Simulation Study of the Observed Radio Emission of Air Showers by the IceTop Surface Enhancement

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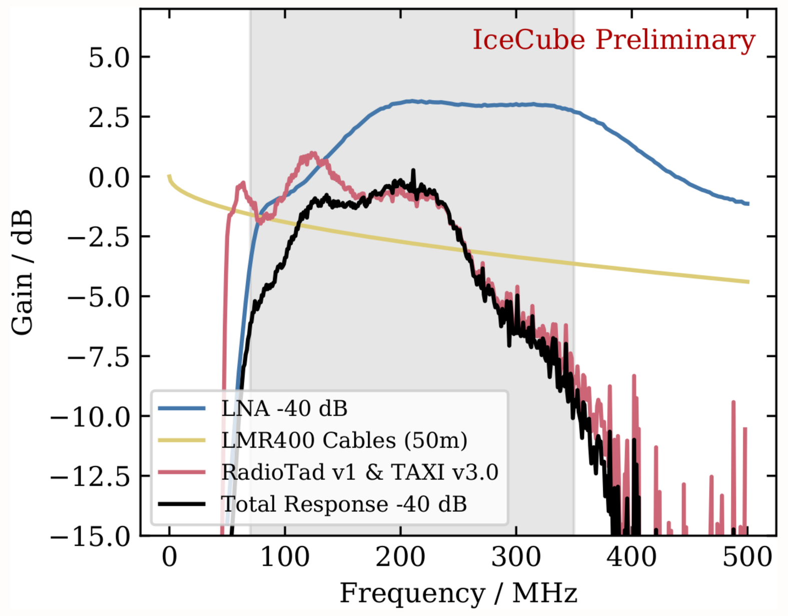
Air Shower Simulation

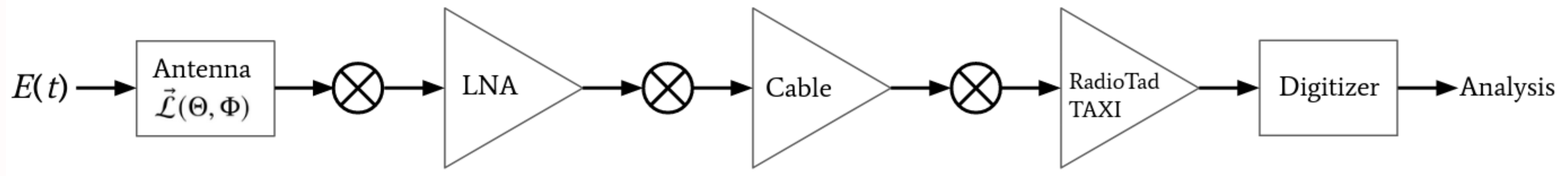
IceTop, the cosmic ray detector of the IceCube Neutrino Observatory, is located on the ice at the South Pole. It will be enhanced by adding scintillator panels and radio antennas. The antennas, most relevant for this work, will allow us to make calorimetric measurements of the electromagnetic energy of air showers and the depth of shower maximum, Xmax. We performed a simulation study of the array to characterize its performance, once completed.

The first step is to include the detector response to the electric fields calculated using the CoREAS simulation code. The electric fields are folded with all relevant hardware:

- Antenna response model, simulated (50-350 MHz)
- Low noise amplifier, simulated
- LMR400 cables, 50 m, measured
- Analog amplifiers/filters and digitizer, measured



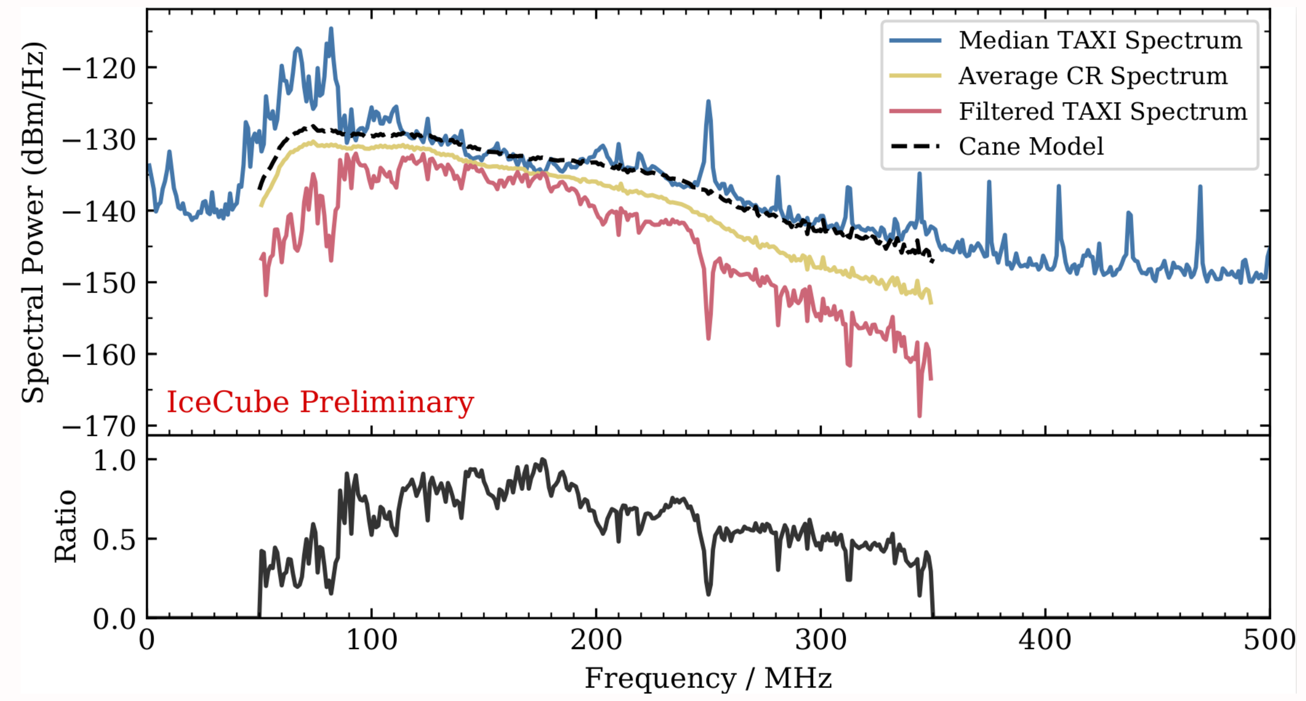
The responses as a function of frequency are shown above. The response of the low-noise amplifier (LNA) and the total response have been shifted downward by 40 dB for visual clarity.



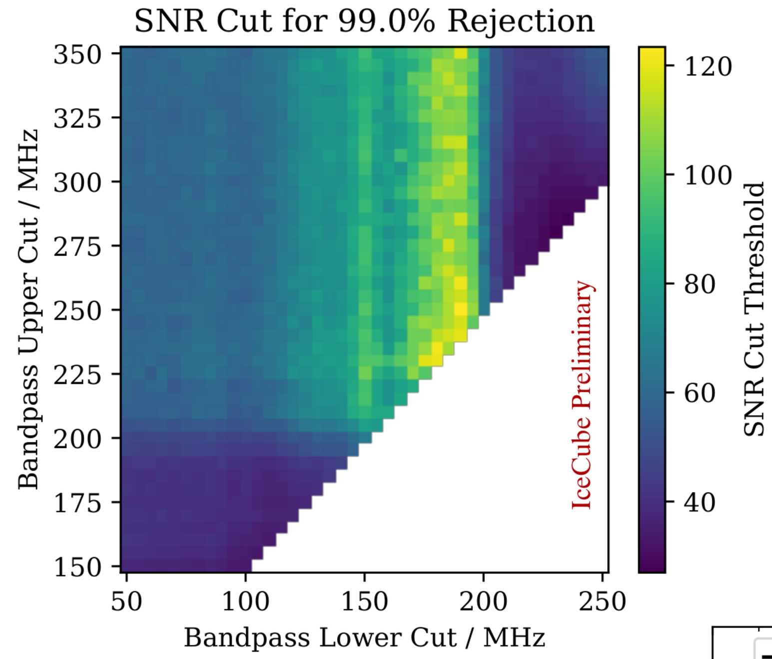
Background Noise Filters

All radio measurement have to contend with the background emission both from radio-frequency interference (RFI) and diffuse emission from extra-terrestrial sources. The background frequency spectrum, as measured by the prototype station at the Pole, is shown below in blue. The general amplitude is consistent with diffuse emission from (extra)galactic sources, as described by the Cane model. There are additional RFI peaks at, for example, 250 MHz.

We constructed a frequency-weighting method to remove these RFI peaks using the average CR frequency spectrum, after convolving the response of the electronics. The weights are given by the ratio of the CR frequency spectrum with the local background.



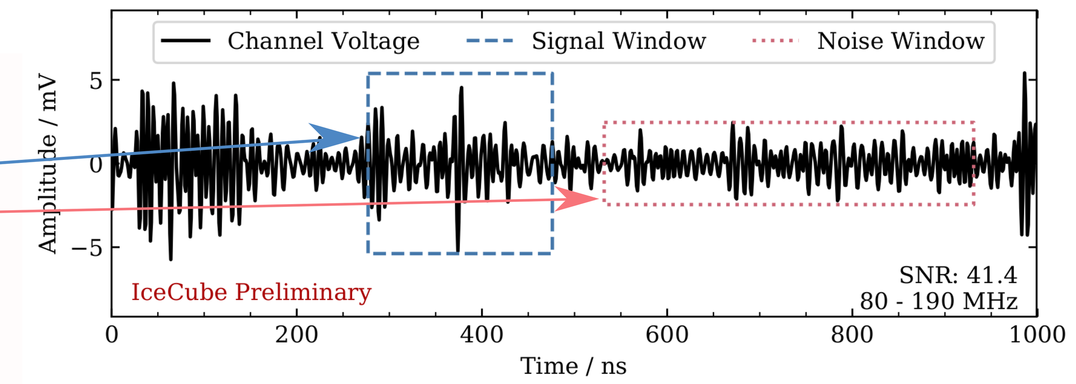
Background Pulse Cut



After applying the frequency weights, we studied the remaining RFI pulses using 10k background waveforms taken at the Pole.

- Randomly choose a 200 ns signal window and a non-overlapping 400 ns noise window
- Calculate the signal-to-noise-ratio (SNR) using a range of frequency bands
- Choose the SNR threshold which rejects 99% of background waveforms for each frequency band
- Add simulated air-shower pulses. Choose the band for which the most antennas pass the SNR cut. We found: 85 - 190 MHz

$$\mathrm{SNR} = \left(\frac{\text{Signal Peak}}{\text{Noise RMS}}\right)^2$$

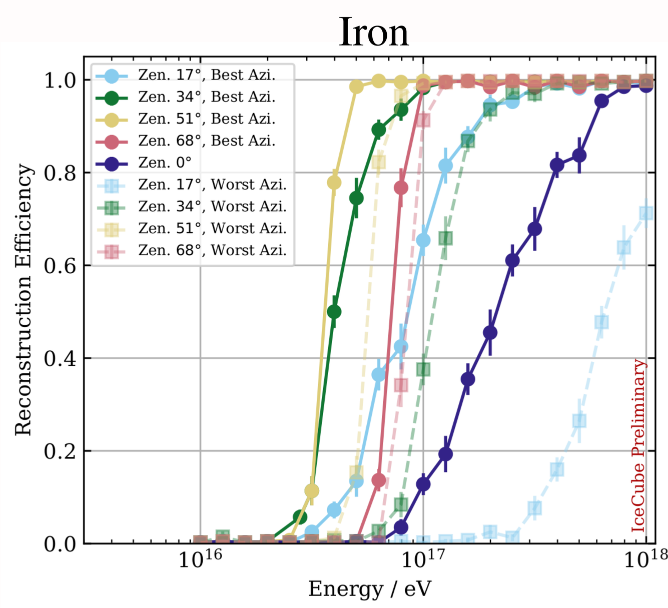


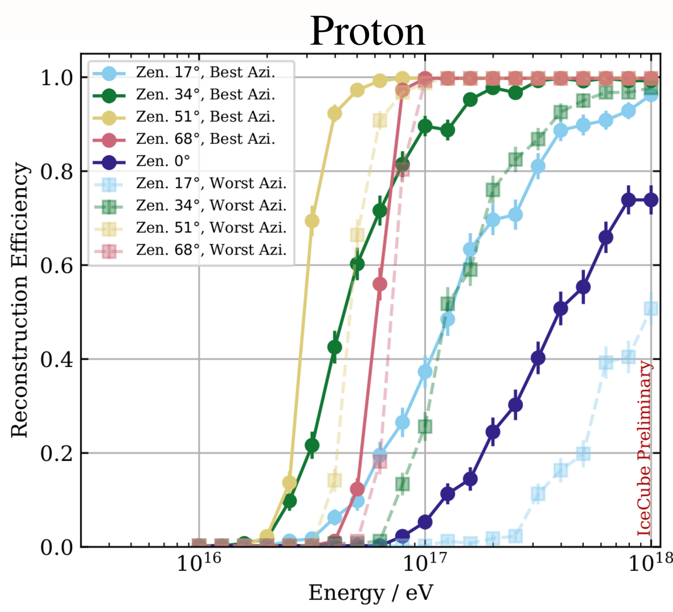
Reconstruction Efficiency

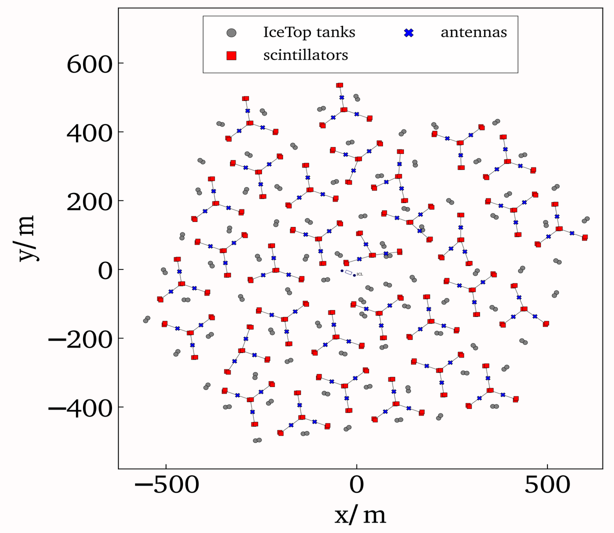
Used a library of proton and iron air-shower simulations
- Sibyll2.3d, South Pole April atmosphere
- Azimuth angles chosen to maximize/minimize geomagnetic angle
- Zenith angles spaced 17 deg
- Cores chosen randomly in a circle with 400 m radius

SImulated external scintillator trigger
- Require >0.5 MIP signal in >2 panels to trigger a station
- Only use waveforms from triggered stations

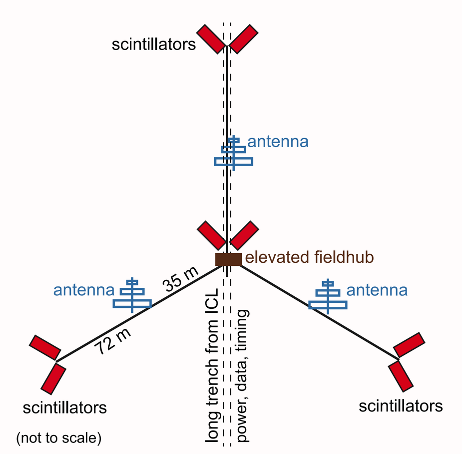
Calculated reconstruction efficiency as a function of energy
- Add measured noise to simulated waveforms and apply filter
- Calculate SNR for each waveform, keep if above 41.4
- Reconstruct arrival direction using a plane shower front, require < 5 deg from true direction





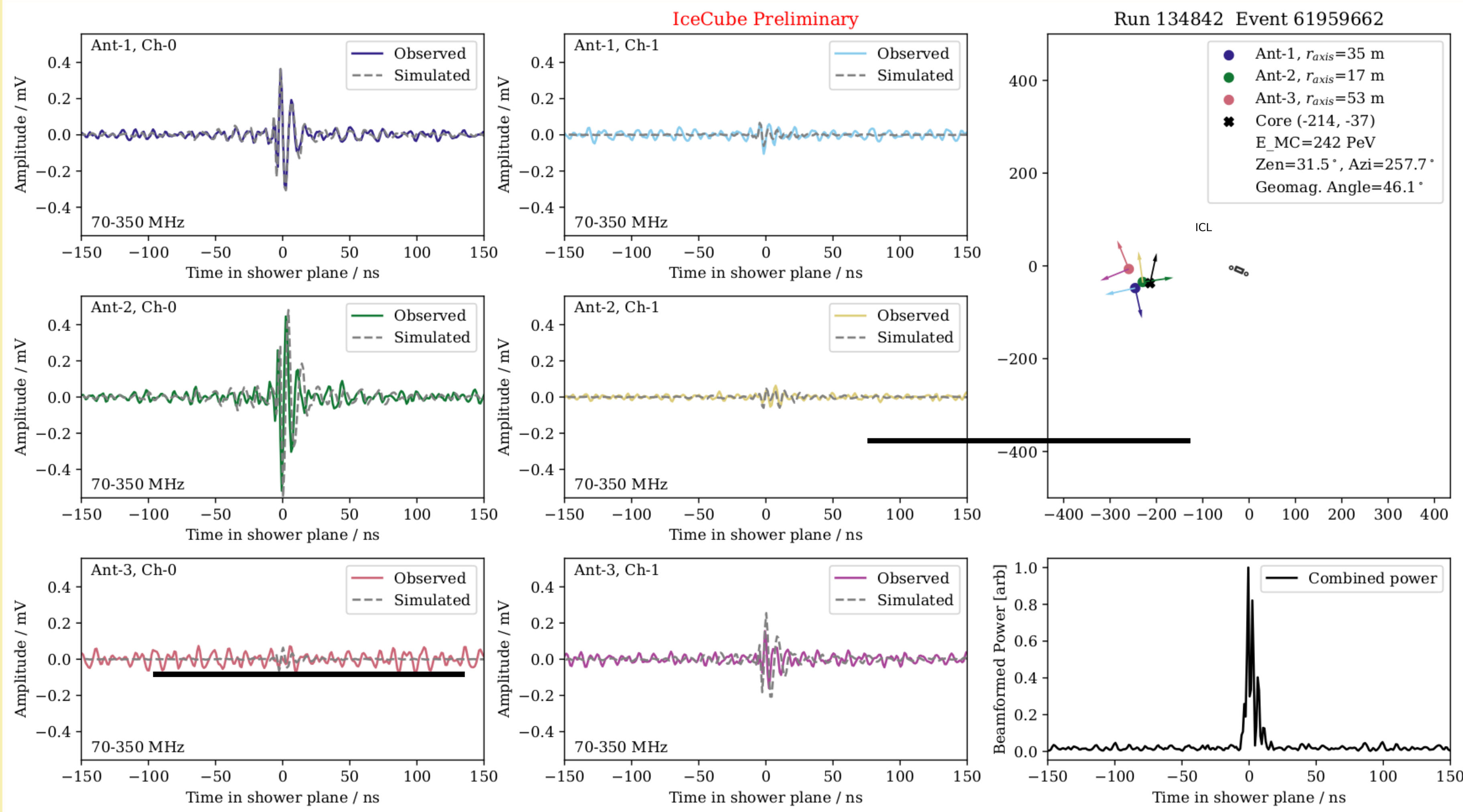


Layout of an IceTop Surface Enhancement station



Comparison to Measured Data

The prototype station has already observed several air showers, determined via the agreement of the timestamps and arrival directions when compared to IceTop. We simulated an air shower with initial conditions as given by the IceTop-reconstructed core, direction, and energy. The resultant waveforms are shown below for each channel.



Conclusions

We developed a code to propagate simulations of the electric field created in air showers with the response functions of the IceTop Surface Enhancement hardware.

To remove RFI peaks and boost the chance of correctly identifying an air shower pulse, we developed a frequency weighting scheme based on the measured background at the South Pole and air shower simulations.

We calculated the efficiency with which a shower can be reconstructed using the IceTop Surface Enhancement. We used an SNR-cut which rejects 99% of background pulses. Air showers will be reconstructed for energies above 40 PeV, depending on the trajectory.

A qualitative comparison of simulated and observed air showers, as seen in the antennas, gives evidence that the simulation chain is working correctly.

Future work will include extending the background pulse rejection using machine learning techniques. Future versions of the hardware will include a reduction of the RFI being generated by the DAQ, itself, which will further boost the reconstruction efficiency.

References and Ackowledgements

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Surface Array Enhancement

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