

The simulation of the sensitivity of the Antarctic Impulsive Transient Antenna (ANITA) to Askaryan radiation from cosmogenic neutrinos interacting in the Antarctic Ice

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The simulation of the sensitivity of the Antarctic Impulsive Transient Antenna (ANITA) to Askaryan radiation from cosmogenic neutrinos interacting in the Antarctic Ice

The ANITA collaboration

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ABSTRACT: A Monte Carlo simulation program for the radio detection of Ultra High Energy (UHE) neutrino interactions in the Antarctic ice as viewed by the Antarctic Impulsive Transient Antenna (ANITA) is described in this article. The program, *icemc*, provides an input spectrum of UHE neutrinos, the parametrization of the Askaryan radiation generated by their interaction in the ice, and the propagation of the radiation through ice and air to a simulated model of the third and fourth ANITA flights. This paper provides an overview of the *icemc* simulation, descriptions of the physics models used and of the ANITA electronics processing chain, data/simulation comparisons to validate the predicted performance, and a summary of the impact of published results.

KEYWORDS: Neutrino detectors; Simulation methods and programs; Particle detectors; Balloon instrumentation

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1 Introduction

The ANtarctic Impulsive Transient Antenna (ANITA) experiment is a NASA-funded, balloon-borne experiment aiming primarily to detect Ultra-High-Energy (UHE) neutrinos and cosmic rays [1–3]. UHE neutrinos may be produced when cosmic rays interact with the cosmic microwave background, either through the Greisen Zatsepin Kuzmin (GZK) [4, 5] mechanism or through photo-disintegration, or directly from an astrophysical source. UHE neutrinos interact in the Antarctic ice and produce a coherent radio pulse of Askaryan radiation [6]. UHE cosmic rays can also interact with the geomagnetic field to produce a coherent radio impulse [7–9]. The geometry of the Earth’s magnetic field in Antarctica allows ANITA to distinguish the signatures of these two types of events through their polarization.

The 8 m tall ANITA experiment flies about 40 km above Antarctica looking for radio signals in the band between 200 and 1200 MHz, produced by UHE neutrinos and cosmic rays. Figure 1 shows a basic scheme of the Askaryan neutrino detection at the ANITA experiment, as well as the UHE cosmic ray detection principle. Four ANITA flights (section 2) have been successfully completed as of 2019, and this paper focuses on the simulations of the third and fourth ANITA flights.

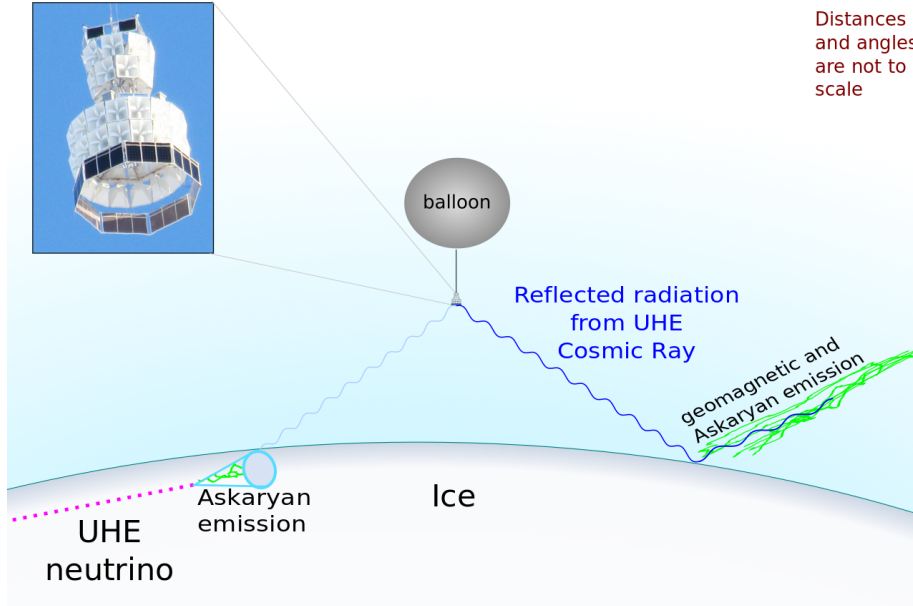


Figure 1. The ANITA detection concept with a photo of the ANITA-IV payload. UHE neutrinos interact with the Antarctic ice and produce a coherent radio pulse of Askaryan radiation. UHE cosmic ray interactions in the atmosphere produce a shower of secondary particles that interact with the geomagnetic field and can also produce a coherent radio impulse. Both these signals are detected by the ANITA instrument.

The `icemc` program is a C++ Monte Carlo simulation program based on ROOT [10] used to simulate the Askaryan radiation produced by neutrino interactions and the response of the ANITA detector to this radiation. This program is used by the ANITA collaboration to tune the selection cuts of the cosmogenic neutrino analysis and quantify the experiment’s sensitivity.

A flowchart of the `icemc` simulation steps is shown in figure 2. At the beginning of each run the user can choose which ANITA flight to simulate and which neutrino energy spectrum to use. For

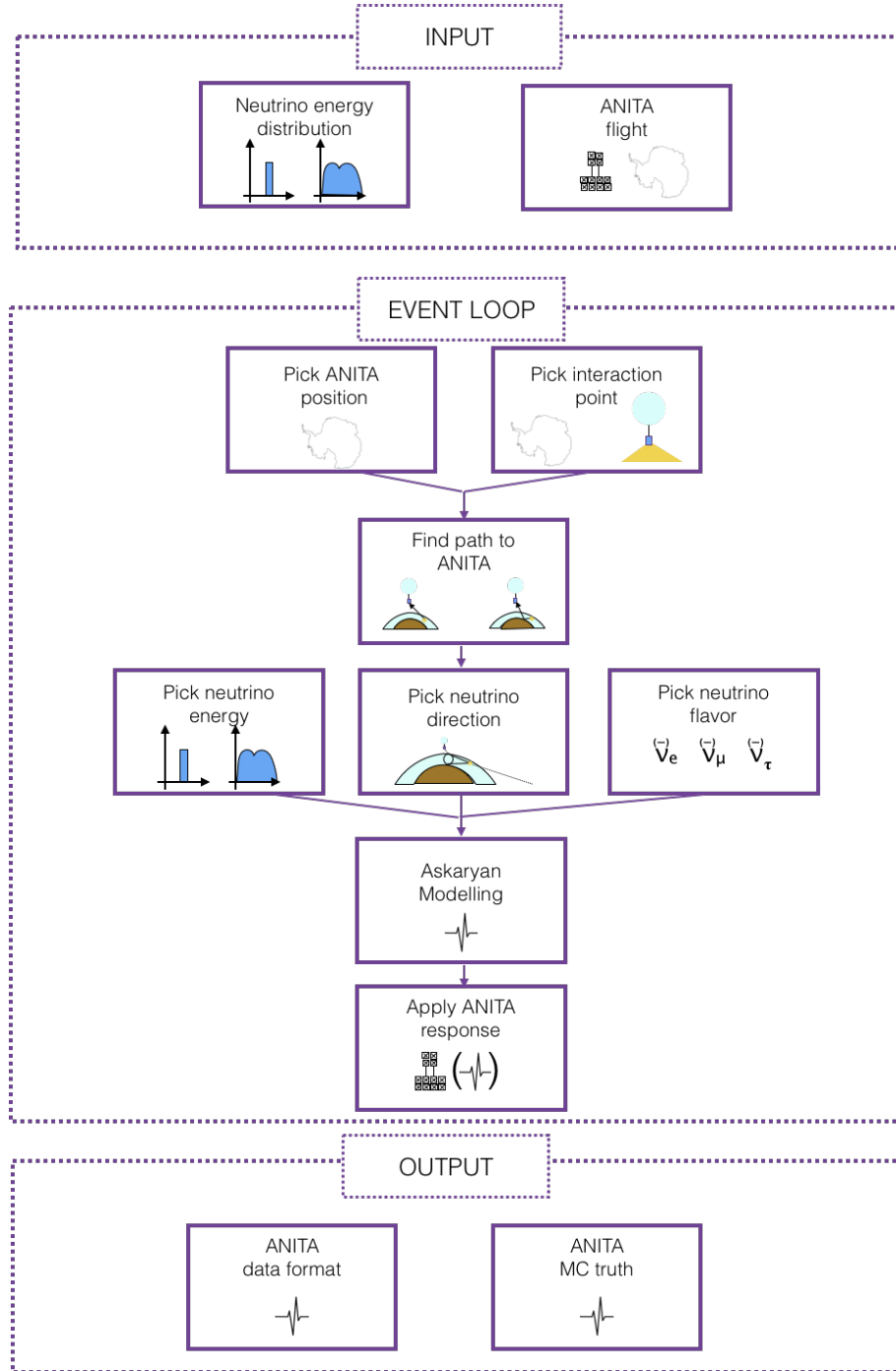


Figure 2. Flowchart of the **icemc** simulation for a single candidate.

each neutrino event, the position of the payload along the ANITA flight path, as well as the neutrino interaction position are randomly chosen. These are used to find the path to the ANITA detector (section 3). The neutrino direction is then chosen within detectable angles; the neutrino energy is chosen following the input theoretical model; and the neutrino flavor and interaction type are chosen

according to their expected ratios. These parameters are used to produce the radio-frequency pulse following the Askaryan model described in section 4. The signal is then propagated through the ice and air to the ANITA detector (see section 5). The response of the ANITA signal chain is simulated, and the resulting data are saved in the same format as ANITA flight data (see section 6). Different parts of the simulation are validated against data taken both at the NASA Long Duration Balloon Facility before the launch and in-flight during the past ANITA flights (see section 7). Finally the neutrino acceptance of the third and fourth ANITA flights, and the contributions of the different parts of the simulation to the uncertainties on the acceptance are presented in section 8.

2 The ANITA flights

The first two ANITA payloads flew in 2006–2007 [2] and 2008–2009 [3], respectively. Although *icemc* can be used to simulate older flights, this paper focuses on the simulation of the third and fourth flights.

Figure 3 shows the flight paths of the ANITA-III and ANITA-IV instruments. The color map shows the Antarctic ice depth. The third ANITA payload (ANITA-III) launched on December 18th, 2014 from the NASA Long Duration Balloon (LDB) facility near McMurdo Station, Antarctica. ANITA-III followed the polar vortex flying at the altitude of 37 km for 22 days until January 9th, 2015 when the flight was terminated near the Australian Davis Station. Similarly, the fourth ANITA payload (ANITA-IV) launched on December 2nd, 2016 from the NASA LDB facility in Antarctica and landed approximately 100 km from the South Pole Station on December 29th, 2016.

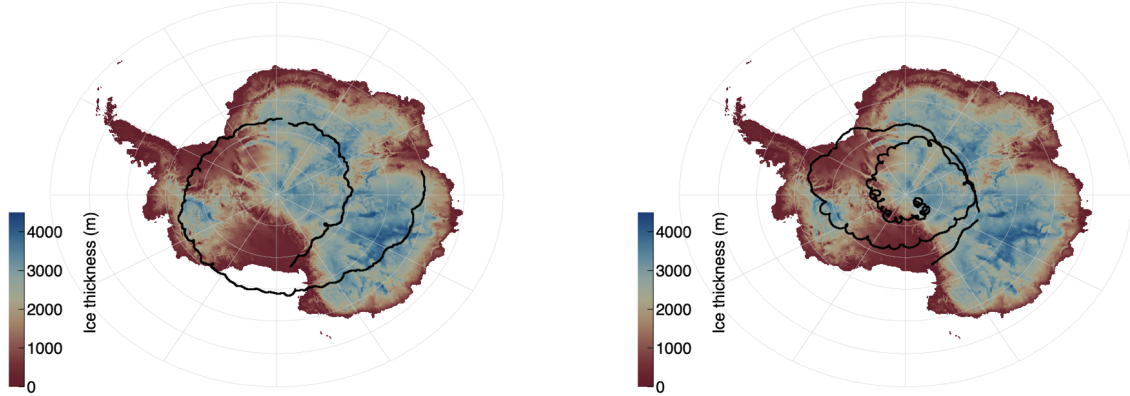


Figure 3. Flight path simulated in *icemc* for the ANITA-III (left) and ANITA-IV (right) flights. Antarctica map produced using the BEDMAP model [11].

The ANITA-III and ANITA-IV instruments were similar to the two previous ones [2, 3], using 48 dual-polarization quad-ridged horn antennas with bandwidth from 200 to 1200 MHz. The antennas were arranged in three rings forming 16 azimuthal sectors per ring, with the top ring divided into two layers to fit the launch envelope specifications, as shown in the top left of figure 1.

As the payload rotates freely, two sets of GPS units were used independently to determine the payload position and attitude. Power was supplied by an octagonal array of photovoltaic panels and stored using four pairs of 12-V lead-acid batteries. Communication to and from the payload was

through the Iridium and TDRSS satellite systems throughout the flight, and by a direct line-of-sight radio link when within range of McMurdo Station.

3 Event geometry

3.1 Modeling the Antarctic continent

Crust 2.0 [12] is used to model the Earth’s interior near the surface. It is based on seismological data published from the Cooperative Studies of the Earth’s Deep Interior (CSEDI). The model gives thicknesses and densities of seven material layers in 2 × 2 bins: ice, water, soft sediments, hard sediments, upper crust, middle crust, and lower crust.

The total Antarctic ice volume is computed by summing the product of ice thickness and surface area for each bin within the Antarctic continent. It is also possible to run the simulation using BEDMAP ice thickness and subglacial topographic model of Antarctica, developed by the British Antarctic Survey [11]. This model has higher resolution, but it is much slower to run, so by default we use Crust 2.0. Using Crust 2.0, the `icemc` program finds $2.976 \times 10^{16} \text{ m}^3$ of Antarctic ice in this model, compared to $3.011 \times 10^{16} \text{ m}^3$ reported by the U.S. Geological Survey [13], a 1.15% difference.

3.2 Picking neutrino interaction point and direction

For each neutrino event, the payload position is chosen at random from a set of positions along the ANITA flight path (see figure 3). To simulate only those neutrino interactions that might lead to a detectable signal, interaction positions are limited to occur within the horizon as seen by the payload (roughly between 700 and 800 km from the payload), and neutrino directions are chosen from an annulus on the sky consistent with viewing angles detectable at the payload (see section 3.3). The maximum angle that the ray may diverge from the axis of the Cherenkov cone for the interaction to still be detectable depends on the electric field, the distance from the interaction to the payload, and shower nature: this is typically between 10 and 13 degrees.

Both direct and reflected detection are simulated. In the first case the signal is propagated from the interaction position upwards to the payload. In the second case, the signal is propagated downwards towards to the ice-rock interface, approximated as a flat mirror, where the signal is then reflected upwards towards the payload.

3.3 Event weighting

To reduce computation time, each event is weighted according to the probability of the neutrino reaching the interaction point without being absorbed in the earth, as well as the “phase space” reduction (defined below), such that only those topologies that give measurable signal are fully simulated. As a neutrino moves through the earth, it encounters varying densities as it passes through layers of the earth’s interior, and thus differing interaction lengths. The neutrino survival probability is calculated from the along-track water-equivalent amount of material traversed.

The phase space factor is the product of the weights derived from the neutrino interaction position and neutrino direction. These weights are assumed to be independent of one another. The position weight arises due to the neutrino interaction position being chosen only within the payload horizon. This is calculated as the ratio of the volume of ice within the horizon for the i event and

the total volume of ice in Antarctica (ratio of the yellow to blue volumes in figure 4). The neutrino direction is chosen such that the axis of the Cherenkov cone lies close in angle to the direction from the interaction point to the payload. The direction weight is calculated as the ratio of the solid angle coming from the Cherenkov cone and a unit sphere.

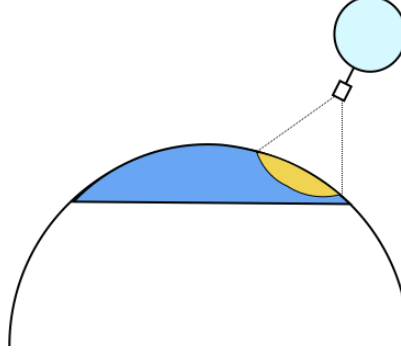


Figure 4. A schematic of the position weight used in `icemc`. The position weight arises because only interaction positions within the balloon horizon are simulated (yellow over blue area, where the blue area represents the entire Antarctica).

4 Radio signal simulation

4.1 Askaryan parametrization

For each event the neutrino energy is picked randomly following the input energy spectrum. Rather than simulating the particle shower development in the ice that would produce the Askaryan radiation, a 1D parametrization is used to find the peak of the Askaryan signal at 1 m from the point of interaction, $r_{@1m}$, according to reference [14] and following:

$$r_{@1m} = 2.53 \cdot 10^{-7} \frac{\sin \theta_{\text{view}}}{\sin \theta_{\text{Ch}}} \frac{E}{\text{TeV}} \frac{1}{\left(1 - \frac{\nu}{\nu_0}\right)^{1.44}} \quad (4.1)$$

where ν is the frequency, $\nu_0 = 1.15$ GHz, E is the shower energy (see subsection 4.2), θ_{view} is the viewing angle and θ_{Ch} is the Cherenkov angle. This parametrization is valid up to 5 GHz, covering the ANITA band of 0.2-1.2 GHz.

4.2 Neutrino flavors and interaction types

The `icemc` program assumes flavor democracy, assuming the flavors are fully mixed before the neutrinos get to the ice. Information about each flavor is stored separately so the sensitivity to each flavor may be quoted separately.

The neutrino undergoes a charged/neutral current interaction in 68.7% / 31.3% of cases. For charged current electron neutrino interactions, the electromagnetic component is calculated as $1 - y$, where y is the inelasticity and is approximated by a double-exponential function [15]. In all other cases the electromagnetic component is considered negligible. The hadronic component is equal to the inelasticity. Secondary particles are not propagated.

4.3 Cherenkov cone

The width of the Cherenkov cone is parametrized separately for the electromagnetic and hadronic components of the shower, according to references [14] and [16], respectively. The width of the electromagnetic component in degrees is characterized by:

$$\theta_{\text{EM}} = \frac{0}{0.14} \frac{E_{\text{LPM}}}{E_{\text{EM}}}^{0.3} \quad (4.2)$$

where E_{EM} is the part of the shower energy associated with electromagnetic particles, and E_{LPM} is the energy above which the Landau-Pomeranchuk-Migdal (LPM) effect becomes important. The LPM effect causes the bremsstrahlung interaction to become suppressed when the longitudinal momentum transfer ($q = k E^2$, where k is the photon energy and E is the electron energy) becomes very small. In this case, the Heisenberg uncertainty causes the interaction to occur over many scattering centers, resulting in destructive interference. This effect reduces the width of the Cherenkov cone, but not the magnitude of the electric field at the Cherenkov angle. Following the recommendation in reference [14], E_{LPM} is set to $2 \cdot 10^{15}$ eV in ice, and can be scaled to other media using the ratio of the respective radiation lengths.

The width of the Cherenkov cone for hadronic showers is modeled as laid out in equation 9 in [16]:

$$\theta_{\text{had}} = \frac{c}{K X_0} \frac{1}{n^2 - 1} \quad (4.3)$$

where c is the speed of light, ω is the frequency considered, ρ is the density of ice, K is a normalization constant determined by a separate Monte Carlo simulation [16], X_0 is the radiation length, and n is the index of refraction.

The signal strength at viewing angle θ_{view} away from the Cherenkov angle θ_{Ch} is also parametrized following equation 13 in reference [16]:

$$F_{\text{view}} = \frac{\sin \theta_{\text{view}}}{\sin \theta_{\text{Ch}}} F_{\text{Ch}} \exp \left(- \frac{\theta_{\text{view}} - \theta_{\text{Ch}}}{\theta_{\text{em,had}}}^2 \right) \quad (4.4)$$

5 Propagation in ice and air

The electric field is propagated to the payload using a standard ray tracing algorithm. The electric field magnitude at the payload position (before applying the ANITA instrument response) is calculated as follows:

$$E_{\text{view}} = E_{\text{Ch}} \cdot \exp \left(- \frac{d_{\text{ice}}}{\ell_{\text{attn}}} \right) \cdot \frac{t_{\parallel}}{t_{\perp}} \cdot F_{\text{view}} \quad (5.1)$$

The first factor after E_{Ch} accounts for propagation in ice, with d_{ice} being the path length and ℓ_{attn} the attenuation length in ice. The second factor accounts for the refraction from ice to air, using the specular Fresnel coefficients, $t_{\parallel}$ and $t_{\perp}$, for the parallel and perpendicular components of the normalized transmitted electric field vector at the ice-air interface with respect to the local surface normal. The surface normal includes a Gaussian 1.2% direction perturbation to account for surface slope effects. Finally, F_{view} is a geometrical attenuation factor of the field strength in air

resulting from viewing the Cherenkov emission at an angle θ_{view} different from the Cherenkov angle θ_{Ch} . The functional form of F is taken to be Gaussian and is set to zero for $(\theta_{\text{view}} - \theta_{\text{Ch}}) > 20 \theta_{\text{Ch}}$, where θ_{Ch} is the width of the Cherenkov cone.

Cherenkov radiation is radially polarized, and the in-ice polarization vector of the Cherenkov radiation is radially outward in the plane formed by the neutrino velocity vector and the Cherenkov propagation vector. Attenuation lengths for radio in Antarctica are based on measurements performed at the Ross Ice Shelf and the South Pole [17, 18]. The index of refraction is taken as 1.79 for deep ice and 1.325 at the surface. A model for the firn, a layer of packed snow above the ice, based on data taken by the RICE Collaboration [19] is used at depths shallower than 150 m.

Surface roughness acts to allow different portions of the ice surface to contribute transmitted power to the payload for a given event, because it allows new scattering geometries at the air-ice interface. The University of Hawaii ANITA group developed a simulation program, used for the ANITA-I and ANITA-II flights, which included surface roughness effects. They found that ice surface roughness contributed to an increase in acceptance of roughly a factor of 50% at low energy (close to 10^{18} eV) and 40% at higher energy. `icemc` currently does not include ice surface roughness effects, and hence provides a conservative estimate of the sensitivity of the ANITA flights. Future versions of `icemc` will include these effects.

6 ANITA detector model

The simulated signal is propagated to the front of each of the ANITA antennas and through the trigger and digitizer paths of the ANITA instrument, taking into account the payload rotation. The payload position chosen along the flight path is used to load appropriate information about the payload rotation, channel threshold values and channel masking. The payload geometry is simulated using photogrammetry measurements and phase-center calibration measurements taken with a ground pulser during the flights. Antenna gains measured prior to the flight are applied to the signal according to the incident angles on the E and H planes.

Figure 5 shows a schematic of the ANITA-III signal chain. The receiving antenna measures vertical (V-POL) and horizontal (H-POL) polarization components of incident radio waves, which then follow twin paths. After passing through filters and amplifiers, the signal is split into the trigger and digitizer paths. In the trigger path the signal passes through a tunnel diode which acts as a square-law detector over the input. The output of the tunnel diode is compared to the channel threshold, which is dynamically adjusted by a PID loop to maintain the rate for each antenna around 500 kHz. ANITA-IV used 90 hybrids to convert the signals into left- and right- circularly polarized (LCP and RCP) components. The ANITA-IV trigger logic also required a coincidence between LCP and RCP signals within a 4 ns coincidence window to select for linearly polarized signals. A combination of first-level (L1) and second-level (L2) triggers forms a global trigger which can be issued in each polarization. When a trigger is issued, a switched capacitor array digitizes the RF signal with 260 samples per channel and a mean sample rate of 2.6 GSa/s. To avoid continuous wave (CW) noise from satellite and station transmissions, the ANITA-IV signal chain included the Tunable Universal Filter Front-end boards (see subsection 6.1 and reference [20]), placed instead of the internal Radio Frequency Control Modules (iRFCMs). In the case of the ANITA-III payload a channel is the

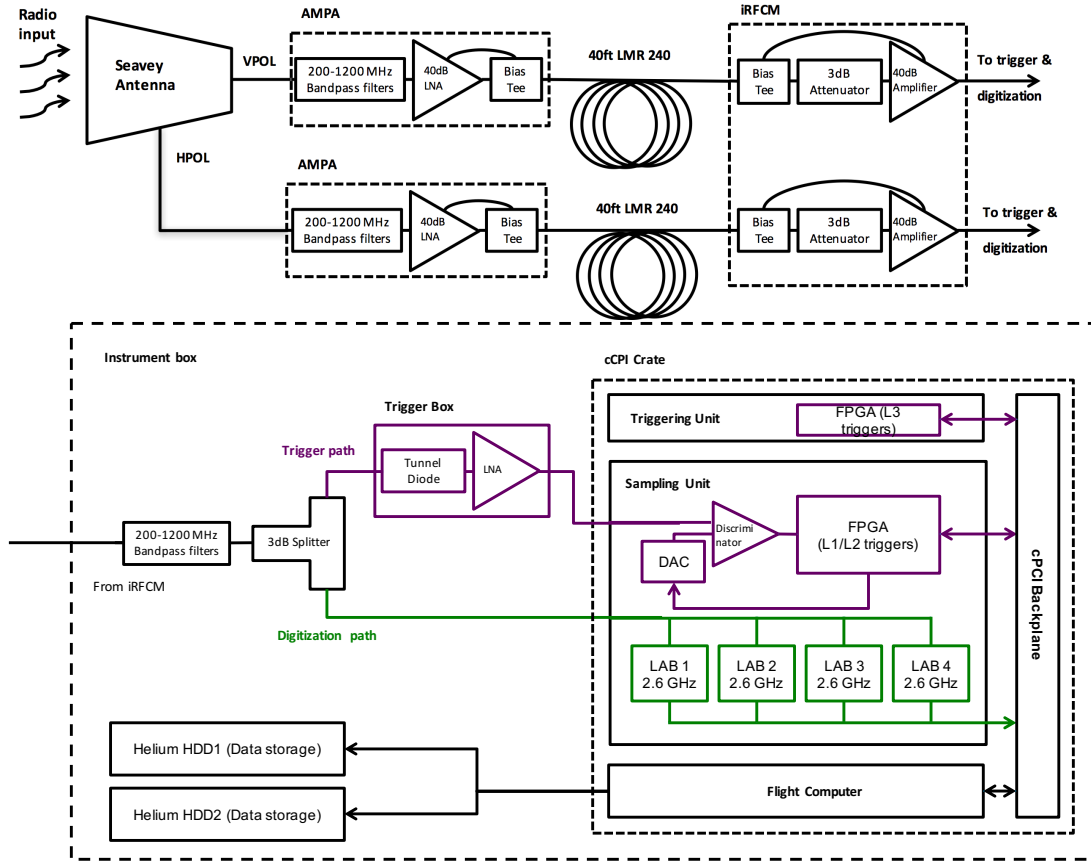


Figure 5. ANITA-III signal chain. The receiving antenna splits signals into vertical and horizontal polarizations which follow identical paths. After going through filters and amplifiers, the signal is split into the trigger and digitizer paths. In the trigger path the signal passes through a tunnel diode and is compared to a threshold. When a trigger is issued, a switched capacitor array digitizes the signal with 260 samples per channel and a mean sample rate of 2.6 GSa/s. The triggering and sampling units, as well as the single board flight computer are contained in the Compact Peripheral Component Interface (cPCI) crate. For ANITA-IV, the TUFFs replace the iRFCMs, performing the second stage amplification and filtering.

V-POL or H-POL component of one antenna; for ANITA-IV a trigger channel is the LCP or RCP component, and a digitized channel refers to the V-POL or H-POL component of one antenna.

The digitizer and trigger responses were measured before the flights by injecting an RF signal directly into the amplifiers behind the ANITA antennas and measuring the output of the digitizer and trigger paths; this ensures that the responses include AMPAs and iRFCMs/TUFFs too. Figure 6 (left) shows the power spectra of the trigger and digitizer impulse responses for a sample channel of the ANITA-III payload. Figure 6 (right) shows the power spectra of the trigger and digitizer impulse responses for a sample channel of the ANITA-IV payload with the most common filter configuration used during flight. Thermal noise is generated based on flight measurements (see section 6.2) and added to the waveforms. Finally, the modeled tunnel diode response (see section 6.3) is convolved with the signal waveforms from all the channels, and if an event passes the trigger logic, the RF signal and truth information about the neutrino interaction are saved in the final output.

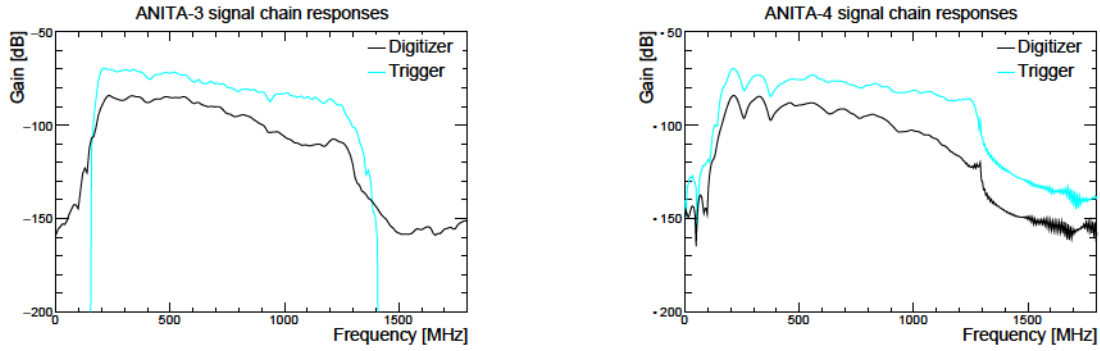


Figure 6. Power spectrum of the trigger and digitizer impulse response for a sample channel, for the ANITA-III (left) and ANITA-IV (right) instruments.

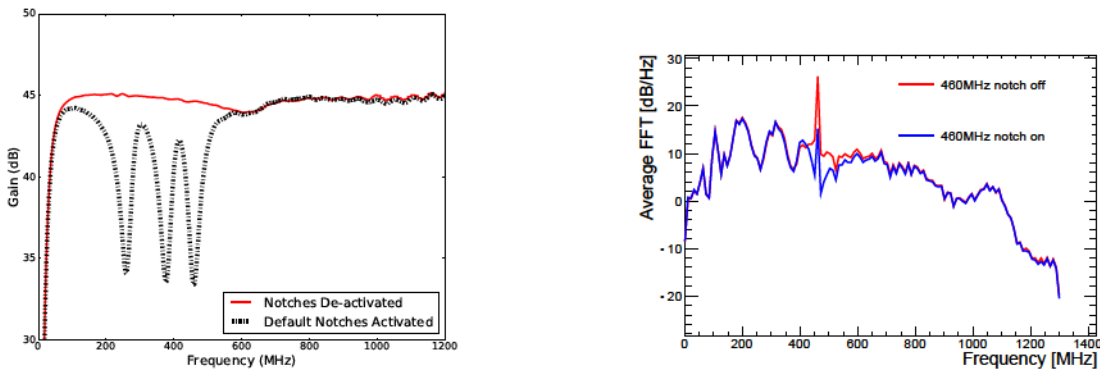


Figure 7. (Left) Measured TUFF response in frequency domain (dB vs frequency) obtained before the flight. The dips in the response clearly mark the 260, 375, and 460 MHz notches turned on in this configuration and the 13 dB attenuation at those frequencies is clear [20]. (Right) Example of CW noise injected in *icemc* with the third notch activated and not activated.

6.1 Tunable universal filter front-end boards

To alleviate the anthropogenic noise observed in ANITA-III that caused significant amounts of deadtime, ANITA-IV added the Tunable Universal Filter Front-end, or TUFF, boards [20]. This board uses up to three notches to attenuate the gain by a maximum of 13 dB around each notch frequency: the notches are tunable, but default to 260, 375, and 460 MHz, corresponding to known satellite communications frequencies. Whether each notch is activated and at which frequency is called a “configuration”. There were 16 TUFF boards with six channels each for the 96 total ANITA channels; there were seven unique configurations for the ANITA-IV flight which are simulated in *icemc*. The measured TUFF response for the configuration when all notches are on and at default frequencies is plotted in figure 7 (left). An example of the effect of the third notch switched on or off when 460 MHz CW noise is simulated is shown in figure 7 (right). The measured TUFF response for a given configuration is loaded into *icemc* and convolved with the trigger and digitizer impulse responses for each channel.

6.2 Thermal noise

Modeling thermal noise correctly is crucial to the simulation of ANITA's sensitivity to neutrino interactions as it affects both the trigger and analysis efficiencies. An accurate model of the thermal noise makes it possible to simulate both the accidental noise triggers and the effect of noise fluctuations on the reconstructed correlation maps used to calculate the event direction in the ANITA analyses [21].

To provide a realistic model of the thermal noise during the ANITA flights, events coming from minimum bias triggers during a quiet time (a portion of the flight when the payload is not close to any areas of high radio activity, such as active bases or ground pulsers) of the ANITA-III flight are used to produce power spectra in bins of 10 MHz for each digitizer channel. As the ANITA-III flight suffered more than the previous flights from CW noise coming from satellites and human bases, frequencies in the ranges 234–286 MHz and 344–410 MHz are filtered out in software analysis using two simple notch filters. Data from antennas facing the sun were also excluded.

For each channel and each frequency bin a Rayleigh PDF is fit to the data:

$$f(A, \sigma) = \frac{A}{\sigma^2} e^{-A^2/(2\sigma^2)}, \quad (6.1)$$

where A is the amplitude in the frequency domain (in mV/MHz) and σ is the Rayleigh amplitude in that frequency bin. As most of the CW noise is in the tail of these distributions, the Rayleigh fits are performed only to the rising edge and peak of the distributions. Figure 8 (left) shows an example of Rayleigh distribution fits for a sample channel in the frequency bin centred at 710.94 MHz. Events in this sample come from minimum bias triggers during the ANITA-III quiet time.

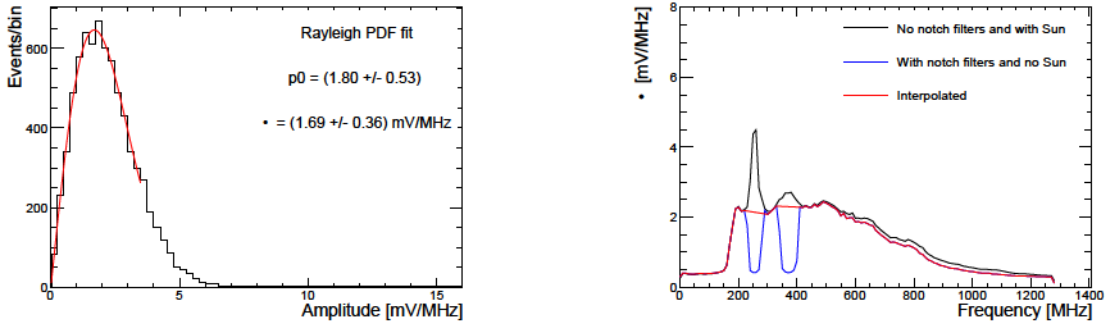


Figure 8. Example of a Rayleigh fit for a sample channel in the 710.94 MHz frequency bin (left). The fit is performed only to the rising edge and peak of the distributions, as most CW noise is in the tail. Right: fitted amplitude, $\sigma(f_i)$, as a function of frequency (interpolating in the frequency range where power is filtered).

Graphs of the fitted amplitude, $\sigma(f_i)$, as a function of frequency were produced for each channel (interpolating in the frequency range where power is filtered), as seen in figure 8 (right). In `icemc` these graphs are used to generate random noise in the frequency domain for each channel: for each frequency bin f_i the real and imaginary part are randomly extracted from a Gaussian distribution with zero mean and amplitude $\sigma(f_i)$, the fitted Rayleigh amplitude in that bin.

This noise is added to the signal in the digitizer path. For the trigger path the noise is re-normalized using the bin-by-bin ratio of the trigger to digitizer path impulse response in the frequency domain before adding it to the signal.

Thermal noise for the ANITA-IV simulation is derived from the ANITA-III measurements, accounting for the different electronics response (including the use of low noise amplifiers and variable filter configurations during the flight) for the two missions. Samples containing only thermal noise are also produced, and they are used in the main ANITA analyses to test the robustness of our analysis selection. Subsection 7.2 details the thermal noise validation for both ANITA flights.

6.3 Trigger simulation

The simulation models the L0 trigger by passing the trigger-path signal through a time-domain tunnel diode model and comparing it to the appropriate threshold from the flight for that channel at the event time. The tunnel diode response can be thought of as an integral of the power over about 10 ns, but the true response is non-trivial. The shape of the diode response is described by the sum of two negative Gaussians and a positive function that is the product of a quadratic and an exponential:

$$f(t) = A_1 \cdot e^{-(t-t_0^1)^2/2\sigma_1^2} + A_2 \cdot e^{-(t-t_0^2)^2/2\sigma_2^2} + A_3 \cdot (t-t_0^3)^2 \cdot e^{-(t-t_0^3)/\sigma_3}, \quad (6.2)$$

where the values for the parameters used for all channels are shown in table 1; $f(t)$ is dimensionless. Figure 9 shows the diode response model function.

Table 1. Tunnel diode model parameters used for the full band trigger in ANITA-III and ANITA-IV. The tunnel diode responses for each channel are sufficiently similar that a single set of parameters gives an adequate treatment.

	Value 1	Value 2	Value 3
A	-0.8	-0.2	0.00964
σ [ns]	2.3	4.0	7.0
t_0 [ns]	15.0	15.0	18.0

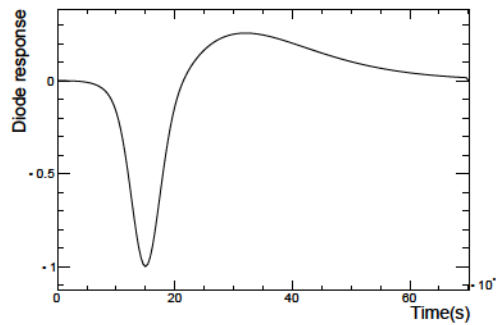


Figure 9. Tunnel diode response model used in `icemc`.

For each signal, the power as a function of time is calculated as:

$$P(t) = \frac{V(t) \cdot V(t)}{Z}, \quad (6.3)$$

where $V(t)$ is the voltage at time t , and $Z = 50\ \Omega$ is the system impedance. The next step is to convolve the waveform power with the diode response to find the diode output $D(t)$:

$$D(t) = (f * P)(t) . \quad (6.4)$$

For each time bin, the diode output is compared to the channel threshold, V_T , multiplied by the RMS voltage of the diode output coming from pure thermal noise, V_{RMS} , following:

$$D(t) < V_T \cdot V_{\text{RMS}} . \quad (6.5)$$

If the diode output is more negative than the threshold multiplied by V_{RMS} at any point, then that channel passes the L0 trigger.

At the beginning of a run, V_{RMS} is calculated for each channel by simulating 1000 noise waveforms (subsection 6.2) and sampling the diode output at the center of each waveform (see figure 10). In ANITA-III, two channels had very large V_{RMS} associated with them that prevents them from triggering in the simulation: one was broken during the flight, and the other one had an additional filter applied during flight to allow an in-flight calibration pulser to be used.

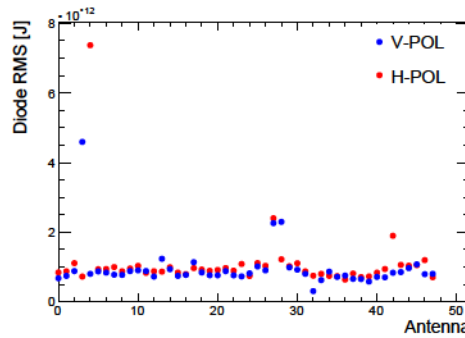


Figure 10. Tunnel diode V_{RMS} for each channel. The two channels with much higher V_{RMS} are the broken channel, and the channel which had an additional filter applied to accommodate the use of an in-flight calibration system.

The trigger logic for the ANITA-III and ANITA-IV triggers is very similar. The main difference is that ANITA-IV used 90 degree hybrids to transform H-POL and V-POL signals into LCP and RCP components of waveforms, so the ANITA-IV L1 trigger requires a LCP and RCP L0 coincidence in the same antenna within one 4 ns clock cycle. For the ANITA-III instrument an L0 trigger implied an L1 trigger too. The L2 trigger is formed by a coincidence of two out of three antennas (top, middle, bottom) in the same azimuthal sector. As ANITA is intended to look for plane-waves from below, a simple causal requirement is enforced on the coincidence windows. An L1 on the bottom antenna opens a coincidence window open for four FPGA clock cycles (nominally 16 ns). Middle and top L1's open the window for three and one-clock cycles (nominally 12 and 4 ns), respectively. Finally, the global trigger is formed by the coincidence of L2 triggers in two adjacent azimuthal sectors within 3 clock cycles. For ANITA-III either polarization or both may produce a global trigger. Either the L2 or global-trigger may be masked for an azimuthal sector if the L2 or global rate is too high in the sector. The actual time-dependent masking status from the flight is used in the simulation.

7 Validation

Different parts of the simulation are validated from measurements taken before (subsection 7.1) and during the flights (subsection 7.2).

7.1 Comparisons with measurements before flights

Before each of the ANITA flights, a series of calibration measurements was taken at the NASA Long Duration Balloon Facility near McMurdo Station, Antarctica. These measurements are used to cross-check different parts of the simulation.

7.1.1 Trigger efficiency scans

Trigger efficiency scans are used to measure the ANITA trigger efficiency for signals with different signal-to-noise ratios (SNRs). The setup used before the ANITA-III flights is shown in figure 11. A Picosecond Pulse generator is used to produce an RF signal with height 1 V and FWHM 0.3 ns. One copy of the signal is recorded with an oscilloscope and the other is passed through attenuators, and a 12-way splitter. Six of these channels (corresponding to two azimuthal sectors in one polarization) are inserted directly into the amplifiers behind the ANITA antennas, and follow the standard trigger and digitizer paths. One reference channel is inserted into the amplifier and routed from the trigger path to the oscilloscope to measure the SNR values at the trigger.

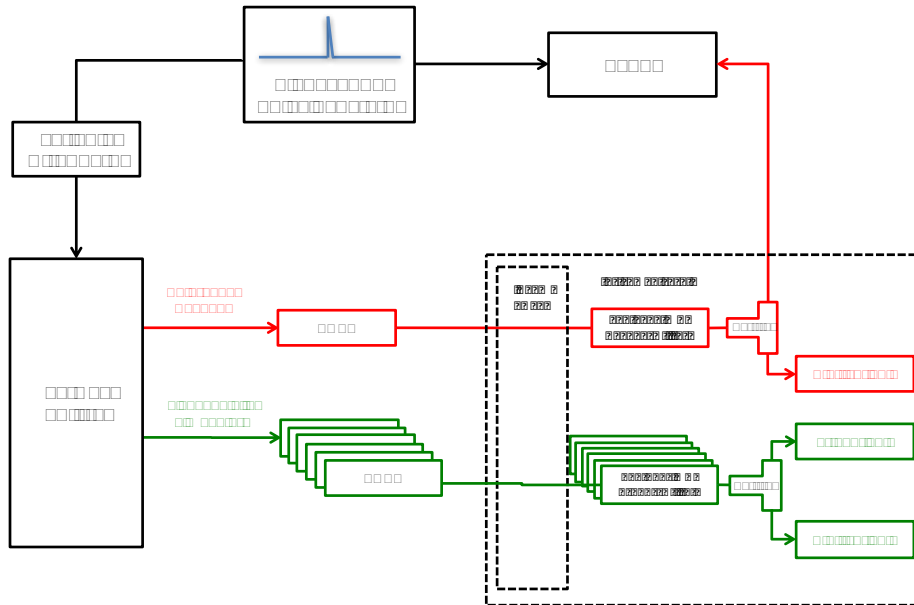


Figure 11. Trigger efficiency scans setup in Antarctica before the ANITA-III flight. A pulser signal is sent to 6 channels (representing 2 azimuthal sectors in one polarization) and is used to measure the trigger efficiency. One reference channel (red line) is sent to the oscilloscope to measure the SNR values at the trigger.

To simulate the trigger efficiency scan setup, the signals measured at the oscilloscope (see figure 11) are inserted (with appropriate attenuation) into the same six channels as used in the hardware efficiency scans. These go through the trigger/digitizer path and produce ANITA data-like outputs.

The signals are recorded at the trigger and the digitizer paths, and are used to validate the simulation. Figure 12 shows a comparison of the measured SNR in data and simulation at the trigger (left) and at the digitizer (right) as a function of the variable attenuation used during the scan. The SNR is calculated as the ratio of half of the peak-to-peak of the time domain signal to the RMS of the last part of the waveform. The measured SNR in the digitizer path generally has larger uncertainties compared to the SNR in the trigger path, because the ANITA digitizer has on average a 2.6 GHz sampling rate, whereas the trigger path is measured with a fast oscilloscope.

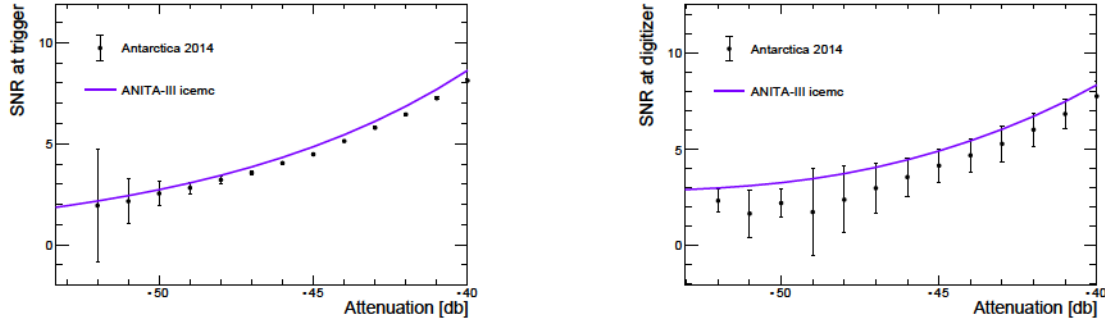


Figure 12. SNR measured at the trigger (left) and digitizer (right) as a function of the variable attenuation applied during the trigger efficiency scans. The data points were measured in 2014 in Antarctica prior to the ANITA-III flight.

Figure 13 (left) shows a comparison between data and simulation of a trigger efficiency scan for the ANITA-III payload. The trigger efficiency is plotted as a function of the SNR measured in the trigger path.

Before the ANITA-IV flight, a similar set of measurements was collected. A data and simulation comparison of the trigger efficiency for the ANITA-IV instrument is shown in figure 13 (right).

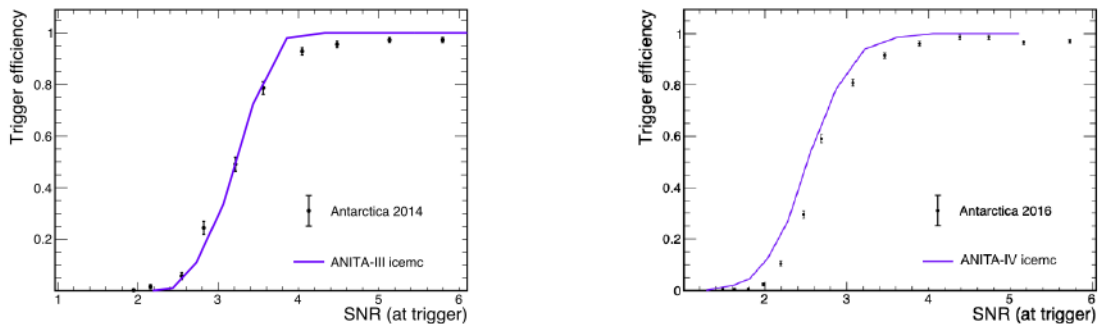


Figure 13. Comparison between data and simulation of a trigger efficiency scan for the ANITA-III (left) and ANITA-IV (right) instruments. The trigger efficiency is plotted as a function of the SNR measured at the oscilloscope for the data, and the SNR estimated in the trigger path for the simulation.

7.2 Comparisons with flight measurements

Data taken during the ANITA-III and ANITA-IV flights are used to validate the thermal noise, the trigger efficiency to a ground pulser, and the pointing reconstruction.

7.2.1 Thermal noise validation

The simulation of thermal noise is validated using distributions of the RMS of the simulated waveforms compared to a relatively quiet time during the flights. Figure 14 shows the voltage RMS of noise-only waveforms produced in *icemc* compared with the ones coming from a quiet time during the ANITA-III (left) and ANITA-IV (right) flights.

As the ANITA-III data contained a significant amount of CW contamination, a fair comparison of the data and simulation thermal noise is done after applying two notch filters to both datasets, improving the data and simulation agreement. The remaining differences are due to CW noise in the data that could not be simply removed with two notch filters.

The ANITA-IV payload was less affected by CW noise, as the TUFF boards were directly filtering out noisy frequencies, and the requirement of the coincidence between LCP and RCP signals to form a trigger ensured that only linearly polarized signals triggered the payload. A direct comparison between the measured and simulated noise is seen in figure 14 (right), where the better data-simulation agreement for ANITA-IV, than for ANITA-III, is due to the reduced CW noise in the ANITA-IV datasets. The simulation slightly overestimates the ANITA-IV thermal noise, but these small differences do not impact the experiment sensitivity.

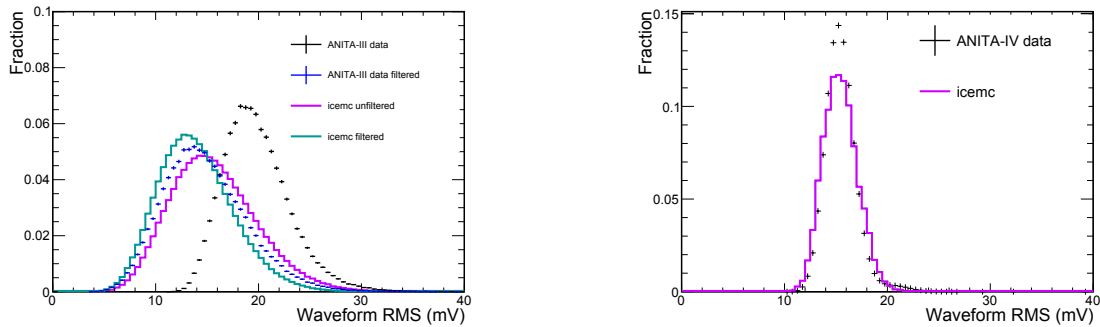


Figure 14. Thermal noise validation. Comparison of RMS of waveforms for an *icemc* simulation and a relatively quiet period of the ANITA-III (left) and ANITA-IV (right) flights. The ANITA-III flight was affected by strong CW noise that for a better comparison has been filtered out. These distributions are normalized to equal area to better compare their shape.

As a second consistency check, the ANITA-III simulated thermal noise is also used to produce Rayleigh fits (as described in subsection 6.2) and shows complete overlap with the fits to the ANITA-III quiet time.

7.2.2 WAIS pulser model

As an additional validation, we model the calibration pulser that was located at the West Antarctic Ice Sheet (WAIS) field camp during the ANITA-III and ANITA-IV flights. The WAIS pulser consisted of a 6-kV FID GmbH brand [22] pulser that generates a broadband impulse and drives a

horizontally polarized antenna. The pulser was triggered on the GPS second with a known delay, permitting a measurement of the ANITA trigger efficiency while the payload is in view of the pulser.

The antenna used at WAIS is a custom design based on a quad-slot model, for which the slots of the antenna are parallel to the ground. The antenna was installed 1 m below the surface of the snow. Similar to a discone, the bottom portion of the antenna acts as a reflector, and the angles of the taper on both the reflector and the upper cone tune the orientation of the peak gain. This design is a scaled down version of the VHF antenna used as a low frequency extension to ANITA-III.

The WAIS antenna response was modelled using NEC antenna modeling software [23]. Figure 15 shows the peak gain for each frequency, the associated phase at that frequency, and the reflection coefficient, Γ , from this antenna model. We then model the electric field (figure 15d) generated by the WAIS pulser by convolving the NEC model of the antenna with measurements of the voltage generated by the FID pulser on an oscilloscope. The electric field at 1 m from the pulser, $E(f)$, results from relating the power density radiated by the antenna to the power density generated by the pulser with a characteristic impedance Z and voltage $V(f)$ at the pulser, accounting for loss from imperfect antenna matching between the antenna and the pulser, the magnitude and phase of the gain, $G(f)$, propagation loss, and the impedance of free space, Z_0 :

$$E(f) = \frac{V(f)}{8Z} \sqrt{1 - \Gamma^2} \sqrt{\frac{Z_0}{2 \cdot 1 \text{ m}^2}} G(f) \quad (7.1)$$

The simulation treats the electric field shown in figure 15 as originating from a source at the location of the WAIS pulser. Figure 16 shows the efficiency of the ANITA-III payload to generate a trigger from pulses coming from WAIS divide (the linear border between the ice flows at WAIS). The simulation efficiency does not asymptote to 1 at high SNR, as it also includes inefficiencies due to the channel masking and the instrument dead time. The data and simulation efficiency are used as systematic uncertainties in the calculation of the sensitivity of the experiment.

7.2.3 Reconstruction validation

A large sample of simulated neutrinos is produced following the cosmogenic neutrino flux arising from a mixed cosmic-ray composition as modeled by Kotera et al. [24] and used to validate the simulated pointing resolution. Simulated waveforms from different triggering channels are cross-correlated to form a pointing map in the ANITA payload coordinates, azimuth (θ_{meas}) and elevation (ϕ_{meas}). The peak of the correlation map is then compared to the expected azimuth (θ_{theory}) and elevation (ϕ_{theory}), calculated from the true neutrino interaction point. The angular resolution in azimuth and elevation of the simulated neutrinos is comparable to the one measured using the WAIS pulser during the flights. Details of our reconstruction and analysis can be found in our previous publications [2, 3, 21].

8 ANITA sensitivity

The simulation files produced with `icemc` are used by the ANITA analysts to tune analysis cuts, check the rate of accidental clustering, and also to simulate sources like Gamma Ray Bursts and Active Galactic Nuclei. Finally, the simulation is used to calculate the experiment sensitivity.

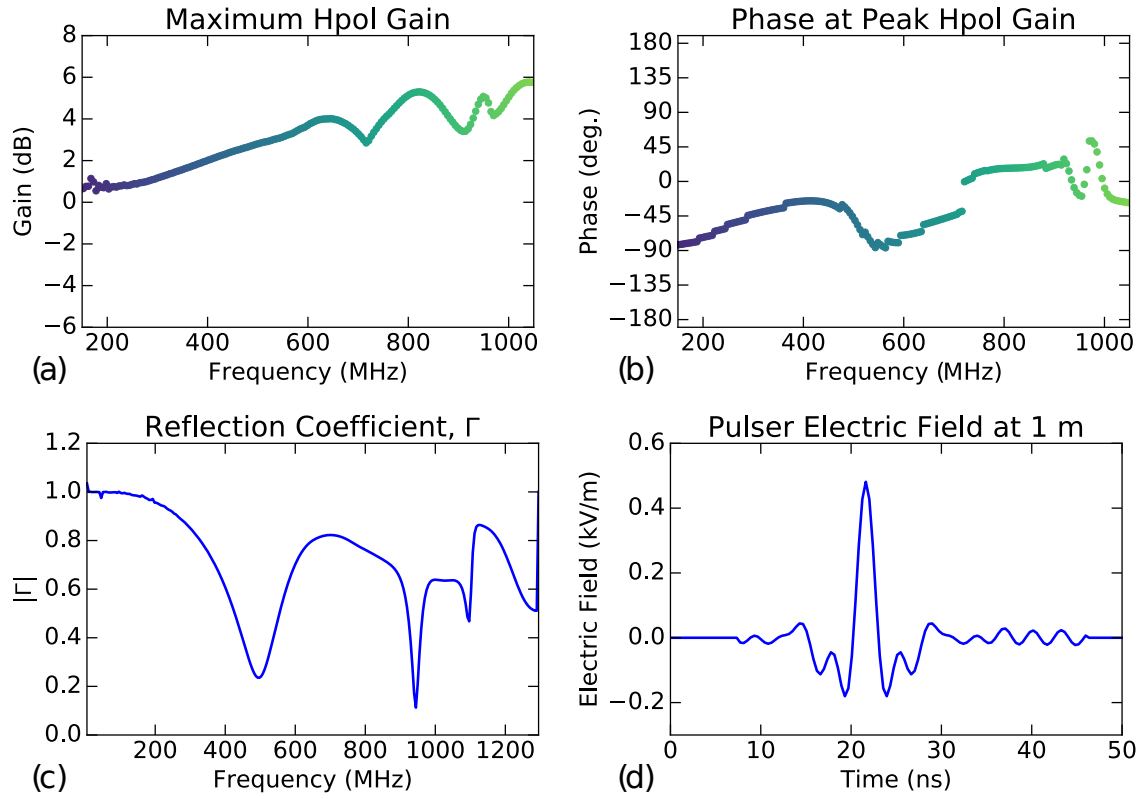


Figure 15. Characterization of the ANITA-III horizontally polarized antenna used in the WAIS pulser.

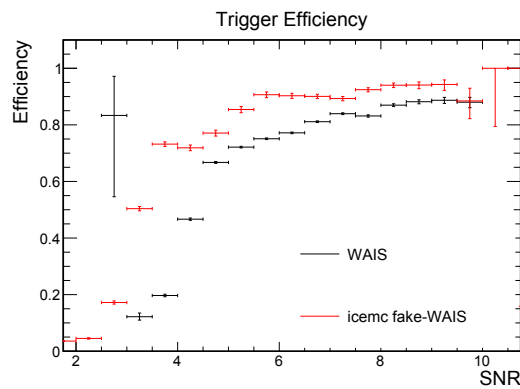


Figure 16. ANITA-III trigger efficiency to a pulser coming from the WAIS divide station as a function of SNR.

8.1 Acceptance

The ANITA collaboration uses `icemc` to calculate the experiment volumetric acceptance $\langle V\Omega \rangle(E)$, following:

$$\langle V\Omega \rangle(E) = \frac{n_{\text{pass}}(E)V_0\Omega}{N(E)}, \quad (8.1)$$

where $n_{\text{pass}}(E)$ is the weighted (see section 3.3) number of events that pass the trigger at a given energy E , V_0 is the volume of ice in Antarctica viewed by ANITA, Ω is 4π steradians, and $N(E)$ is the number of neutrino events thrown by each simulation at that energy E .

The ANITA acceptance ($\langle A\Omega \rangle(E)$) is calculated following:

$$\langle A\Omega \rangle(E) = \frac{\langle V\Omega \rangle(E)}{\ell_{\text{int}}(E)}, \quad (8.2)$$

where $\langle V\Omega \rangle(E)$ is the volumetric acceptance and $\ell_{\text{int}}(E)$ is the average interaction length in that energy bin. The interaction length is calculated following:

$$\ell_{\text{int}}(E_\nu) = \frac{M_{\text{NUCL}}}{\sigma(E)\rho_{\text{H}_2\text{O}}}, \quad (8.3)$$

where M_{NUCL} is the atomic nuclear mass ($1.66 \cdot 10^{-27}$ kg), $\sigma(E)$ is the neutrino cross section for ν charged-current interactions, and $\rho_{\text{H}_2\text{O}}$ is the density of water (1000 kg/m^3). Currently the neutrino cross section is calculated using either the Reno et al. [25] or the Connolly et al. [26] parametrizations. The latter is the default.

Although recent neutrino cross section measurements by the IceCube Collaboration reached the multi-TeV scale [27, 28], above this energy there are only cross section measurements with an uncertainty of a factor ± 5 up to 300 TeV. The current theoretical models can extrapolate the cross sections up to 10^{21} eV [25, 26], but the associated uncertainties are large, and the impact on the ANITA acceptance is non-negligible. Figure 17 (left) shows the effect of changing the cross section parametrization on the ANITA-III acceptance. The nominal Connolly et al. parametrization is compared to the upper and lower bound set by reference [26], and to the alternate parametrization suggested by reference [25].

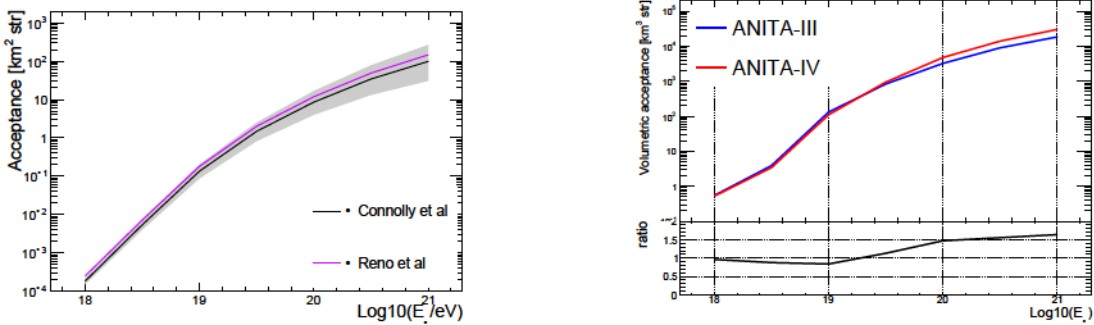


Figure 17. (Left) ANITA-III acceptance for different cross section parametrizations: Connolly et al. [26] and Reno et al. [25]. (Right) ANITA-III and ANITA-IV volumetric acceptance comparison as a function of energy.

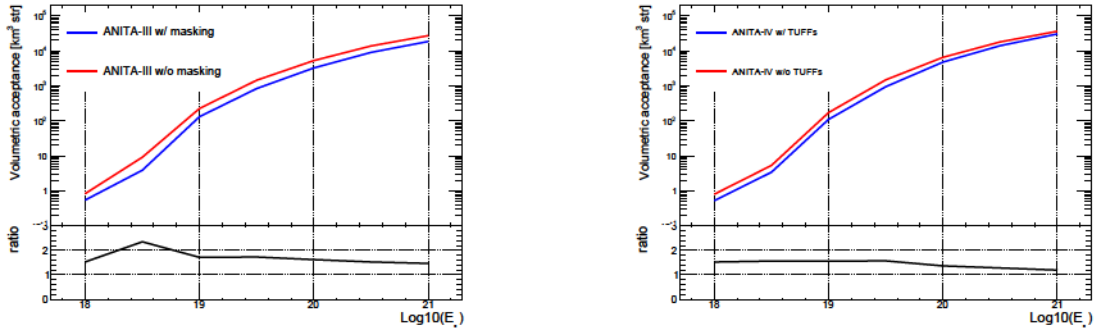


Figure 18. (Left) Comparison of ANITA-III volumetric acceptance with and without channel masking. (Right) Comparison of ANITA-IV volumetric acceptance with and without TUFF boards.

Figure 17 (right) shows the ANITA-III and ANITA-IV volumetric acceptances and their ratio. The ANITA-IV hardware improvements (use of better low noise amplifiers, the tunable notch filters to avoid CW noise, and the use of LCP-RCP trigger coincidences to avoid satellite noise) enabled ANITA-IV to increase the volumetric acceptance by 50% at the highest energy.

Volumetric acceptances are also used to evaluate the impact of different hardware choices. ANITA-III was highly affected by CW and satellite noise and had to employ channel masking throughout the entire flight to avoid overloading the trigger. Figure 18 (left) shows that channel masking reduced the ANITA-III sensitivity by more than 50% across all energy bins. ANITA-IV used the TUFF boards and the coincidence of LCP-RCP triggers to avoid CW and satellite noise, hence only used channel masking for a relatively small fraction of the flight. Nonetheless, the TUFF boards filtered out significant fractions of the frequency range and had a non-negligible impact on the sensitivity of ANITA-IV: figure 18 (right) shows the impact of the use of the TUFF boards on the ANITA-IV sensitivity, which was reduced by 25–50%.

Figure 19 shows the variation of the ANITA-IV volumetric acceptances coming from different `icemc` parameter variations. The black solid line shows the effect of using BEDMAP instead of CRUST 2.0 as Antarctica ice model; the more finely binned BEDMAP map results in a roughly 20% lower acceptance over all energies. Future versions of the simulation will use BEDMAP2 [29], with improved ice bed, surface and thickness datasets for Antarctica. The orange solid lines shows the effect of varying the random surface inclination, the two cases shown are 0 and 2.4%, where the latter is double the nominal value. The violet area shows the change in acceptance resulting from using a range of fixed trigger thresholds (from the maximum to the minimum threshold) instead of the dynamic threshold actually used during the flight.

8.2 Limit

The projected 90% confidence level on the diffuse neutrino flux is set by using:

$$\left(\frac{E d^4 N}{dE dA d\Omega dt} \right)_{\text{lim}} = \frac{s_{\text{up}}}{T \cdot \epsilon_{\text{ana}}(E_{\nu}) \cdot \langle A\Omega \rangle(E) \cdot \Delta}, \quad (8.4)$$

where s_{up} is the upper (one-sided) limit for the mean of a Poisson variable given 0 observed events in the absence of background for 90% CL, T is the live time (17.4 days for ANITA-III and 24.25 days

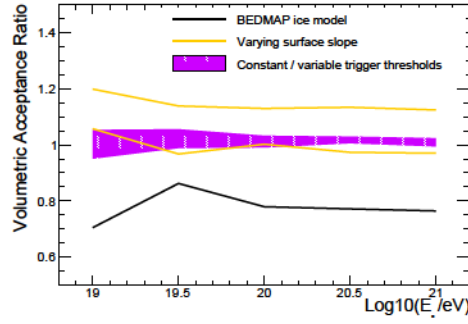


Figure 19. Ratio of ANITA-IV volumetric acceptances as a function of energy found varying different `icemc` parameters. The solid black line shows the variation coming from using BEDMAP instead of CRUST 2.0 as Antarctica ice model. The orange solid lines are calculated by setting the surface slope inclination at 0 or 2.4% (double the nominal). The upper and lower boundaries of the violet area correspond to the change in volumetric acceptance that would have resulted if the trigger thresholds had been set respectively at their minimum or maximum values for the entire flight rather than using the dynamic threshold.

for ANITA-IV), $\epsilon_{\text{ana}}(E_\nu)$ is the neutrino analysis efficiency, $\langle A\Omega \rangle(E)$ is the experiment acceptance as a function of the neutrino energy, and $\Delta = 4$ is a model-independent factor following reference [19].

Figure 20 shows the ANITA-III, ANITA-IV and ANITA I-IV limits as calculated in references [30, 31]. These are compared to the latest constraints coming from the IceCube [32] and Auger experiments [33], as well as four cosmogenic neutrino models [34–37].

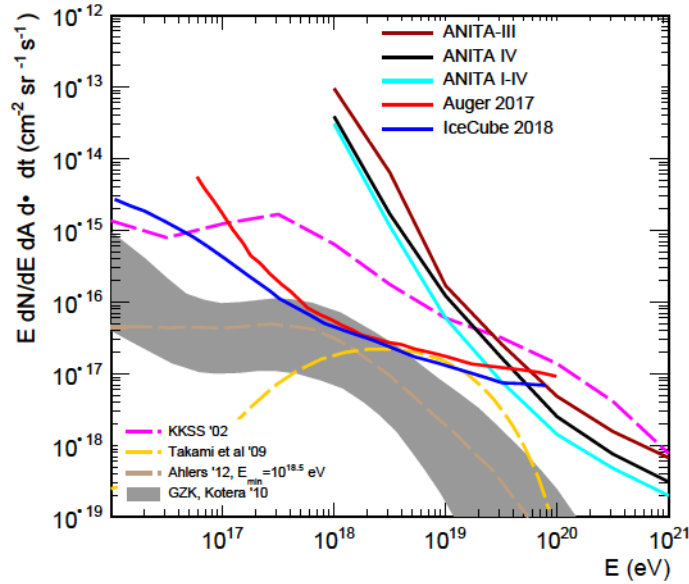


Figure 20. ANITA-III and ANITA-IV limit on the all flavor diffuse UHE neutrino flux and a combined limit from ANITA I-IV, as calculated in references [30, 31]. The most recent UHE neutrino limits from the Auger [33] and IceCube [32] experiments, and four cosmogenic neutrino models [34–37] are also displayed.

9 Summary and future improvements

The `icemc` Monte Carlo simulation program is used for the simulation of ultra high energy neutrino interactions in the Antarctic ice and their detection by the ANITA experiment. The data taken before or during the ANITA flights are used to validate the simulation. The latest ANITA-III, ANITA-IV and ANITA I-IV performance is provided in the form of the acceptance and energy dependent neutrino limit.

Future versions of the program will include the possibility to use extensive air showers inputs from ZHAireS [38]; improved ice bed, surface and thickness datasets from BEDMAP2 [29]; refined ice properties modeling and surface roughness effects; the contribution of the sun to the thermal noise; and CW noise as measured during the ANITA-III and ANITA-IV flights. We are also working towards expanding the framework so that it can be used by multiple radio experiments based in Antarctica.

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A Obtaining and using `icemc`

`icemc` can be obtained from the GitHub repository <https://github.com/anitaNeutrino/icemc>. The only mandatory requirement for the compilation of `icemc` is a ROOT [10] installation. The compilation can be executed via the Makefile or using the CMake structure.

To run `icemc` one needs to define two environment variables and add them to the global path:

- `ICEMC_SRC_DIR` should point to the directory where the source code is saved;
- `ICEMC_BUILD_DIR` should point to the directory where the executable programs are.

To run `icemc` one can simply do:

```
./icemc -i {inputFile} -o {outputDirectory} -r {runNumber}
-n {numberOfNeutrinos} -t {triggerThreshold} -e {energyExponent}
```

All of the parameters are optional and if they are not specified inputs from `inputs.conf` are used. The two standard input files for the ANITA-III and ANITA-IV flights come with the package.

The output directory contains a series of root files with information about all the neutrinos simulated, as well as a text file containing the neutrino survival efficiency at different stages of `icemc`, and the volumetric acceptance.

Other programs test a portion of the full `icemc` program:

- `testThermalNoise` simulates only the thermal noise at the payload for a specific ANITA flight.
- `testInputAfterAntenna` simulates the injection of an RF impulse after the antenna feed; this program is used to produce trigger efficiency scans similar to the ones taken before each ANITA flight.
- `testWAIS` simulates the WAIS pulser as described in subsection 7.2.2.

To produce ANITA-like output files and use more advanced features of `icemc`, the installation of `libRootFFTWrapper` (<https://github.com/nichol77/libRootFftwWrapper/>) and the ANITA `eventReaderRoot` (<https://github.com/anitaNeutrino/eventReaderRoot>) is necessary.

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