Application of Attosecond Techniques to Condensed Matter Systems

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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Abstract

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Dedicated to ???

Acknowledgments

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Vita

Oct 17, 1990 .... Born—Kolkata, India

May, 2013 .... B.S., NC State University, Raleigh, NC

Dec, 2015 .... M.S., Ohio State University, Columbus, OH

Publications

"Constraints on the Diffuse High-Energy Neutrino Flux from the Third Flight of ANITA", P. W. Gorham, P. Allison, **O. Banerjee** *et al.*, Physical Review D. I am a lead author and contributor of the new binned analysis presented, which is one of the three complementary analyses in the paper. Link to electronic version.

"Dynamic tunable notch filters for the Antarctic Impulsive Transient Antenna (ANITA)", P. Allison, **O. Banerjee** *et al.*, Nuclear Instruments and Methods A. I led this paper and served as **corresponding author**. This paper is on the filters that I played a lead role in commissioning for ANITA-4, that helped to triple the livetime of the experiment. Link to electronic version.

I am also a co-author on all ANITA publications (6 total) since Jan 2016.

Fields of Study

Major Field: Physics

Studies in Particle Astrophysics: Connolly group

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Chapter 1
Introduction

1.1 Exciting astrophysics happen far, far away

We live in a boring part of the Universe. This allows life and the life sciences to thrive here. However, everything that is interesting in astrophysics takes place far, far away. For example, most Gamma Ray Bursts (GRBs) take place about 1 Gpc away from us. That is over three billion light years away!

Why are GRBs interesting? Well, in short, they are Nature's most powerful accelerators and they outshine an entire galaxy when they occur, with luminosity $\sim 10^{52}$ erg/s. What is more, the physics behind these exotic events continue to remain mysterious for over 50 years. Figure 1.1 shows a depiction of a Gamma Ray Burst (GRB).

1.2 Astrophysical messengers

Traditional astrophysical messengers are not able to completely probe physics that take place at the farthest distances and at the highest energies. Since the beginning of astronomy, we have relied on optical light to study objects in the sky. In the last few decades, we have started utilizing light of other wavelengths such as X-rays and gamma rays. However, light of energy 1 MeV and above can undergo pair production. Light of energy 13.6 eV gets absorbed by Hydrogen atoms, the most abundant element in the Universe, while light at other wavelengths gets absorbed by other atoms and molecules. Light is the astronomer's best friend, but there is an inevitable need for complementary messengers.

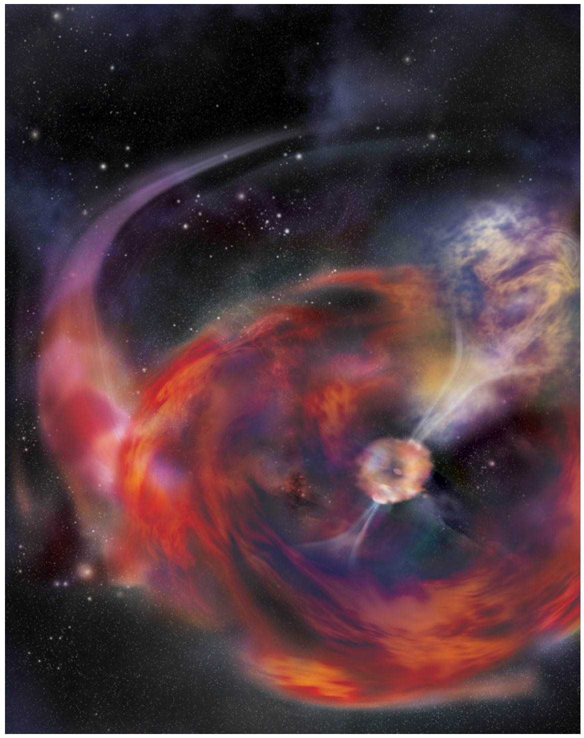


Figure 1.1: Depiction of a GRB. Picture Credit: NASA E/PO, Sonoma State University, Aurore Simonnet.

Fortunately, in the last century, we have opened up multiple new windows to peer into the Universe. About a 100 years ago, cosmic rays were discovered by Victor Hess in a balloon-based experiment. In the last several years, the IceCube neutrino observatory has discovered the first astrophysical neutrinos up to energies of a few PeV [1]. Moreover, gravitational waves were discovered by the LIGO collaboration in the last few years, confirming, for example, the association of short GRBs with neutron star - neutron star mergers [2]. Figure 1.2 summarizes the astrophysical messengers we have discovered so far.

1.3 Neutrinos as astrophysical messengers

Neutrinos are potentially perfect candidates for carrying information about distant particle accelerators all the way to us. Due to being neutral and weakly interacting, neutrinos would remain unattenuated and point straight back to their source. In this way, they would have a definite advantage over messengers such as cosmic rays. Neutrinos are the side product

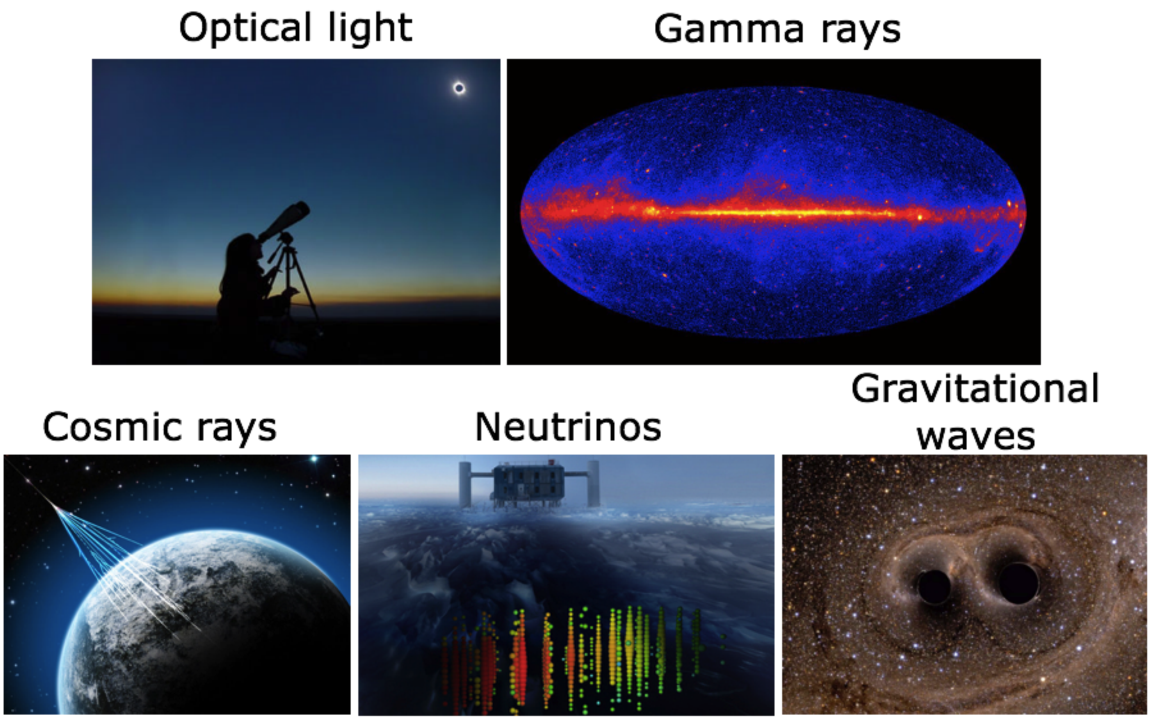


Figure 1.2: Astrophysical messengers. Pictures are all borrowed from Fermi, IceCube and LIGO collaborations, and the Internet.

of almost every nuclear reaction and can carry versatile information about particle physics taking place at cosmic distances. Their association with sources such as GRBs would confirm, for example, whether protons, in addition to electrons, get shock accelerated in the fireball model of the GRB [3].

Despite a lack of observation so far, ultra-high-energy (UHE) ($> 10^{18}$ eV) neutrinos are predicted to be produced in two ways, the more commonly referenced of which is known as the cosmogenic method. The cosmogenic method entails the interaction of cosmic rays with Cosmic Microwave Background (CMB) photons, as depicted in Figure 1.3a. UHE cosmic rays are predicted to travel only about 50 Mpc before they interact with CMB photons, a phenomenon known as the GZK Effect. This is thought to cause the sharp drop in flux at the highest energies as seen in Figure 1.3b. Such an interaction can also, potentially, lead to the production of UHE neutrinos, although no cosmogenic neutrinos have been observed so far.

The second way of producing UHE neutrinos is the astrophysical method, which is the one I find to be more motivating. The astrophysical method involves the production of UHE neutrinos in Nature's most powerful particle accelerators such as GRBs. This will be discussed in more detail in Chapter 1.1. In both the cosmogenic and astrophysical methods of producing UHE neutrinos, a commonly referenced process of production of the same is through the interaction of a proton and a photon creating intermediate pions, as shown in Figure 1.4.

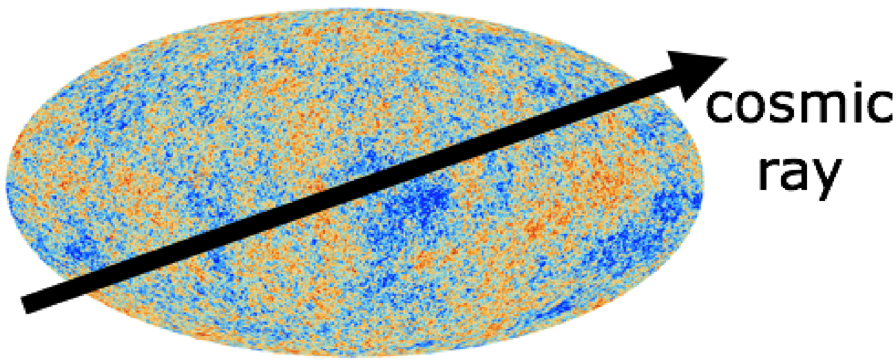
1.4 Optical Cherenkov neutrino detectors

Optical Cherenkov neutrino experiments look for high energy neutrinos in the energy regime of $10^{11} - 10^{15}$ eV. In this section, we briefly introduce two optical Cherenkov experiments, IceCube and ANTARES. Being located in complementary hemispheres of the earth, these two experiments have complementary fields of view. Where they are on the energy scale as compared to other particle physics experiments is shown in Figure 1.5.

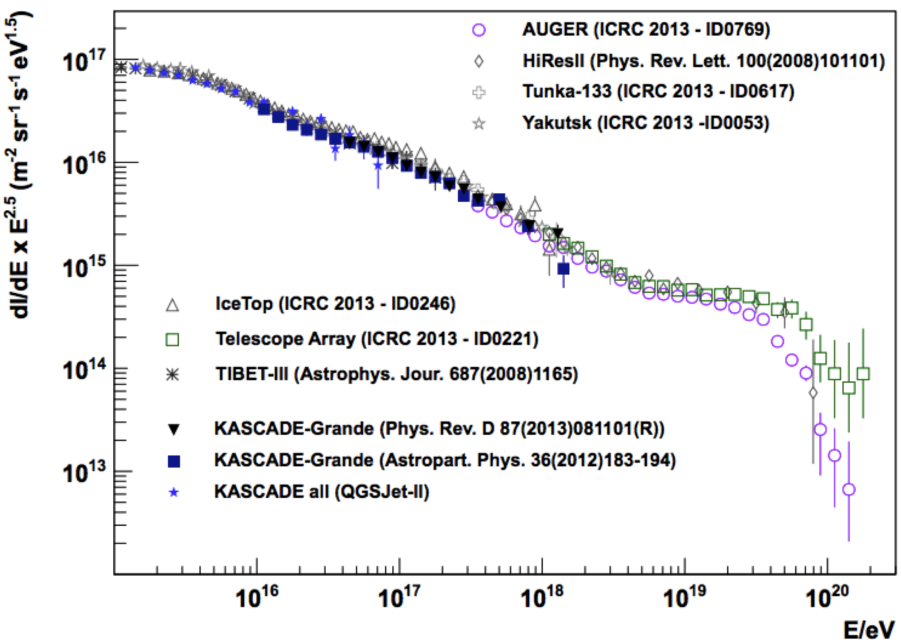
IceCube is the optical Cherenkov detector in the southern hemisphere. The observatory is located in the South Pole. The completed IceCube observatory is composed of 5160 digital optical modules (DOMs), each containing a 10−inch photomultiplier tube, with 60 DOMs placed at depths between 1450 and 2450 m on each of 86 vertical strings. The total instrumented volume of IceCube is $1\,\mathrm{km}^3$.

ANTARES is the optical Cherenkov detector in the northern hemisphere. It is located in the Mediterranean Sea. Located at a depth of 2.4 km, it consists of 12 vertical strings, separated from each other by a typical distance of 70 m. Each string is anchored to the seabed and held upright by a buoy at the top. Over a length of 350 m, it is equipped with 25 triplets of photo-multiplier tubes (PMTs), building a 3-dimensional array of 885 PMTs in total. The instrumented volume of ANTARES is $\sim 0.02\,\mathrm{km}^3$.

IceCube and ANTARES are both optimized for the detection of muons from charged current interactions of high energy astrophysical neutrinos. IceCube uses the Antarctic ice as a target medium for high energy neutrinos to interact in. ANTARES uses sea-



(a) t



(b) b

Figure 1.3: Top: Depiction of a cosmic ray interacting with the CMB. Thanks to the Planck telescope for the CMB picture. Bottom: Energy spectra of cosmic rays measured by different experiments. Andreas Haungs showed this plot at the 13th International Conference on Topics in Astroparticle and Underground Physics. UHE cosmic rays can only travel for about 50 Mpc before they interact with CMB photons and lose energy, therefore, we see a sharply falling spectrum at about 10^{20} eV energy.

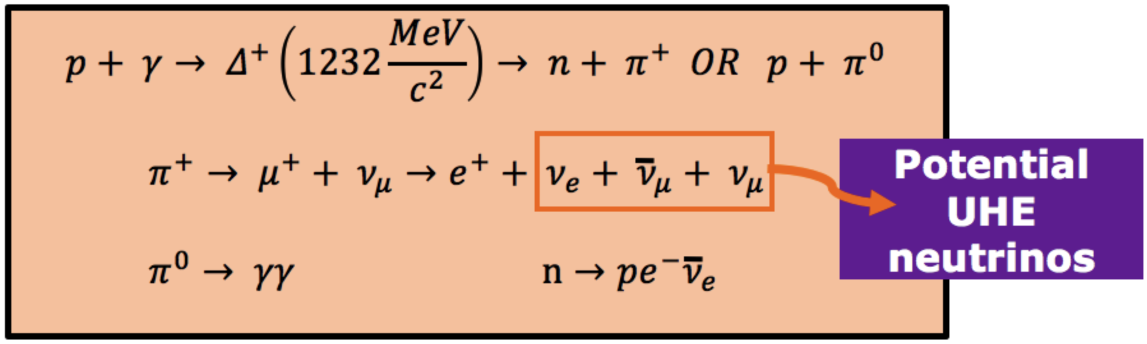


Figure 1.4: A process for production of UHE neutrinos.

water instead. They both look for optical Cherenkov signatures of high energy neutrino interactions. ANTARES is sensitive to neutrinos of energy 10 GeV - 100 TeV. IceCube was built to detect neutrinos of energy 100 GeV and higher. However, as shown in [4], IceCube can also detect neutrinos of energy of order MeV.

1.5 Radio Cherenkov neutrino detectors

Radio Cherenkov neutrino experiments look for UHE neutrinos in the energy regime of $> 10^{16}$ eV. The main challenge for detection by these experiments and a potential solution for detection are presented below. We also introduce two complementary radio Cherenkov experiments, ANtarctic Impulsive Transient Antenna (ANITA) and Askaryan Radio Array (ARA) in this section. Where they are on the energy scale as compared to other particle physics experiments is shown in Figure 1.5.

1.5.1 Challenge of detecting ultra-high-energy neutrinos

In this era of rapid growth in multi-messenger astronomy, UHE neutrinos remain undiscovered. One of the major challenges is that observation of these rare particles requires a huge detection volume. The interaction length of an EeV neutrino and a nucleus is about 300 km. Less than 0.01 UHE neutrinos are predicted to hit the earth per cubic kilometer per year, implying that to be sensitive to the UHE neutrino flux we need a detection volume much greater than a 100 cubic kilometers. Such a huge detection volume would be too expensive

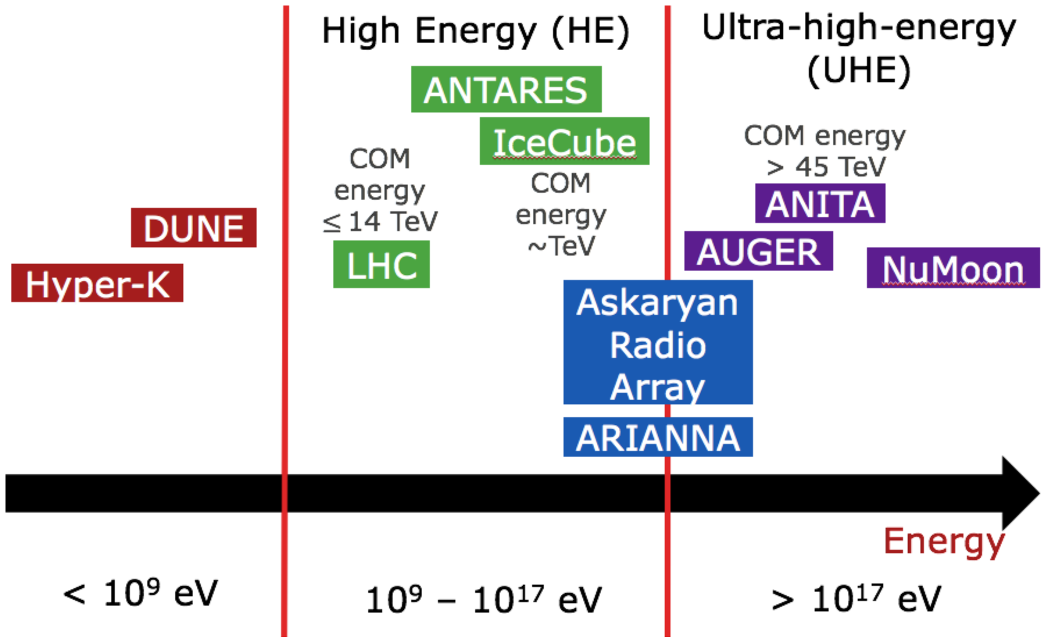


Figure 1.5: The ANITA experiment looks for particles, specifically, neutrinos of energies that are to close to the extreme right of the energy scale.

to instrument using optical Cherenkov detectors as optical light is attenuated over order tens of meters.

1.5.2 Askaryan Effect

A proposal by [5], known as the Askaryan Effect, stating that UHE neutrinos could be observed through their interaction in a dielectric medium, comes to the rescue. The principle is that a relativistic, UHE neutrino would interact with a nucleus in a dielectric to produce a particle shower traveling in the medium at a speed greater than the speed of light in the medium. The particle shower would mainly consist of photons, electrons and positrons. As it travels through the dielectric, the particle shower develops about a 20% negative charge. This happens primarily due to Compton scattering of electrons in the medium (so electrons leaving the medium and joining the shower) and secondarily due to annihilation of positrons in the shower with electrons in the medium (so positrons leaving the shower). As this charged particle shower travels through the medium at a speed greater than the speed of light in the medium, Cherenkov radiation is produced. If this Cherenkov radiation

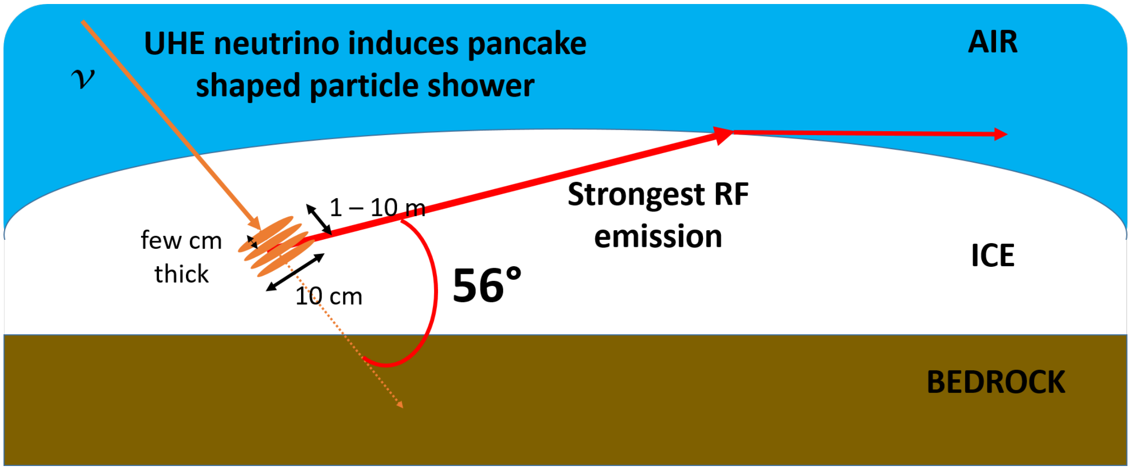


Figure 1.6: A UHE neutrino could start a pancake-shaped particle shower in the ice. Cherenkov radiation due to this particle shower would be coherent at wavelengths greater than the shower size of $\sim$ 10 cm, which correspond to radio waves.

is observed at wavelengths larger than the shower's transverse dimension of about 10 cm, then it would be seen as coherent waves in radio frequencies.

1.5.3 ANITA

ANITA is an experiment dedicated to discovering UHE neutrinos via the Askaryan Effect utilizing the Antarctic ice as the necessary dielectric target medium for neutrino interaction. Where ANITA's sensitivity lies in the energy scale as compared to other experiments in particle physics and particle astrophysics is presented in Figure 1.5. A cartoon of an UHE neutrino coming in to the ice and starting a particle shower that leads to Cherenkov radiation emitted coherently at an angle of about 56° is shown in Figure 1.6. ANITA looks for radio Cherenkov signals with an array of radio antennas. The ANITA detector is hung from a Helium-filled balloon and launched from near McMurdo Station, Antarctica, during the Austral Summer. After it is launched, ANITA floats up to an altitude of about 40 km and utilizes the polar vortex to fly in roughly circular orbits over the continent of Antarctica. At its float altitude, the balloon, upon gradual inflation, is bigger than the Ohio Stadium. There have been four flights of ANITA so far. These are summarized in Figure 1.7.

During its flight, at any given time, ANITA can scan about a **million** cubic kilometers

Year	Flight	Length of flight	Status
2006 - 2007	ANITA-1	35 days	Data analysis published
2008 - 2009	ANITA-2	30 days	Data analysis published
2014 - 2015	ANITA-3	22 days	Results public now
2016	ANITA-4	27 days	Data analysis ongoing
2020?	ANITA-5	--	Improving digitizers and trigger

Figure 1.7: Summary of ANITA flights.

of ice. This makes ANITA the neutrino detector with the largest instantaneous detection volume. The use of the radio Cherenkov technique goes hand in hand with covering a detection volume that is orders of magnitude larger than what is possible with optical Cherenkov techniques such as in IceCube (1 cubic km detection volume). Radio waves have attenuation lengths of order 1 km while optical light attenuates over order tens of meter. For ANITA, radio waves from neutrino cascades are produced in the ice, but then have to travel 40 km through air before they can reach the detector. Therefore, ANITA is sensitive only above about an EeV neutrino energy so it is looking for the rarest neutrinos. A cartoon of radio waves from a particle shower caused by an UHE neutrino in the ice reaching the ANITA detector is shown in Figure 1.8.

1.5.4 ARA

In contrast to a balloon-borne detector such as ANITA, ARA is ground-based and the ARA radio antennas are embedded in the ice of Antarctica. When ARA is deployed, it can, potentially observe all year round, as opposed to only about a month of observation time in ANITA.

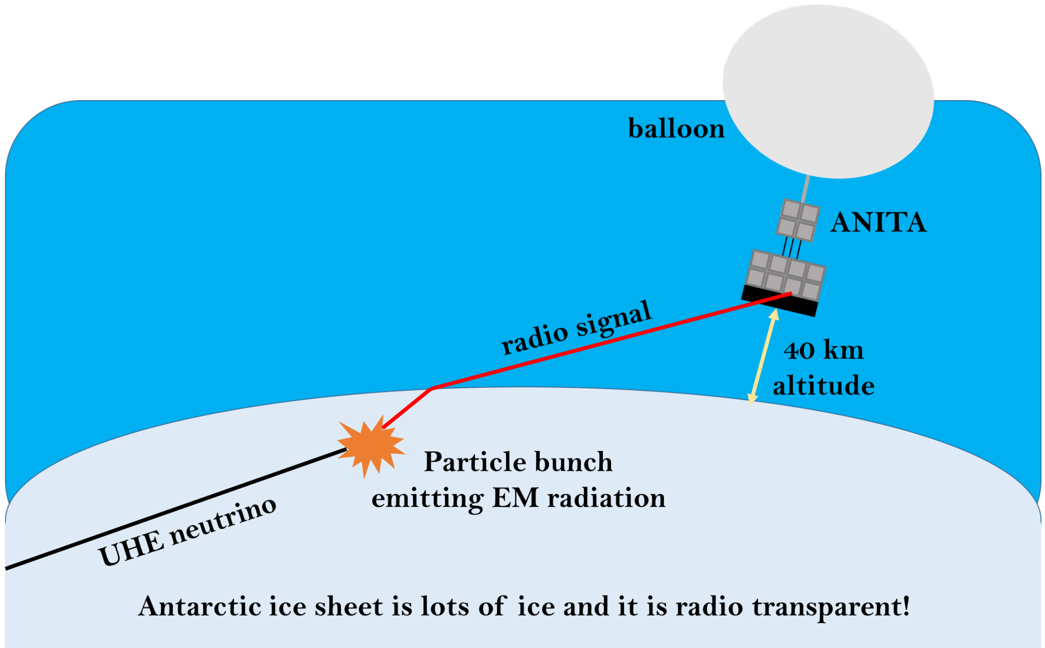


Figure 1.8: Concept of detection of UHE neutrinos with ANITA.

The completed ARA detector will consist of 37 deep stations spaced 2 km apart at a depth of 200 m. Currently, ARA has five deep stations in the ice. A station or a single array element consists of a cluster with around 16 embedded antennas, deployed up to 200 m deep in several vertical boreholes placed with about ten meters horizontal spacing to form a small sub-array [6]. ARA is highly modular in that each station comprises a standalone neutrino detector for its surrounding ice. All borehole antennas have a bandwidth of 150 MHz to 1 GHz.

Like ANITA, ARA too relies on the Askaryan Effect [5] for observation of UHE neutrinos. ARA, too, utilizes the Antarctic ice as a target medium for neutrino interactions to look for radio signatures from these interactions. The main distinction between ANITA and ARA is the area of target medium (ice) they each observe, and therefore, the neutrino energy range they are each sensitive to. ANITA observes an area of roughly a million km^2 and is sensitive to very rare neutrinos of energy 10^{18} eV and above. ARA covers roughly a 200 km^2 area and is sensitive to the neutrino energy range of $10^{16} - 10^{19}$ eV.

1.5.5 ARA vs. IceCube

The main distinction between ARA and IceCube is that ARA is able to observe a hundred times bigger target volume than IceCube with fewer detector units than IceCube. This is because the attenuation length of radio signals of the frequency range that ARA detects is $\sim$ 1 km allowing for a sparsely distributed array of detector units, whereas, the optical signals that IceCube detects are restricted to $< 100\,\mathrm{m}$ lengths. The energy threshold determines the expected flux, and thus the size of the detector. With a smaller instrumented volume IceCube is typically sensitive to energies lower than the UHE regime, whereas, ARA is sensitive to ultra-high-energies up to 10^{19} eV.

1.6 Summary of remaining chapters

The work presented in this thesis is with regard to the ANITA experiment. Chapter **??** describes the ANITA instrument and highlights new electronics that tripled the instrument livetime of ANITA. Chapter **??** describes the development of a new technique for analysis known as the "binned analysis" with a focus on background reduction. The first physics results from this new analysis are presented in Chapter **??**. Chapter 1.1 is a review of GRBs, my favorite transients, in the context that these exotic events could be sources of UHE neutrinos. Chapter **??** describes the developments in adapting the simulation and the binned analysis to a search for neutrinos from sources, specifically, GRBs. Mysteries, thoughts, ideas, and associated results are presented in Chapter **??**.

Appendix A
How to run the ANITA-3 binned analysis

The ANITA binned analysis software is maintained, backed up and version-controlled on GitHub at the link:

https://github.com/osu-particle-astrophysics/BinnedAnalysis

Inside this repository, there exist code to perform the binned analysis for ANITA-2 as well as code for ANITA-3. These are located in the directories called `anita2code` and `anita3code`, respectively. In this appendix, we will cover how to run the analysis for ANITA-3. Note that the ANITA-3 analysis could be adapted to work for ANITA-4. The ANITA-2 flight had a significantly different triggering system, among other differences, making it difficult to adapt its analysis to newer flights. However, I will try to include a separate note on how to run the binned analysis for ANITA-2 as well.

Doing the ANITA-3 binned analysis involves running a set of code. Details on the development of this code base can be found in [7–9] and in various chapters of this thesis. To run the analysis, the order of operations to follow are below.

Run interferometry

Run analysis stage 1

Run analysis stage 2

Optimize LD cut

Run analysis stage 2

A.1 How to run the interferometry

Go into the file called runInterferometry.cxx and change two things: the input and the output. Specifically, this might involve setting the variables called `dataDirLocal`, `outputFilename`, and `outputDirStr`. I show below what I have set these to for my current work.

dataDirLocal: `$OINDREE_SIM/kotera_march30/Energy_222`

This is the simulated data over which I currently want to run the interferometry. It may not be what you need.

What you change this to depends on which simulation data you want to run interferometry over.

outputFilename: `/fs/scratch/PAS0174/anita/oindree/InterferometryOutput/simKoteraMarch30/geomFilter/analyzerResults..root`

outputDirStr: `$OINDREE`

You should change the outputDirStr and OutputFilename to something else, such as some directory where you want the output. Then run:

make `runInterferometry`

qsub `runInterferometrySim.job`

showq -u osu0426

The last command is to see whether the job started or not. A `.o` file will appear when the job has finished, check it and make sure everything looks right . Mainly you are checking that the input and output that you intended for it to use is actually being used. Once the job has finished go to the output dir and check the root file `analyzerResults*.root` that was made to make sure it looks fine. There should be only one root file, for one run.

We have not run the interferometry for all the runs yet. If this looks good we can run interferometry for all the runs now. This is done by running the following:

```
./runInterferometrySim.sh
```

This starts a job for each run.

Recap of code files we used for interferometry:

```
runInterferometry.cxx
runInterferometrySim.job
runInterferometrySim.sh
```

Also commonly useful to know is how to run the interferometry for a particular event from the real data:

```
./runInterferometry-PB--FILTER_OPTION=4,-BbaselineSampleSmooth_1_2.00.root
383 69969708
```

This command will run the interferometry for a single event 69969708 from run 383.

- $FILTER\_OPTION = 4$ invokes the geometric filter with a noise baseline from the file indicated in the -B parameter
- $FILTER\_OPTION = 2$ and $SINE\_SUBTRACT\_THRESHOLD = 0.1$ will give a reasonable implemetation of sine subtraction filter
- $FILTER\_OPTION = 0$ means no filtering
- -O parameter directs the output to the directory name contiguously following the -O
- -G displays the the interferometric maps interactively

A.2 How to run analysis stage 1

To run the analysis stage 1, you can compile the associated code as follows:

make `runAnalysisStage01`

Currently, there are lots of warnings that you get at this stage and that is the "normal." Next run it as follows.

For simulation:

qsub `stage01_sim.job`

For data:

qsub `stage01.job`

When stage 1 finishes running, it makes several files in the output folder you assigned.

Most importantly, this file is made as an output from stage 1 :

`analysisOutput_1_99.root`

This is from me running the code for simulation with runs going from 1 to 99. The run numbers will depend on which runs you had the code run over. The more runs you run it over the longer it takes. This file is the input in stage 2 of the analysis, so in that sense this is the most important file because without this you can't do the next stage of the analysis.

If you want to run stage 1 for ONE event from data (ANITA-3), say, for an interesting event such as the mystery event 2 or ME2, this is how you could do it:

```
./runAnalysisStage01 -CA -9
-D/fs/scratch/PAS0174/anita/2015_05_19/sample_90/geomFilter 175 439 15717147
```

This would actually take a while as you are saying to run over all the runs used in the analysis so you would need to run a job with this command (see `stage01.job`)

To save time you could also just run using the run that the particular event is in, e.g. ME2 is in run 176 so you could do :

```
./runAnalysisStage01 -CA -9
-D/fs/scratch/PAS0174/anita/2015_05_19/sample_90/geomFilter 176 176 15717147
```

The `-CA` flag tells the stage 1 code to apply analysis cuts. The `-9` flag tells it to use the 90% data sample. The `-D` flag tells it the location of the interferometry results. The 176 and 176 tells it the run(s) to run the code over and the 15717147 is the specific event number for which the code would be run. When an event number is not specified at the end then the code is run for all events in the specified runs.

When you get to the point of running stage 1 and have made the `analysisOutput... .root` file, you should try looking inside that file and see what things are in there and try to visualize them to get a better idea.

A.3 How to run analysis stage 2

The stage 2 code is run twice, once before the optimize code and once after. In this section, we discuss how to run it before the optimize code.

The stage 2 code takes as input a file that was output from the stage 1 code:

`analysisOutput_188_193.root`

The above file is made by running the stage 1 code over the ANITA-3 data using runs 188 through 193. If other runs were used the associated run numbers would appear in the filename instead. If stage 2 also needs to be run over those same runs then the following command can be used:

```
./runAnalysisStage02
-D/fs/scratch/PAS0174/anita/oindree/Stage1Output/BgOnly/GRB1
-I/fs/scratch/PAS0174/anita/2015_05_19/sample_10/geomFilter 188 193 -b -PV
-S_v -FanalysisOutput_188_193.root
```

The -D flag tells the stage 2 code where the file output from stage 1 is. The -I flag tells the code where the associated results from running the interferometry is. 188 and 193 are the start and end runs over which stage 2 will run. -b tells it to re-bin. -PV tells it to run for vertically polarized (VPol). `-S_v` labels an output file with the subscript `_v` denoting

VPol. The -F flag tells the stage 2 code the name of the input file from stage 1 that it has to use.

When stage 2 finishes running it also makes a file called `analysisOutput_188_193.root`, for example, which can then be used as input by the optimize code.

A.4 How to run the optimize code

Before running the optimize code, make sure to change the variables `outputDir` and `inFilename`. To run the optimize code using the optimized healpix orientations, use the following commands.

VPol: `./optimizeLDCut -pV -r --PHI_HP_OFFSET=.56 --THETA_HP_OFFSET=-5.04`

horizontally polarized (HPol): `./optimizeLDCut -pH -r --PHI_HP_OFFSET=3.92 --THETA_HP_OFFSET=0.00`

A.5 How to run analysis stage 2 again

After optimizing, the stage 2 analysis must be run again - this time, with final cuts. This should be the last step of the analysis resulting in finding out which events pass all cuts. To run the stage 2 analysis with final cuts for VPol run something like this command:

```
./runAnalysisStage02 -b -D/users/PAS0654/osu0426/BinnedAnalysis/anita3code/
Diffuse/stage2inputs/fullDataSet
-I/fs/scratch/PAS0174/anita/2015_05_19/sample_90/geomFilter 175 439 -PV -S_v
-a -FanalysisOutput_175_439.root
```

The `-a` says to apply final cuts. Use it when optimizeLDCut has been run and you want to know which events pass all cuts. Things are getting serious now!

In order to successfully run stage 2 with final cuts, you need two files per polarization. First, you need to provide a file containing the bin numbers of bins that you will be using for your search. These should be named as follows.

Optimization results: slope=-6.000000 simulation scale factor=0.020654

bin number	status code	bin status	total-events sample	events-in fit-range	sim-events pre-rotated-cut	at-least 5-fit-bins	optimized cut-intercept	bin-fit p-value	p-value >0.05	sim-events passing	expected background	expBG High Error	expBG Low Error	sim-events before-cuts	Poisson CDF
3015	0	0	625.901733	136.935959	1.622395	1	9.300000	0.762976	1	0.788421	0.414216	0.585330	0.335798	2.125789	0.562356
3036	0	6	111.913727	34.120750	1.192751	1	7.800000	0.986500	1	0.741594	0.448480	0.769886	0.302279	6.312552	0.589136
3018	0	6	53.724117	15.465314	0.941968	1	9.099999	0.594600	1	0.534662	0.376481	0.778110	0.256713	5.769096	0.679675
3028	0	6	114.886307	16.944582	0.697135	1	7.500000	0.999700	1	0.422050	0.216915	0.470998	0.146389	1.289163	0.716202
3027	0	5	15.099290	9.099289	0.687625	1	21.754019	0.626463	1	0.635053	0.100000	15.002881	10.531096	2.569870	0.567227
3005	0	5	26.728806	17.416401	0.660619	1	40.637096	0.124312	1	0.623138	0.100000	37.120384	29.445889	0.266121	0.573534
3010	0	6	119.138695	33.755928	0.271338	1	7.200000	0.783600	1	0.182408	0.236224	0.426356	0.158666	0.018167	0.872518
3021	0	6	144.812424	45.275242	0.185426	1	13.099999	0.649865	1	0.049299	0.692559	1.001481	0.525463	0.198548	0.972648
2980	0	5	46.401596	22.279423	0.121427	1	65.305275	0.089309	1	0.118415	0.100000	78.598969	58.800343	0.000000	0.905030
2999	0	5	65.132187	36.072979	0.033741	1	15.647315	0.595300	1	0.015696	0.100000	2.845446	1.493319	0.033623	0.987225
2951	0	5	19.351412	7.608637	0.003686	1	37.333008	0.877988	1	0.003686	0.100000	39.407188	19.454659	0.000000	0.996999
3012	0	3	676.947937	286.142334	1.067907	1	9.400000	0.001600	0	0.419911	1.069419	1.331300	0.907240	4.578308	0.798896
3006	0	3	15.999999	9.999999	0.440770	1	3.100000	0.004800	0	0.440770	25.141794	31.272455	20.878748	0.224227	0.936849
2972	0	3	309.661682	160.227173	0.118793	1	3.500000	0.000000	0	0.118793	342.794250	358.291412	328.243073	0.069654	0.995024
3013	-1	1	87.133751	0.000000	1.850425	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	5.316202	1.000000
2969	-1	1	4.000000	0.000000	1.208815	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	2.008498	1.000000
3017	-1	1	25.900707	0.000000	0.826785	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	2.928531	1.000000
3034	-1	1	3.339602	0.000000	0.782504	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	13.668590	1.000000
3035	-1	1	26.425903	0.000000	0.766622	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	8.422397	1.000000
3020	-1	1	0.042925	0.000000	0.731981	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	6.285310	1.000000
3031	-1	1	299.533997	0.000000	0.546763	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	1.569314	1.000000
3033	-1	1	0.247982	0.000000	0.500577	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	16.444756	1.000000
2992	-1	1	81.301979	0.000000	0.495786	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.158826	1.000000
3026	-1	1	1.791851	0.000000	0.436710	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	2.700963	1.000000
3032	-1	1	1.000000	0.000000	0.300041	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	13.362612	1.000000
2993	-1	1	0.895434	0.000000	0.289072	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	3.430911	1.000000
2995	-1	1	1.000000	0.000000	0.258197	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	7.595967	1.000000
2966	-1	1	1.000000	0.000000	0.214085	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	4.652981	1.000000
2994	-1	1	0.368535	0.000000	0.204499	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	8.585691	1.000000
3039	-1	1	0.019456	0.000000	0.144504	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.865015	1.000000
3001	-1	1	1.067150	0.000000	0.139735	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2941	-1	1	28.746054	0.000000	0.136695	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.004368	1.000000
2960	-1	1	1.671515	0.000000	0.054840	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2981	-1	1	1.000000	0.000000	0.051858	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2965	-1	1	6.162866	0.000000	0.043694	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.491306	1.000000
2982	-1	1	1.000000	0.000000	0.024283	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2963	-1	1	0.990272	0.000000	0.024153	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2964	-1	1	1.336207	0.000000	0.018457	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.001804	1.000000
2942	-1	1	46.884235	0.000000	0.006868	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2903	-1	1	0.195330	0.000000	0.005710	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2929	-1	1	0.338213	0.000000	0.002114	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2928	-1	1	0.923122	0.000000	0.000797	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
3063	-1	1	0.776540	0.000000	0.000775	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	4.137301	1.000000
2952	-1	1	16.982901	0.000000	0.000183	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2943	-1	1	2.000000	0.000000	0.000003	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2975	-1	1	4.932849	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
2959	-1	1	0.067150	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
3064	-1	1	8.640919	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.006624	1.000000
3065	-1	1	8.911909	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.018564	1.000000
3066	-1	1	0.941613	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.525997	1.000000
3070	-1	1	3.729016	0.000000	0.000000	0	0.000000	0.000000	0	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000

```
 TOTAL                 18.113115                                      5.093896         126.637634
 ACCEPTED               6.418112                                      4.114422          18.582930
 FRAC                   0.354335                                      0.807716           0.146741
14 bins fitted
6 bins accepted
 total probability = 0.162968

                                                                                          44,1       All
```

Figure A.1: The table produced by the optimize code and needs to be used as input to run the stage 2 analysis with final cuts.

`binsOver0.01_h.txt`

`binsOver0.01_v.txt`

You will know the final bins to use for the search from the table produced in the optimize step called something like `oindree_optimization_final_sl_06_sf_0.020654.txt`. This table also needs to be provided to stage 2 as an input. Re-name the `oindree_optimization_final_sl_06_sf_0.020654.txt` file as the following before doing so.

`intercept_h.txt`

`intercept_v.txt`

A screenshot of an example table is shown in Figure A.1. Note that the eighth column from the left shows the optimized LD cut for each bin. This information, for example, is needed to run stage 2 with final cuts.

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