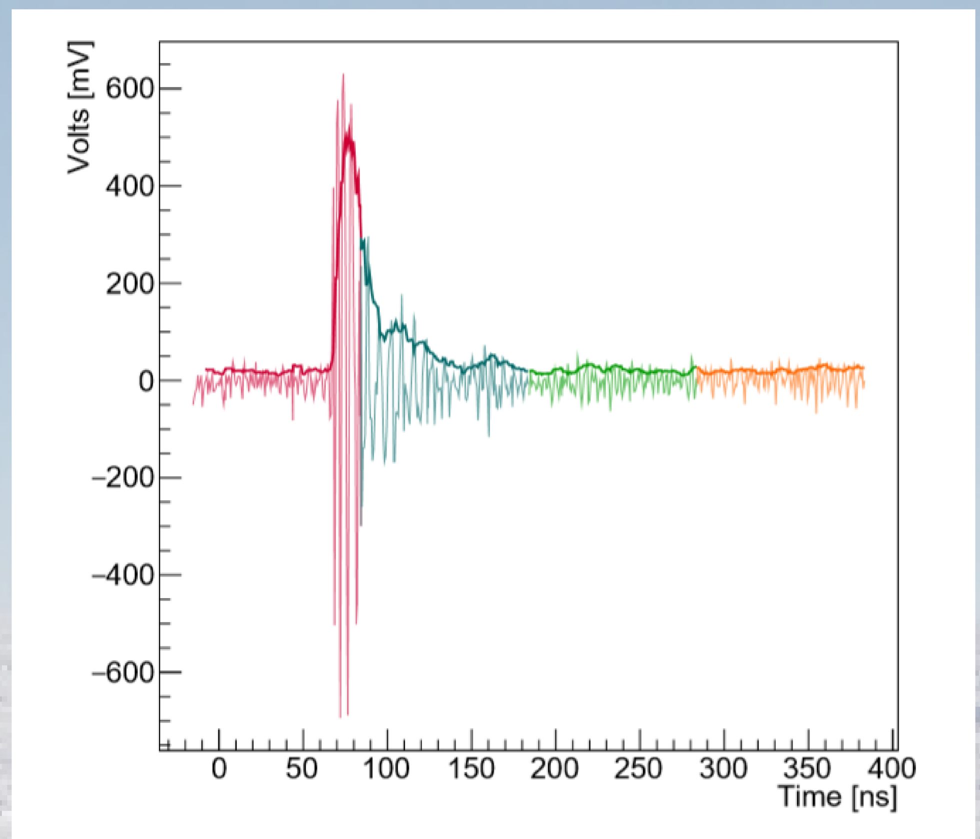

## Importance

Due to the bending of radio waves propagating close to the surface of the ice, a phenomenon occurring due to the dependence of the index of refraction on depth, radio waves are not able to propagate from certain regions of space, so called "shadow zones," to the receiving ARA stations, according to classical linear optics. It has been observed at ARA, however, that the classical picture is violated in practice. Although a shadow zone does exist, it is smaller than what theory predicts. Analysis of the SpiceCore data can be used to map shadow zones in the ice and compare it to classical theory predictions. Robust understanding of these shadow zones will aid in detection of UHE neutrinos.

## Methods

In the SpiceCore data set, events induced by the transmitter have a characteristic signature of two pulses, corresponding to the direct electromagnetic wave propagation to the station recording as well as the propagation with reflection from the surface. This signature can be used to identify SpiceCore events from among normal events recorded by the stations at the same time. SpiceCore events are identified by analysing the first eight channels of a station for each recorded event during the time when the transmitter was active. The procedure was:

1. Break the envelope of a waveform into four quadrants
2. Threshold level for each waveform is equal to 16.0 times the average mean voltage value of the two smallest envelope quadrants (noise level)
3. An excursion is any number of sequential points above this threshold level
4. A SpiceCore event is any event where four of the first eight channels had at least two excursions.

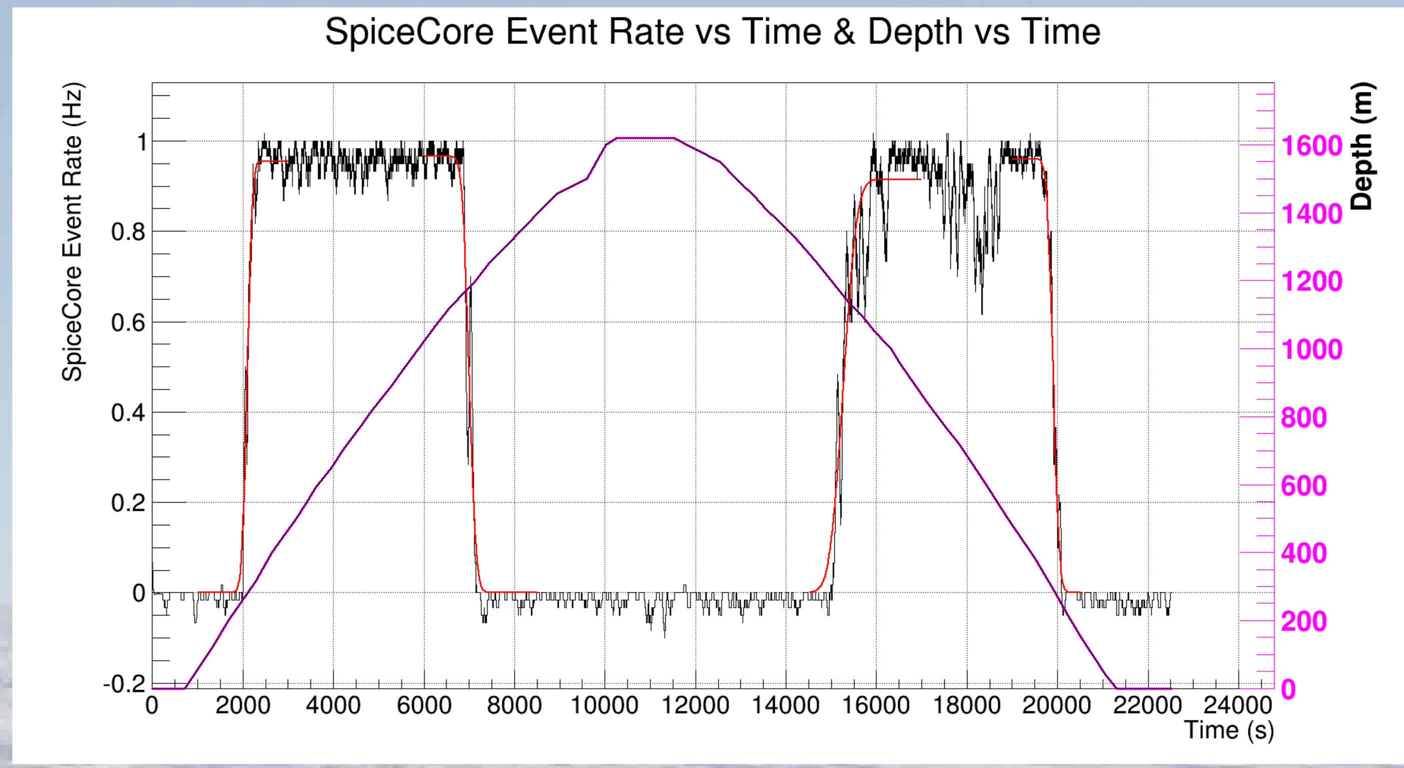



An example of a waveform envelope is illustrated in the figure above. Using this envelope, SpiceCore events can be automatically distinguished from other event types. However, from certain regions of the ice, the two distinct SpiceCore pulses can become so close together, that they are indistinguishable from a single single pulse to the software, and they appear to be another type of calibration data, Calpulser events. These events are tagged in their data files, which allows for the "single pulse" SpiceCore events to be successfully identified.

## Results

The figure below is an overlay of two graphs made using data from the Dec 26 data run. The first (in purple) is the depth of the SpiceCore radio transmitter versus time. The second (in black) is the rate of SpiceCore events, found by looking at the past 60 seconds of data, versus time. This graph has two prominent regions of time during which SpiceCore events were recorded by the ARA station, between an upper and a lower shadow zone as the transmitter was dropped down into the SpiceCore hole and pulled back up to the surface.

By fitting both sides of both regions with an error function (in red), the times at which the transmitter left or entered one of the two shadow zones were determined. Along with the depth vs time graph, the approximate boundary depths of these shadow zones were determined to be 280.3 (1) / 290.4 (1) m for the upper shadow zone which runs to the surface and 1154.2 (2) / 1236.6 m for the lower shadow zone which runs to the ice floor.




## Conclusions

Using the methods described, measurements of shadow zone depths can be made for each day of SpiceCore data, and they can be compared to simulated shadow zone depths. Each day of data can also be compared based on what type of radio transmitter was used, as well as the specific settings of the ARA data acquisition system, to see whether the shadow zone boundaries depend on any of those parameters.