A new ray tracing algorithm for complex ice models and the analysis of ice properties using weather balloons

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SUMMARY

Outside our earth various kinds of events take place which we wish to observe: Black hole outbursts, supernovae, cosmic jets, ... These events produce various kinds of messengers which are useful to obtain information on the event: Gravitational waves, gamma rays, protons,... But one particle within this set of messengers is quite unique and the subject of our study: The neutrino.

The neutrino is unique in that it points back to the event itself. Due to the neutrino not having any charge, nearly no mass and interacting weakly it doesn't get bent nor absorbed and re-emitted on it's way to us unlike, say, the proton. This means that if we observe a neutrino back here on earth it's very likely that the direction we observe it in is the direction it came from.

We wish to detect neutrinos in a specific energy range: The ultra high energy (UHE) neutrino. There have been lots of neutrino detectors around but none of them have been able to observe *cosmogenic neutrinos* which would live past the 3 PeV energy range. This is probably caused by the exponentially falling flux with increasing energy, implying that a really big detector volume is required to detect neutrinos with such high energies.

Due to cost requirements, it was necessary to work in the radio regime. A really big detector working in the visible spectrum would cost way too much. As neutrinos can produce radio waves upon interacting in ice through the Askaryan effect and as radio waves can travel for way longer distances in there before interacting than visible light, it was previously decided in experiments like ARA and ARIANNA to detect on the principle of radio waves. The Radio Neutrino Observatory in Greenland or RNO-G which is currently under construction builds on the knowledge of these experiments to make a quite complex detector which should be capable of detecting UHE neutrinos.

The ice properties have an impact on how radio waves propagate. As mentioned before, RNO-G is a detector built in the Greenland icecap. As the radio waves get produced in the ice we need to figure out how they propagate towards our detector. An important part in figuring out how they propagate is the local index of refraction which seems to be linearly related to the density of the ice. The density of the ice seems to vary continuously with depth. A function describing

this overall relation of the index of refraction with the depth is called an *ice model* and it is crucial for future studies to understand this ice model.

Due to the ice model seeming to deviate from the theoretically expected single exponential, it was necessary to develop a new algorithm to find the paths the radio waves could take with more complex ice models. The software used within this thesis to figure out the path radio waves take is called *radiopropa*. Even though this software can be used to work with most kinds of ice models, it still needs to be used within some kind of algorithm to be useful. Such an algorithm has already been developed called the *Iterative ray tracer* as is explained in section 3.4 but it had its shortcomings, that's why in this thesis a new algorithm was developed called the *hybrid ray tracer* which is explained in chapter 4. The hybrid ray tracer makes it possible to both find a more accurate solution and find it faster.

It is, however, crucial to make sure we actually need a new kind of ice model. The measuring of the index of refraction can be accomplished indirectly through weather balloon fly-byes as is explained in chapter 5. This weather balloon is equipped with an antenna which sends out a 403MHz sinusoidal signal, upon close fly-byes with detectors this signal can be observed in the detectors (as is visualized on the cover). By looking at the difference in arrival time of the signal, the difference in timing can be made out from which a plane wave reconstruction can be done. As this plane wave reconstruction is heavily dependent on the local index of refraction in the ice, it can be indirectly measured through this reconstruction. After this analysis the following data was found:

Depth (m)	$n_{\text{exponential}}$	n_{fit}
-94.518	1.7397	1.7045 ± 0.006

It shows a big discrepancy with the exponential model. We reason that this clearly shows that there's a need to investigate the index-depth relation further.

SAMENVATTING

Er vinden verscheidene gebeurtenissen plaats in het heelal waarover we meer wensen te weten zoals Black hole outbursts, supernovae, cosmic jets,... Al deze gebeurtenissen produceren vormen van informatie dewelke we kunnen infereren door hun op een manier te detecteren zoals de protonen en fotonen maar ook meer exotische bronnen van informatie zoals zwaartekracht golven. Maar één bepaald deeltje vinden wij bijzonder interessant: de neutrino.

De neutrino heeft als erg unieke eigenschap dat het terugwijst naar het event waar ze gecreëerd werd. In tegenstelling tot andere deeltjes zoals protonen heeft de neutrino geen lading, bijna geen massa en interageert ze zeer zwakjes. Door deze eigenschappen zal ze op de weg naar de aarde niet afgebogen worden door magneetvelden en hoogstwaarschijnlijk niet interageren met tussen media zoals gaswolken. Deze eigenschappen impliceren dat, als we erin slagen een neutrino te detecteren, de richting waarin ze gedetecteerd wordt hoogstwaarschijnlijk eenzelfde richting is als waar ze vandaan komt.

Neutrino's komen in verscheidene energieën voor maar wij zijn geïnteresseerd in één bepaald gebied, boven de 3 PeV oftewel de ultra hoge energie (UHE) neutrino. In de verscheidene experimenten die neutrino's hebben gedetecteerd is er nog geen een in geslaagd neutrino's te observeren met energieën boven de 3 PeV. Dit is het regime waar zich zogenaamde *cosmogenic neutrinos* zouden bevinden en dus uiterst interessant om te bestuderen. Maar, om zo'n hoge neutrino energie waar te nemen, blijkt een zeer grote detector nodig te zijn.

Aangezien het zeer snel zeer duur zou zijn om een voldoende grote detector te bouwen om deze neutrino's te detecteren in het visuele spectrum, wat bijvoorbeeld gebruikt wordt in detectoren zoals IceCUBE, werd besloten om te leunen op het Askaryan effect. Dit is het effect dat zorgt voor de productie van radiogolven bij interactie van een neutrino in ijs. Aangezien radio golven verder vrij kunnen propageren in ijs dan zichtbaar licht maakt dit het mogelijk om de verscheidene antennes verder van elkaar te plaatsen. Enkele experimenten zijn op dit principe gebouwd zoals ARA en ARIANNA. Uit de expertise van deze en soortgelijke experimenten werd dan de Radio Neutrino Observatory in Greenland of RNO-G gemaakt. RNO-G moet het mogelijk maken om UHE neutrino's te observeren en deze thesis wenst bij te dragen tot het gebruik van deze detector.

Het blijkt dat de eigenschappen van het ijs een effect hebben op hoe radiogolven zich propageren door het ijs. Aangezien RNO-G gebouwd is in Groenland op een groot volume ijs en ze werkt op het principe van radiogolven is het nodig dit te onderzoeken. Het blijkt dat de propagatie sterk afhankelijk is van de locale refractieve index van het ijs, dewelke lineair lijkt gerelateerd te zijn aan de dichtheid van het ijs. Hoe de locale refractieve index afhangt van de ruimtelijke positie wordt het *ijs model* genoemd. Theoretisch verwacht men een exponentiële afhankelijkheid van de dichtheid met de diepte, maar uit metingen blijkt deze af te wijken van het theoretische model.

De ray tracing simulaties die gebruikt worden om na te gaan waar de neutrino vandaan komt zijn sterk afhankelijk van het ijs model. Er werd vroeger een algoritme gemaakt dewelke enkel met het exponentieel model kan omgaan, maar door de recent gevonden tekortkomingen aan dit ijs model bleek het nodig een nieuw algoritme te bedenken. Zo'n algoritme, genaamd de *iterative ray tracer* werd daarom uitgevonden (zie sectie 3.4) maar bleek enkele tekortkomingen te hebben. Daarom vonden wij het nodig om een nieuw soort algoritme uit te vinden dewelke steunt op dat algoritme genaamd de *hybrid ray tracer*, de werking van dit algoritme kan gevonden worden in hoofdstuk 4. Dit algoritme maakt het mogelijk om beide een meer accurate oplossing te vinden en deze eveneens sneller te vinden.

Maar om over te schakelen op een nieuw ijs model met een ander algoritme is het nodig aan te tonen dat er effectief een groot verschil is tussen het theoretische exponentiële model en de echte refractieindex. Om dit aan te tonen kunnen we gebruik maken van weerballonnen. Deze weerballon beschikt over een antenne dewelke een sinusoïde signaal uitstuurt aan 403MHz, als zo'n ballon toevallig dicht bij een detector komt zal dit signaal kunnen gedetecteerd worden. Door een plane wave reconstructie te doen van dit signaal en gebruik te maken van de positie van de ballon kunnen we infereren wat de locale refractieve index is in het ijs. Deze procedure wordt volledig uitgelegd in hoofdstuk 5. Na deze procedure toe te passen werd de volgende data gevonden:

Depth (m)	$n_{\text{exponential}}$	n_{fit}
-94.518	1.7397	1.7045 ± 0.006

Er is een duidelijk verschil tussen de gemeten index van refractie (n_{fitted}) en die uit het exponentieel model ($n_{exponential}$) te zien. Wij concluderen dat dit duidelijk toont dat er een nood is om de refractieve index-diepte relatie verder te onderzoeken aangezien deze de concusies uit neutrino metingen sterk zal beïnvloeden.

DANKWOORD

CONTENTS

INTRODUCTION

NEEDS TO BE CHANGED Outside our earth various kinds of events take place which we wish to observe: Black hole outbursts, supernovae, cosmic jets, ... These events produce various kinds of messengers which are useful in detecting them: Gravitational waves, gamma rays, protons,... But one particle within this set of particles is quite unique and the subject of our study: The neutrino.

The neutrino is unique in that it points back to the event itself. Due to the neutrino not having any charge, nearly no mass and interacting weakly it doesn't get bent or absorbed and re-emitted on it's way to us unlike say the proton. This means that if we observe a neutrino back here on earth it's very likely that the direction we observe it in, is the direction it came from.

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Due to cost requirements, it was necessary to work in the radio regime. As much as we'd like a really big detector working in the visible spectrum, it would cost way too much. As neutrinos can produce radio waves upon interacting in ice through the Askaryan effect and as radio waves can travel for way longer distances in there before interacting than visible light, it was previously decided in experiments like ARA and ARIANNA to detect on the principle of radio waves. The Radio Neutrino Observatory in Greenland or RNO-G which is currently under construction and the subject of this thesis builds on the knowledge of these two experiments to make a quite complex detector which should be capable of detecting UHE neutrinos.

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crucial for future studies to understand this ice model.

It has become apparent that the ice model seems to deviate from the theoretically expected single exponential density expectation. In this thesis a new algorithm will be developed which makes it possible to work with more complex ice models and the verification of the shortcomings of the exponential model, which is now the only model that gets used, will be layed out.

CHAPTER

1

NEUTRINO AS ASTROPARTICLE

When looking at phenomena outside our earth the astronomer will turn to electromagnetic radiation, but he's missing out on a big part of the full picture. Not only do interesting events emit photons but also muons, nuclei, gravitational waves,... All kinds of particles which might also be of interest, that's where the astroparticle physicist comes in.

Of all these particles there is one particle which has properties we're quite interested in: the neutrino. Neutrinos don't have any charge, meaning that they are not deflected by magnetic fields. Also neutrinos interact very weakly, because of this they are often called "ghost" particles; on average 100 trillion neutrinos pass through your body per second, none of them having any effect. You'd even need a light year of lead to give you just a 50% chance of stopping a neutrino. These properties makes them ideal messenger particles as, when we detect a neutrino and it's arrival direction, we can be quite sure it came to our detector unhindered from a far away event in the exact same direction. Neutrinos can serve as unique clues about what's happening elsewhere in the universe including the cosmic collisions, galaxies, supernovae, Gamma-ray bursts (GRBs),... Where they are created.

In this chapter we'll give an overview of neutrinos and the various kinds of energies we expect to see them in when coming from outside our earth.

1.1 Discovery

When researching β^- decay, the decay of a neutron, researchers detected a proton and an electron coming from the neutron. However on closer inspection it became apparent that energy was lost somewhere in violation with the conservation law of energy, and angular momentum wasn't conserved either [14]. In particular, in the proton-electron model for the β^--decay of a nucleus (A,Z) you would expect the final result to be (A,Z+1) + e^-. But in the experiment the sum of the measured final energies didn't equal the initial energy of the nucleus. The solution postulated by Wolfgang Pauli was to introduce a new, really hard to detect particle with no charge and a very small mass: the neutrino. The neutrino comes in three flavors: electron, muon

and tau neutrinos, each corresponding to their respective lepton denoted as

$$\nu_e \quad \nu_\mu \quad \nu_\tau \tag{1.1}$$

and each also having an anti-particle.

$$\bar{\nu}_e \quad \bar{\nu}_\mu \quad \bar{\nu}_\tau \tag{1.2}$$

Now with the introduction of the neutrino the full β^- decay becomes

$$n \rightarrow p^+ + e^- + \nu_e \tag{1.3}$$

The inverse can then also be used to detect neutrinos:

$$p^+ + e^- + \nu_e \rightarrow n \tag{1.4}$$

Which is called beta capture and was first experimentally detected in 1956 [18] also making it the first experimental detection of a neutrino.

1.2 The weak interaction

As with the strong and electromagnetic interaction which interact via gluons and photons respectively, the weak interaction which is the primary way neutrinos interact, is also mediated by the exchange of elementary spin-1 bosons. Namely the charged bosons W^+ and W^- and the neutral Z^0 boson. Contrary to the gluons and photons however, these bosons are massive:

$$M_W = 80.40 \text{ GeV} \quad M_Z = 91.19 \text{ GeV} \tag{1.5}$$

Following general arguments, it can be derived that the range of any force is given by the Compton wavelength of the particles transmitting it [37], as the Compton wavelength is given by

$$\lambda = \frac{h}{mc} \tag{1.6}$$

The very large masses of the "force carriers" imply a very short-range interaction, in the order of 10^{-3}fm and can even be treated as a zero-range interaction at low energies.

These bosons can couple to leptons (e.g neutrinos, electrons, tauons and muons) but also to quarks. If they couple via the charged bosons then the coupling process is called a *charged current* reaction and if they couple via the Z^0 boson than the process is called a *neutral-current* interaction.

A simple interaction is sketched below

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{1.7}$$

Here the muon decays via a charged current reaction.

1.3 Neutrino sources

As shown in figure 1.1 [32] there are various kinds of neutrino sources. We'll discuss these one by one in order, leaving out the reactor anti-neutrinos and the terrestrial anti-neutrinos as we're only interested in neutrinos of astrophysical nature. The ones we'll thus discuss are the cosmological, solar, supernova, background from old supernovae, atmospheric, AGN and cosmogenic neutrinos.
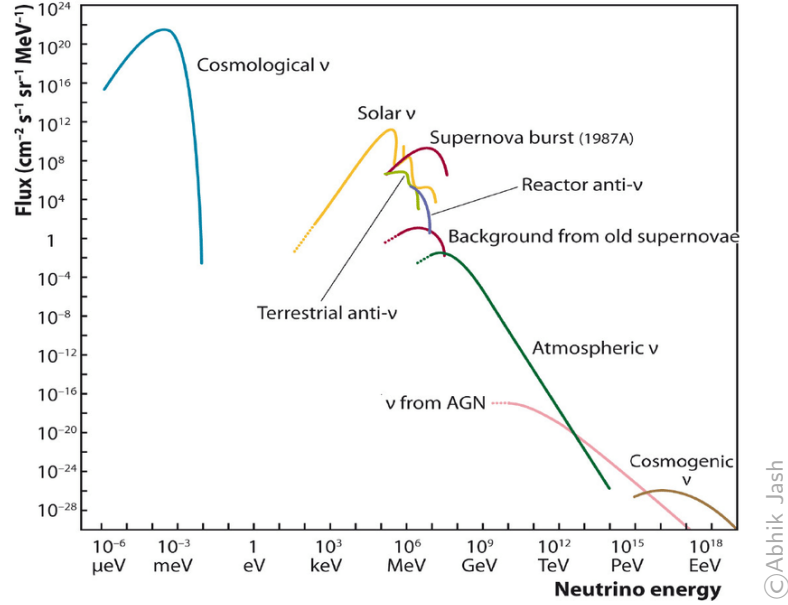
Figure 1.1: Less neutrinos will be observed for higher energies

1.3.1 Cosmological/Primordial neutrinos

The first source of neutrinos we'll talk about is the one in blue to the left of the figure termed the *Cosmological neutrinos*: the neutrino version of the CMB. To understand this source we'll have to go back all the way to just after the big bang: The very early universe was hot and dense. As a result, interactions among particles occurred much more frequently than they do today. As an example, a photon today can travel across the observable universe without deflection or capture, so it has a mean free path greater than 10^{26} m. When the universe was 1 second old, though, the mean free path of a photon was about the size of an atom. Thus in the time it took the universe to expand by a factor of 2, a given photon interacted many, many times. These multiple interactions kept the constituents in the universe in thermal equilibrium. But as the universe expanded there were times when reactions could not proceed rapidly enough to maintain equilibrium conditions, these particles then fall out of thermal equilibrium. This falling out of equilibrium is termed *decoupling*. And we're interested in when neutrinos decoupled. Neutrinos were kept in equilibrium through the interaction

$$\nu e \leftrightarrow \nu e \tag{1.8}$$

Up until the universe cooled down to about 1MeV when they decoupled. To estimate the temperature of the neutrinos who decoupled at the start of the universe, we can take a look at conservation of entropy [19] from which we'll find that the temperatures are related by:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \tag{1.9}$$

Note that they decoupled before the photons making them lower in temperature. As T_γ is the CMB temperature which, nowadays, is measured to be around 2.7K or 2.3×10^{-4}MeV. This would imply $T_\nu = 1.66 \times 10^{-4}$MeV which is roughly where the peak flux is located. These primordial neutrinos are thus very low in energy.
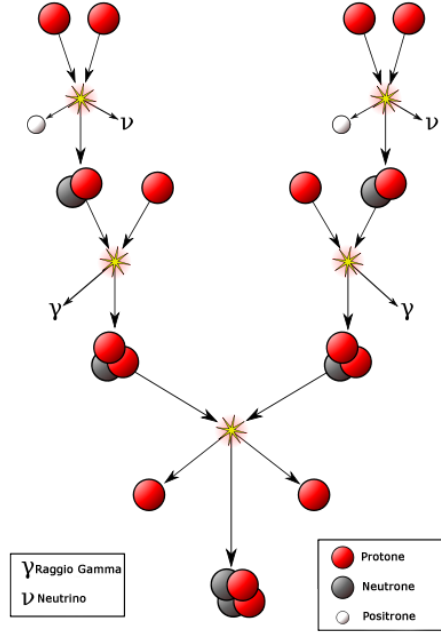
Figure 1.2: illustration of the full fusion cycle in the sun

1.3.2 Solar neutrinos

The sun fuses elements to release energy and thus keeping itself from collapsing in on itself, with most of the various ways particles get fused, neutrinos get released as is shown in figure 1.2 [3] where the neutrinos are electron neutrinos. Now with this and some information about the sun like the pressure and mass, the *standard solar model* was made. This model predicted a certain amount of electron neutrinos to be hitting the earth from the previously mentioned thermonuclear fusion, it was however 3 times higher than the observed amount of electron neutrinos back at our planet. This led to a little bit of hysteria as this could've meant that the sun was dying and we'd see the aftermath only in a couple of years. Through various experiments however, it became apparent that this was due to the different kinds of neutrinos oscillating into each other on their way to earth, i.e 2/3 of the original electron neutrinos had oscillated into mu and tau neutrinos. But for them to oscillate into each other, they not only require mass but each flavor also should have a different mass as can be seen from an example 2D approximation to the transition probability [13]:

$$P(\nu_e \to \nu_\mu) = |\langle \nu_\mu | \psi(L,T) \rangle|^2 = c_\mu c_\mu^* = \sin^2(2\theta)\sin^2\left(\frac{\Delta\phi_{12}}{2}\right) \tag{1.10}$$

with

$$\Delta\phi_{12} \approx \frac{m_1^2 - m_2^2}{2p} L \tag{1.11}$$

In full generality (3D):

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \tag{1.12}$$

With $U_{\alpha i}$ the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. This phenomenon has been experimentally verified e.g through the discrepancy from the observed and expected neutrino events coming from a nuclear reactor [20].

1.3.3 Supernovae

A star starts its life as a ball of pure hydrogen. At the core, due to the gravitational pressure of the outside plasma, fusion of hydrogen into deuterium and helium happens. Thus converting mass into energy. The pressure of this energy counteracts the pressure of gravity and the star is stable.

When the hydrogen at the core runs out no more hydrogen can be fused. For stars with masses between $8M_\odot$ and $30M_\odot$ ($M_\odot$ being the mass of the sun) the fusion of heavier elements starts, this can't keep going on however as at some point the star starts to form the most stable element: iron.

It costs energy to both make lighter elements than iron and heavier ones as can be seen on figure 1.3 [2]. As the iron core builds up the outside pressure from the core starts to decrease as no new
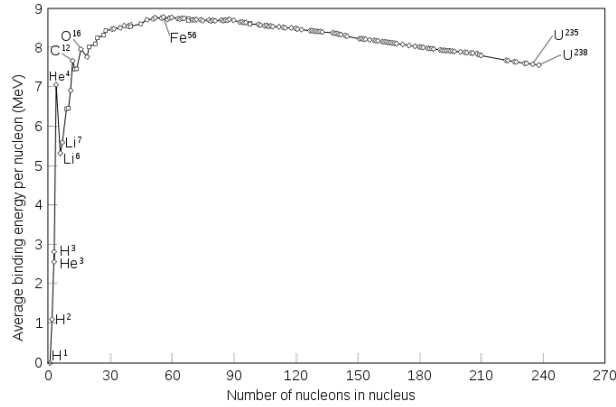
Figure 1.3: Energy curve showing that iron is the most stable atom

energy is released. This goes on until the treshold of an iron core with a mass of $1.4M_\odot$ known as the Chandrasekhar limit is reached and the inwards pressure becomes too large compared to the outward pressure, making the electrons surrounding the iron core fuse with the protons (uud), creating neutrons (udd) and neutrinos, diagramatically shown in figure 1.4.
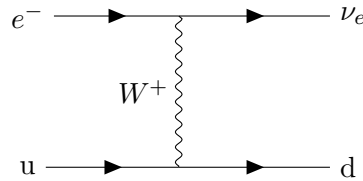
Figure 1.4: fusion of protons with surrounding electrons into neutrons via charged current exchange

This last part happens in a split second as the collapse goes at 25% the speed of light, creating a very dense neutron star (3000km in diameter iron core to 30km in diameter neutron star) and up to 10^{52} ultra-relativistic neutrinos, carrying up to 99%[1] of the released energy [38]. As the density has suddenly increased so much there's a huge distance of pure vaccuum between the plasma outer layer and the (now) neutron star. This plasma starts free-falling inward, also at 25% the speed of light whilst the neutrinos carrying tremendous amounts of energy start going outward from the neutron stars core.

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[1] $\approx$1% is released as kinetic energy, only 0.001% as electromagnetic radiation

The neutrinos then collide with the plasma resulting in what we observe as a "supernova", wrongly thought of by Kepler as being a "new (nova) star" rather being a violent death of an old star.

This is quite unexpected as neutrinos rarely interact, it's only as the incoming plasma is so dense and due to the tremendous amount of neutrinos that collissions happen at all. Some, however, escape and will be visible on earth in our neutrino detectors $\approx$ 18h before the light escapes the exploding star.

Neutrino observatories are thus also useful to know where to point our various telescopes before the supernova is actually visible in the night sky.

1.3.4 Background from old supernovae

Also termed the *diffuse supernova neutrino background* (DSNB), as the universe is quite old various supernovae have happened over it's lifetime, each generating a lot of neutrinos as was discussed in section 1.3.3. This is postulated to have generated a continuous neutrino background.

1.3.5 Atmospheric neutrinos

Before we can talk about atmospheric neutrinos it's necessary to discuss *cosmic rays*. Cosmic rays are ionized nuclei of which 90% are protons, 9% are alpha particles and the rest are heavier nuclei. Almost all of them originate from outside the solar system but from within our galaxy. The few particles that do come from our solar system can be temporally linked to violent events on the sun. In contrast to this the particles coming from outside our solar system show an anti-correlation with the sun as they can more easily reach the earth if solar activity is low. It has been observed that they roughly follow a power-law spectrum $N \propto E^{-\gamma}$ [22].

Cosmic rays hit the Earth's atmosphere at a rate of about 1000 per square meter per second and interact with atomic nuclei in the Earth's atmosphere, creating showers of particles, many of which are unstable and produce neutrinos when they decay. These neutrinos are what's called *Atmospheric neutrinos*. Most notably neutrinos can be produced together with muons in the two-body decays of charged pions and kaons wherever these hadronic interactions occur. The most important production channels and their branching ratios for neutrinos are:

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)(\sim 100\%) \tag{1.13}$$

$$K^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)(\sim 63.5\%) \tag{1.14}$$

Neutrinos are subsequently also produced when these muons decay:

$$\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu) \tag{1.15}$$

which is a process mainly happening at low energies in the atmosphere. The atmospheric neutrino spectrum shown in figure 1.1 roughly follows a power spectrum as the cosmic ray flux follows a power spectrum. But the correspondence isn't one-to-one as, due to the difference in kinematics, the contribution from kaons to neutrinos is significantly more important than to muons, especially at high energies.

1.3.6 neutrinos from AGNs

An AGN (active galactic nucleus) is deemed to be the reason why several abnormal galaxies exist with an extra bright (and mostly variable) light source in their core which even the biggest

of telescopes can't spatially discern. The general concensus is that this phenomenon is caused by one particular kind of object: a supermassive black hole (a black hole with a mass of at least $105M_\odot$) surrounded with a close torus of dust and gas. This torus of gas is called an *accretion disc* and is an enormous source of energy. The conversion of potential energy of the incoming gas to highly energetic radiation is a very complex physical process with which we have to account for various factors like gravitational instabilities, magnetic fields, hydrodynamical turbulence,... And thus produces a spectrum that's quite complex. It would appear that the luminocity of an AGN would increase indefinitely with incoming mass, but this process is limited: if too much matter accretes on the black hole the radiative pressure becomes too massive and the matter on the disc gets blown away. This phenomenon is termed a *black hole outburst*.

The emission of high energy neutrinos from AGNs rests solely on the premise that relativistic protons of sufficiently high energy and energy density in the AGN's accretion disc will be present [33] as they may interact to create e.g pions whom decay into neutrinos. A direct consequence of the occurence of these relativistic protons is the production of γ-rays of similar energies to those of the neutrinos, thus high energy neutrino- and γ-ray astronomy are closely related. However, even though γ-ray photons can be produced even in the absence of relativistic protons (e.g via high energy electrons), neutrinos can not. Thus the detection of these high-energy neutrinos (which might have already been detected [16]) will provide unique information about the workings of AGNs. As these ultra high energy neutrinos get produced near the source (the AGN) they are what's called *astrophysical neutrinos*

1.3.7 Cosmogenic neutrinos

In contrast to the previous source of UHE neutrinos which was generated at the source, called *astrophysical neutrinos* we'll now talk about UHE neutrinos whom are generated through the interaction of ultra-high energy cosmic rays during propagation with the cosmic microwave or other photon backgrounds termed *cosmogenic neutrinos*. The mechanism by which these get created is quite simple, if a proton has sufficiently high energy the cross section to interact with the CMB (Cosmic Microwave Background) becomes non-negligable. These protons can scatter off the photons to resonantly produce a Δ^+ baryon. This resonance has enough mass to dominantly decay to a pion and a nucleon:

$$\Delta^+ \rightarrow \pi^0 + p \quad (2/3) \tag{1.16}$$

$$\Delta^+ \rightarrow \pi^+ + n \quad (1/3) \tag{1.17}$$

Of which the charged pion decays to neutrinos as previously mentioned in 1.3.5, these neutrinos carry most of the original energy.

1.4 How do they fit into the full detector spectrum?

The origin of the most energetic cosmic rays is still not conclusively identified. One approach to solving this problem is *multi-messenger astrophysics*, where several types of cosmic particles are used to identify the sources of these ultra-high energy cosmic rays (UHECRs). E.g we simultaneously measure gravitational waves with the Einstein telescope, neutrinos with RNO-G, photons with various telescopes and muons with a muon detector.

CHAPTER

2

RADIO NEUTRINO DETECTION

Neutrinos on their own aren't detectable. Unlike say protons we can't expect them to produce Brehmsstrallung or any other kind of directly observable radiation as they aren't charged and thus don't couple to photons. We'll need to convert them to charged particles first which then can generate some kind of detectable signal.

To this end we'll need a big volume in which they can interact to produce charged particles, we'll be choosing ice for this. Even though there are a lot of large volumes such as water or solid rock, we prefer ice as it has a few particular properties which makes it more usable:

- contrary to some kind of sediment, ice is mostly see-through for electromagnetic radiation but it's still possible to differentiate between neutrino signals and other particles

- contrary to water as a medium which is used e.g in the Super-Kamiokande detector [21], ice was naturally formed and there is no need to construct some kind of dome

2.1 Neutrino interactions in ice

As neutrinos propagate through ice they can interact weakly with the nuclei (see section 1.2) . The main mechanisms of interaction is via charged- and neutral currents [23] as is also depicted in figure 2.1.
With the produced leptons in the W boson mediated interaction being either electrons, resulting in an electromagnetic shower, muons which typically go undetected as they live too long or tauons which will decay via

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \tag{2.1}$$

or, less ideally

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \tag{2.2}$$

In both of the possible interactions (W or Z exchange) the resulting nucleus will result in an hadronic shower. For the neutral current interaction (mediated by the Z boson) the fraction of the neutrino energy that gets transferred to the nucleon is described by the inelasticity y and is heavily shifted towards small values of y [5]. This causes a big, irreducible uncertainty

Figure 2.1: Most prominent ways of neutrino-nucleus interaction

when trying to estimate the original neutrino energy from these kinds of events. With the charged current interaction (mediated by the $W^\pm$ bosons) this isn't a problem however as the full neutrino energy ends up in the resulting cascades.

2.2 Askaryan effect

For a particle shower to emit strong radio signals, two conditions have to be met:

- There needs to be a separation of positive and negative charges in the shower front

- The signals produced over the length of the shower profile need to overlap coherently.

The *Askaryan* [10] effect, which is responsible for the production of Askaryan radiation describes the effect at radio frequencies which abides by both of these conditions. In general it's a quite difficult effect but we'll give a crude overview. The previously described interactions of the neutrinos with nuclei create a shower of secondary charged particles containing a charge anisotropy. This charge imbalance is a result of medium electrons either Compton scattering into the advancing shower or annihilating with shower positrons. In the end you have a moving charge anisotropy, propagating faster than the speed of light in the medium, creating Cherenkov radiation.

Cherenkov radiation is like the electromagnetic equivalent of a sonic boom. A sonic boom happens when something goes faster than the speed of sound in the medium; A particle emits Cherenkov radiation if it goes faster than the speed of light in the medium. Choosing the particle trajectory to lie along the z axis an approximate equation can be found [31] for $\frac{\mathrm{d}^2 \mathscr{J}}{\mathrm{d}\omega\mathrm{d}\Omega}$, which is the energy radiated per elementary unit solid angle and per elementary unit frequency interval:

$$\frac{\mathrm{d}^2 \mathscr{J}(\omega)}{\mathrm{d}\omega\mathrm{d}\Omega} = \frac{q^2}{4\pi}\sqrt{\frac{\mu}{\epsilon}}\beta^2\omega^2\delta^2[\omega(1-\beta\mathbf{e}_r\cdot\mathbf{e}_z)]|\mathbf{e}_r\times\mathbf{e}_z|^2 \tag{2.3}$$

Now we can re-write this equation in spherical coordinates, which gives $1-\beta\mathbf{e}_r\cdot\mathbf{e}_z = 1-\beta\cos(\theta_c)$ in the delta function. We thus only expect radiation if

$$\cos(\theta_c) = \frac{1}{\beta} = \frac{c'}{u} = \frac{c}{n}\cdot\frac{1}{u} \tag{2.4}$$

With u the local speed of light in the medium and n the index of refraction, an optical property of a medium which we'll later on thoroughly discuss. If $u > \frac{c}{n}$, Cherenkov radiation will be emitted along a cone surface with half angle $\frac{\pi}{2} - \theta_c$ as illustrated in figure 2.3. Integrating equation 2.3 over the solid angle and formally dividing by the time interval we get:

$$\frac{\mathrm{d}^2 \mathscr{J}}{\mathrm{d}\omega\mathrm{d}t} = \frac{q^2}{4\pi}\sqrt{\frac{\mu}{\epsilon}}\beta\omega\left(1-\frac{1}{\beta^2}\right) \tag{2.5}$$
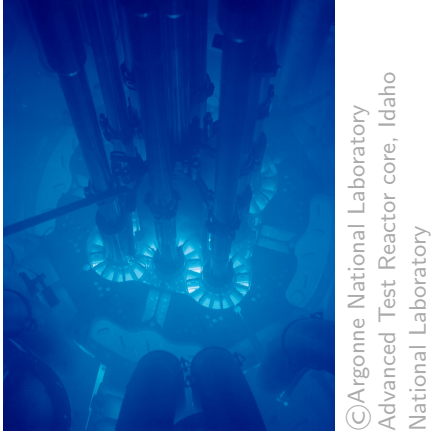
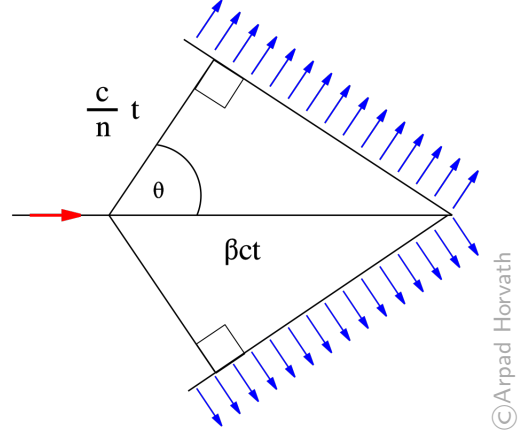Figure 2.2: Cherenkov radiation in a nuclear reactor

Figure 2.3: Diagrammatic representation of Cherenkov radiation

We see that the energy is proportional to ω, so we expect that most radiation will be emitted "in blue" with a cut-off frequency above which the equation $\cos\theta = 1/(n\beta)$ can no longer be satisfied. This "in blue" characteristic is responsible for the blue glow seen in nuclear reactors as seen in figure 2.2 . For ice the index of refraction is roughly 1.78 in deep ice [15], so we expect an ultra-relativistic particle to produce the most radiation at around 56° opening as

$$\cos(\theta_c) \approx \frac{1}{n} \implies \cos^{-1}\left(\frac{1}{1.78}\right) \approx 56° \tag{2.6}$$

Of course this is just an estimate, as the actual index of refraction is depth-dependent which we'll get to in section 3.2. Now this explains how the signals get generated but logically, from only knowing this we'd expect radio waves to almost be non-existent due to the "in blue" nature of Cherenkov radiation.

To understand why this isn't the case we'll need another piece of the puzzle: coherent overlap. Coherent overlap in the radio wave spectrum range can be intuitively explained as follows: generally the shower is of length $\mathcal{O}(10\text{cm})$ [30], over this length the radiation gets emitted, most frequencies decoherently interfering, but radio waves with wavelengths of $\approx 10\text{cm}$ coherently interfere, and it's these waves we then wish to detect. The radiation generated trough this Askaryan effect is called *Askaryan radiation*.

The Askaryan radiation is polarized perpendicular to the Cherenkov cone, this can be useful to discern between different Cherenkov cones whom, timely, would generate the same response. This concept is illustrated below in 2D where two neutrinos from different directions would generate the same signal in a non-polarized detector.
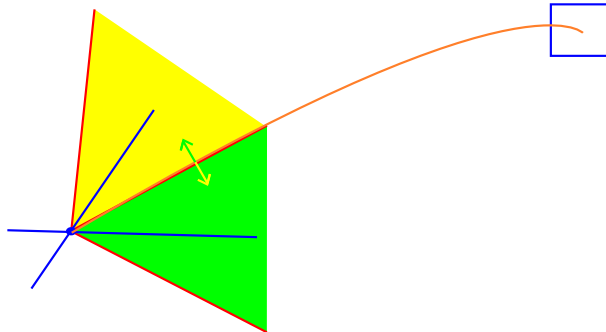
Figure 2.4: orthographic projection of Greenland with the red star representing the approximate RNO-G location

If the detector has a way to differentiate between polarization however, there would be no doubt where the neutrino originated from as the one producing the yellow Cherenkov cone would have a downwards polarization and the one producing a green Cherenkov cone would have an upwards polarization, note that in 3D infinite different Cherenkov cones could generate the same timely signal (think of rotating the cone around a line on the cone) so both vertical and horizontal polarization information is needed.

2.3   RNO-G

Both cosmic ray and neutrino detectors face the same main problem at the highest energies: the steeply falling flux (as was previously seen in figure 1.1) requires large effective areas, which leads to the construction of neutrino detectors with volumes on the cubic kilometer scale like IceCube [7] which works on the principle of detecting neutrinos with visible light. But even IceCube has it's limitations, it's still too small to observe many neutrino events above the 10 PeV scale [6] in acceptable timescales. That's why a new detector was needed which was even bigger and able to observe cosmogenic neutrinos. We could just make IceCube bigger but this would cost a lot of money as the individual detectors need to be spaced closely as the attenuation length is quite short for light in the visible spectrum propagating through ice.

The proposed solution was to work with radio wave detectors, leveraging the previously discussed Askaryan effect (see section 2.2). Radiowaves can propagate way further in ice than visible light making it possible to space the individual detectors further apart. The proposed location is Greenland, an island country in North America and part of the Kingdom of Denmark which has large ice sheets as shown in figure 2.4 [4]. The proposal for RNO-G, which was later funded and now in the construction phase, is for it to be an array of autonomous radio stations each of which having both surface channels and various deep channels resulting in a total of 24 channels per station. The whole project builds heavily on the knowledge obtained through previous radio based neutrino detectors like the NuMoon [17] project, ANITA [41], ARA [9],ARIANNA [11] and RICE [35].
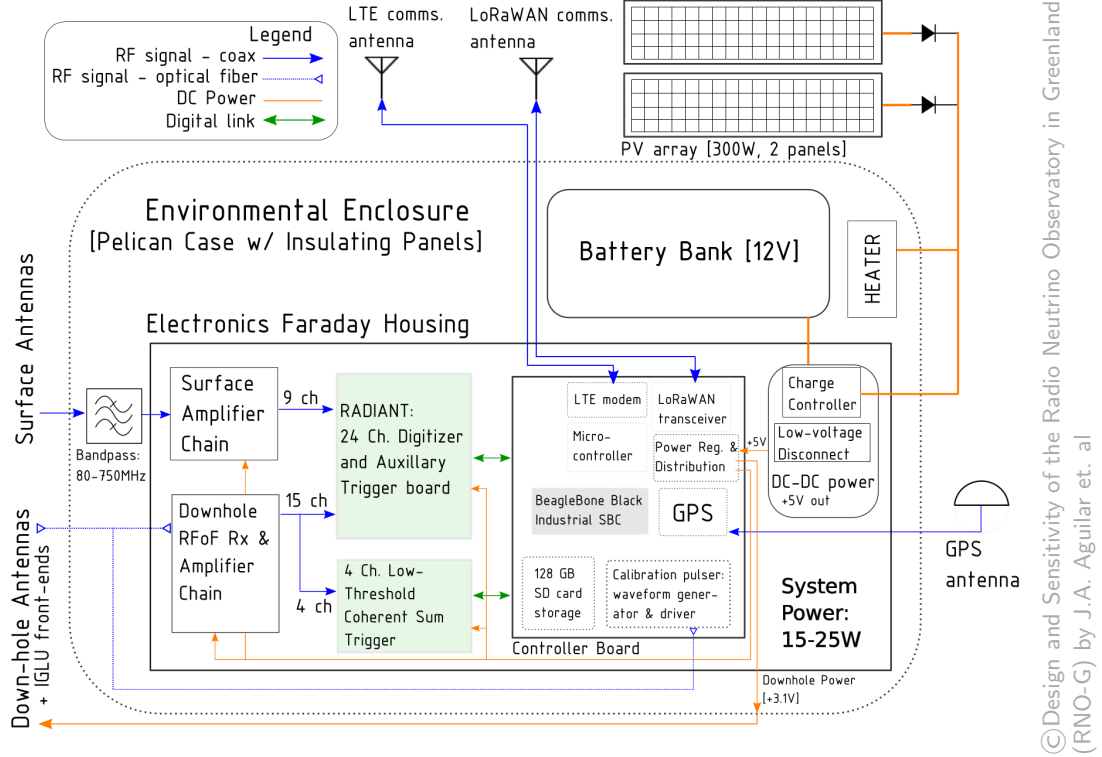
Figure 2.5: System diagram for a RNO-G station

2.3.1 Hardware

A station is illustrated in figure 2.7, the plan is to build 35 of these as is shown in figure 2.8[1] [1]. Looking closely at one such detector we see just below the surface 9 Log Periodic Dipole Antennas (LPDAs), these are used to detect air shower muon signals as muons will also generate Cherenkov radiation in the ice whose signals can then be filtered out. Aside form these surface detectors there are also deep components of the detector which can be split up in three parts: Two *helper strings* and the *power string*.

The helper strings are the 2 vertical cables shown on the right of figure 2.7 each housing 2 vertically polarized antennas (Vpols), one quadslot antenna for the horizontal polarization component (Hpol) and one radio pulser on each helper string which can be used to generate calibration signals. As was previously mentioned the polarization can be used to distinguish between possible Cherenkov cones generating the same resulting pulse, that's why both the helper and power string are equipped with both kinds of polarized antennae.

The power string (the leftmost vertical cable) is more densely instrumented than the helper strings: At the bottom it houses a set of four Vpol and two Hpol antennas with a spacing of 1m called the *phased array*. Arguably the most important channels in a station as it's spaced closely together and can thus use the principle of phasing the channels to get higher precision. Further up the string, with a spacing of 20m, are three more Vpol antennas.

A full system diagram for a RNO-G station is shown in figure 2.5 [8], I'll give a walk trough of how data gets collected. The signal from each of the deep antennae are fed into a low-noise amplifier directly above it, from there the signal is send to the data acquisition (DAQ) system

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[1]note that all the individual detectors are numbered but also named after various species living in Greenland (in the native tongue)

Figure 2.6: example simulation showing both direct and refracted path from a neutrino vertex (bottom left) to a detector (top right)

at the surface via a Radio Frequency over Fiber (RFoF) cable. The signals coming from the surface antennae are first passed through a Bandpass filter of 80-750MHz[2] after which both the resulting signals and the deep component signals get sent up to the RAdio DIgitizer and Auxiliary Neutrino Trigger (RADIANT). There it's again amplified, digitized and, if a trigger threshold is reached, saved onto an SD card. This data is then transmitted via a Long Term Evolution (LTE) telecommunications network to a local server[3], from where it is sent via a satellite link. As a power source, battery banks are used whom are charged via solar panels. But as there isn't enough light during the Greenland winters, there are plans to build wind turbines (with one of the problems being the possibly detectable RF noise the 'engine' would produce).

As was previously explained the radio signal from a neutrino often travels along both direct and refracted paths, designated DnR, to the deep array (as shown on figure 2.6). This double pulse characteristic would be a smoking-gun signature of an in-ice source. The two helper strings are needed for a full direction reconstruction. Three independent measurements are needed for azimuthal information, which is provided by the Vpol (Vertical polarization) antennas and placing the Hpol (Horizontal polarization) antennas at different depths on every string, both zenith and azimuth information will be provided for those signals. The helper strings' calibration pulsers, as well as one on the surface, will ensure regular monitoring of the performance of the station and provide information useful for precise calibration of the antenna geometry.

2.3.2 Reconstruction: Lookup tables

The main simulation code we'll be using consists of 2 parts: NuRadioMC [24] and NuRadioReco [25]. NuRadioMC uses Monte Carlo simulations to generate neutrino events in the ice and simulates how they propagate to the various channels, which will be covered more in-depth in the next chapter. NuRadioReco is reconstruction software, it simulates how the various detectors would respond to the detected radio waves. This simulation software is needed as the plan is to simulate a lot of neutrino events and record the detector responses in a giant database, then, when an actual neutrino event occurs, we'll only have to look in the database and match the actual detector response to the simulated detector responses, thus finding the origin.

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[2]i.e a filter that only lets frequencies in this range pass

[3]There is additionally a Long Range Wide Area Network (LoRaWAN) antenna as backup in case of problems with the LTE network

Figure 2.7: diagram showing the numbering and locations of the various antennae

RNO-G Planned Layout
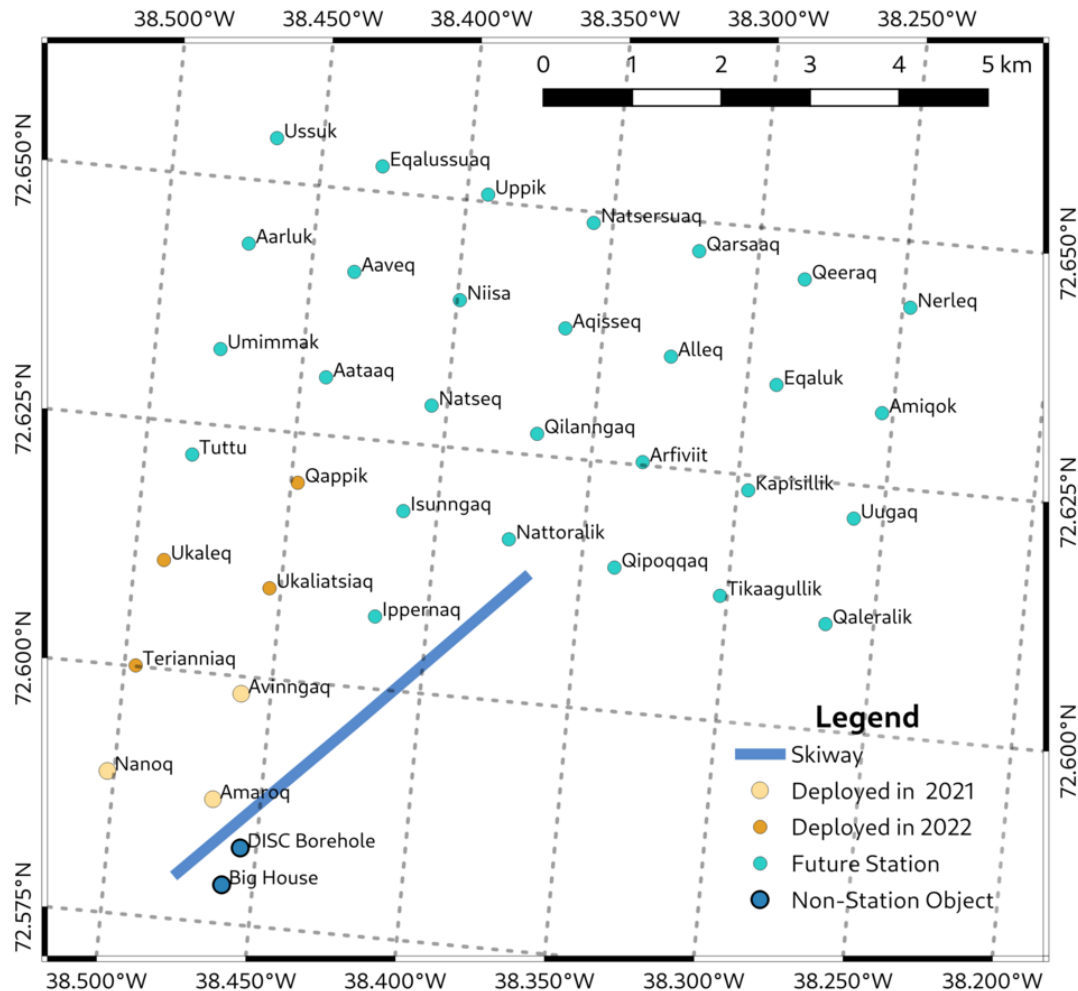
Figure 2.8: planned station layout

CHAPTER

3

RAY TRACING

As previously hinted it is necessary to be able to simulate how radio waves propagate through the ice for various reasons like building up a database, calibrating channels,...

It will also become necessary in the last chapter for doing actual measurements, that's why in this chapter we'll give a brief introduction to the way radio wave paths are found within the NuRadioMC framework.

3.1 Wave propagation

Figure 3.1: illustration of radio wave paths generated by a neutrino event

The way we simulate the strongest waves propagating to the detector from a radio source is

through ray tracing, an illustration of such a simulation is shown in figure 3.1. Here the detector is located at (0,-100) and a radio source at (480,-108), note that there are two possible paths leading to the detector.

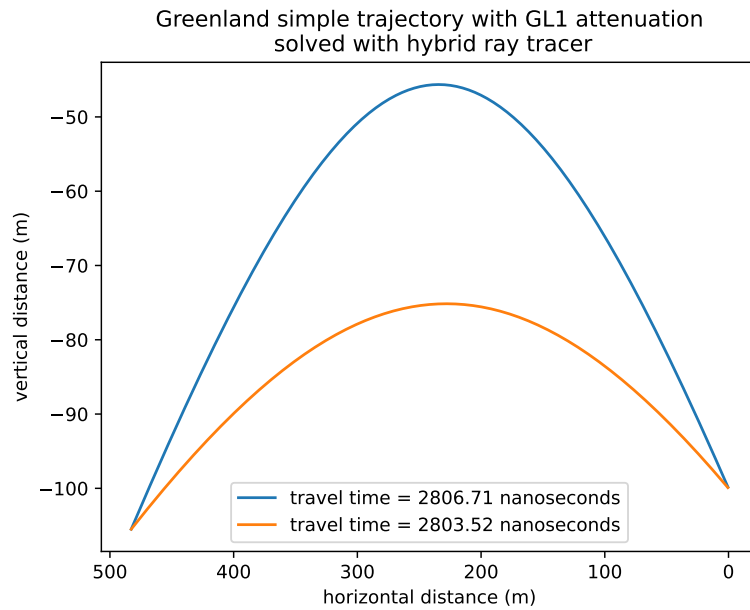The amount of solutions and how the waves are bent are consequences of the properties of the ice we work in. In a dielectric medium a ray propagates with it's signal wave-speed determined by the local index of refraction as $v = c/n$. The effect on speed isn't the only effect the index of refraction has which we'll need to concern ourselves with. However, if a ray propagates towards a boundary dividing 2 media with different indexes of refraction, the ray will refract and the refracted angle can be found from Snell's law:

$$n_i \sin \theta_i = n_o \sin \theta_o \tag{3.1}$$

Where n is the index of refraction, θ the angle with respect to the surface normal and "i" and "o" indicating incoming and outgoing respectively. The system we'll consider however, isn't homogeneous with some specified boundary. Ice in Greenland has a continuously varying density and index of refraction.

How do we know how the waves propagate in a medium? The software we'll be using to simulate how the radio waves behave is called *Radiopropa* [42]. As simulations of the wave propagation in full detail with the finite-differences-time-domain (FDTD) technique [43] are, even though they are more accurate, too time consuming. The authors of radiopropa opted to build their program on geometrical optics, i.e ray tracing. A path of a ray $\mathbf{r}(s)$ with path parameter s in a medium with index of refraction n($\mathbf{r}$) is described by the eikonal equation [27]:

$$\frac{d}{ds}\left(n(\mathbf{r})\frac{d\mathbf{r}}{ds}\right) = \nabla n \tag{3.2}$$

in radiopropa the local paraxial approximation (small angle approximation) is used, i.e if we assume that in any individual step of the algorithm the change of the refractive index along the path ds is small it's possible to re-write the equation as:

$$n(\mathbf{r})\frac{d^2\mathbf{r}}{ds^2} \approx \nabla n \tag{3.3}$$

Which is then iteratively solved using the Cash–Karp method. The way you would go about using this program is thus: find a start and end point (e.g a supposed neutrino interaction point and a detector respectively), "shoot" your ray in a certain direction for which the path will then be iteratively solved using radiopropa. And if you chose your direction right you have the path a ray might take from your start to the end point. The difficulty is this direction choosing which we'll get to later. If there are boundaries (such as defects or the surface) these are treated separately using Snell's law.

3.2 Ice model

Ice has a density gradient which we'll need to account for. Due to the way the ice bonds there will be more air trapped in between the molecules closer to the surface than at greater depths where the pressure due to the overhead ice prevents this. Due to this air being trapped the density of ice will be smaller closer to the surface than at greater depth.

Purely from classical gravity and density considerations it can be derived that the density scales exponentially. To see this let's consider a sheet of ice in the Greenland firn with a surface A and a height dz, the extra pressure this sheet of ice exerts on the ice just below it is:

$$d\sigma = \frac{dF}{A} = -\frac{gdM}{A} = -g\frac{A\rho(z)dz}{A} = -g\rho(z)dz \tag{3.4}$$
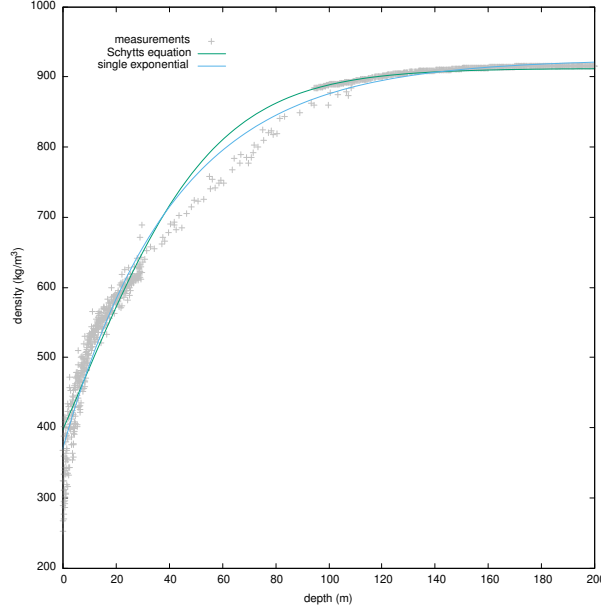
Figure 3.2: Illustration of the shortcomings of the analytical models

with $\rho(z)$ the depth-dependent density. Robin assumed the proportional change in air space to be proportional to the change in pressure [28]:

$$\frac{dV}{V} \propto d\sigma \tag{3.5}$$

As the volume scales inversely with the density let's assume the relation $V \propto (\rho_i - \rho)$ with ρ_i the density of pure ice, this yields:

$$\frac{d\rho}{\rho_i - \rho} \propto \rho dz \tag{3.6}$$

$$\frac{d\rho}{\rho(\rho_i - \rho)} \propto dz \tag{3.7}$$

Which can be solved to give

$$\rho = \frac{A\rho_i e^{z/z_0}}{1 + Ae^{z/z_0}} \tag{3.8}$$

Schytt also empirically fitted the following function:

$$\rho = \rho_0 e^{z/z_0} + B \tag{3.9}$$

Figure 3.2 shows how both of these functions fit the density curve[1]. There is one big downside however. It seems that the ice actually doesn't follow these exponential curves perfectly.

Equation 3.3, and thus the path, depends on the index of refraction on a given location. The dependence of the dielectric constant on density for ice can approximately be given by [34]:

$$\epsilon(z) \approx (1 + 0.845\rho(z))^2 \tag{3.10}$$

Here ρ is called the *specific gravity* as to make the equation dimensionally correct, this is the same as the density in g/cm^3 but stripped off it's units. As the dielectric constant is the square

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[1]The density with depth data can be found here

Figure 3.3: Wave surface of Fresnel with two sheets

of the index of refraction we can find an approximate index-density relation, which is sometimes called Schytts equation [12]:

$$n(z) \approx 1 + 0.775\frac{\rho(z)}{\rho_0} \approx 1 + 0.78\frac{\rho(z)}{\rho_0} \tag{3.11}$$

Where we introduced ρ_0, the density for solid ice (917 kg/m³). For the development of the simulation software equation 3.9 was taken and after assuming Schytt's equation (equation 3.11) to hold we find that the index of refraction abides by

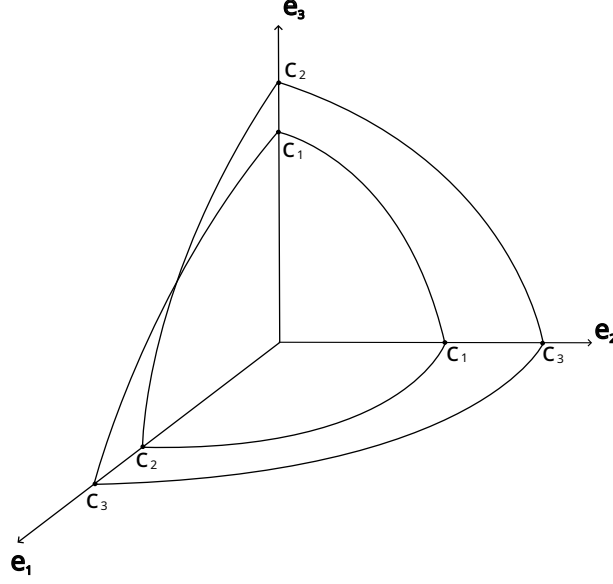$$n(z) = n_{ice} - \Delta n e^{z/z_0} \tag{3.12}$$

with n_{ice} the refractive index of solid ice and $\Delta n = n_{ice} - n_s$ with n_s the index of refraction of snow. This exponential dependency of the index of refraction on depth is called the *single exponential model*.

This single exponential model has a huge advantage as it's analytically solvable, meaning that we can know which direction we'll have to shoot our ray in (as mentioned previously) after the location of the neutrino interaction and the detector are specified. The ray tracing algorithm developed using this exponential index is called the *analytic ray tracer*.

The discrepancy between the single exponential model and the actual data for the density implies that the analytic ray tracer will make the wrong predictions. This is why the development of a different ray tracer was needed which will be able to handle more complex ice models. One such ray tracer will be explained in section 3.4 but this ray tracer has it's shortcomings. That's why the development of a new ray tracer was needed which is the partial work of this thesis and we'll get to that ray tracer in chapter 4.

Lastly there is an effect which might become important in the future: birefringence. Up until now we have implicitly assumed that ice is isotropic meaning that both it's permittivity ε and it's permeability μ are scalars but these could very well be tensorial in nature for radio waves in ice. In general, after calculating this tensorial nature through you'd find that in every direction two different indices of refraction can be found implying two different types of waves each propagating with a different speed as illustrated in figure 3.3. Which of the two speeds in a certain direction
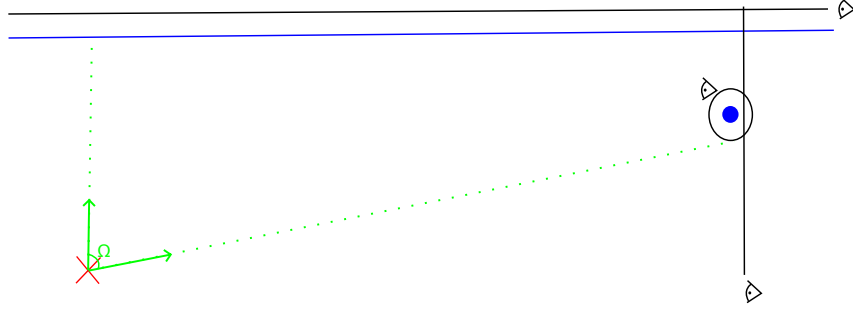
Figure 3.4: Illustration of the workings of the iterative algorithm

is then dependent on the polarization of the wave, which in our case thus depends on the Askaryan effect (see section 2.2). The optical property coming from the anisotropic nature of the material is what's called *birefringence*. Birefringence has been researched for implementation in the simulation software NuRadioMC used in the RNO-G group, e.g in [29].

3.3 Shortcomings of the exponential ice model

As mentioned in section 3.2, complex ice models will be necessary moving forward as the exponential ice model fails to fit the density curve. The software the RNO-G team chose to determine the way radio waves propagate through ice is radiopropa [42], but due to the way it works you'll have to know the launch angle of your ray to work out the path it will take from a start to an end point. This isn't difficult for the analytic model as it's exactly solvable, but for a general ice model you'll somehow have to find where to *shoot* the ray, this is where the Iterative ray tracer comes in.

3.4 Iterative ray tracer

The iterative ray tracer [40], as can be derived from it's name, iteratively searches the path a ray might take. The workings of the first part of the explanation is illustrated in figure 3.4. Say we have a neutrino interaction point $\mathbf{X}_i$ (the red cross on the figure) and a detector located at $\mathbf{X}_d$ (the blue dot on the figure), the algorithm starts by constructing an *observer* sphere with radius r_1 with the detector, located at $\mathbf{X}_d$, as the center. This means that any ray that gets shot and propagates to the sphere will get stopped and counts as a solution. Then, to reduce the time spent simulating, there are also observers placed whose purpose is to stop the ray tracing but not count the observed signal as a solution. One such observer is placed just above the ice surface as a ray that escapes the ice won't be able to make it back, and one is placed just behind the detector looking from the point of the interaction vertex $\mathbf{X}_i$ as a ray is not able to reach the detector anymore after it has passed it in the lateral direction.

Finally it's noted that due to the way the ice's index of refraction continuously increases with depth, rays can't propagate upwards, this means that we only have to look for solutions within the angle Ω which is just the zenith angle the detector makes with the bottom of the observer sphere.

Now that the setup has been established we'll just iteratively shoot rays from the neutrino interaction point starting at an angle $\Delta\theta_1$ then at an angle $2\Delta\theta_1$, $3\Delta\theta_1$,... Until we have reached Ω. This process is illustrated on the left side of figure 3.5. After we have gone over all the different launch angles we'll have some solutions (marked in green) and some that don't
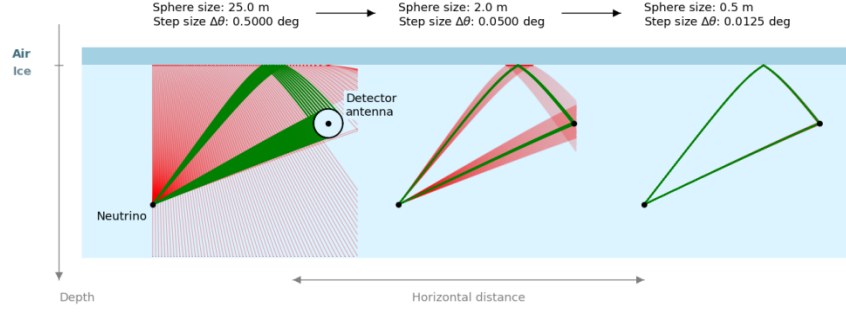
Figure 3.5: Illustration of the steps of the iterative ray tracer

end up on the detector (marked in red) we can now make the observer sphere's radius smaller ($r_2 < r_1$) and the step size of the angle smaller ($\Delta\theta_2 < \Delta\theta_1$). And again iteratively find the rays which end up on the sphere, only this time looking within the angles of the solutions of the previous step. We can keep on making the sphere and step size smaller in iterative steps until we've reached the precision we want. We then take, for each bunch of solutions within an angle interval, the most normal to the detector as the final solutions.

CHAPTER

— 4 —

HYBRID RAY TRACER

An algorithm was developed to work out the path the rays would trace out in more complex ice models called the *iterative ray tracer* [40], which was discussed in section 3.4. The way this algorithm works is however a sub-optimal solution in python as an optimization library will generally work faster and more accurate, work had been done on trying to implement such an algorithm deemed the "minimizer" but this attempt failed. As we saw this work the idea came to mind to combine the iterative ray tracer and the code using the optimization libraries. This way we built the algorithm which will be discussed in this chapter: The hybrid ray tracer, in the source code called the "hybrid minimizer" which can be found here under the radiopropa/hybrid_minimizer branch.

It succeeds in more rapidly finding the path from the event to the detector, is more accurate and also arrives closer to the detector as the final result is not limited by the final drawn sphere size but by a given tolerance making it useful for simulations in which high time and space precision is needed like plane wave reconstruction, which we'll do in the next chapter.

4.1   How the hybrid ray tracer works

The hybrid minimizer can be seen as an extension of the iterative ray tracer as it starts out the same way: Say our source of radiation is at position $\mathbf{X}_1$ and our detector is located at position $\mathbf{X}_2$, we start by defining the vector $\mathbf{v} = \mathbf{X}_2 - \mathbf{X}_1$, then we clone it as a new vector $\mathbf{u}$ and set it's z coordinate to 0, making it a normal vector of a plane parallel to the z direction in the lateral direction of the detector. We now want to constrain the search to where solutions are actually possible. Looking at figure 3.1 we see that no solutions below the direct path are possible as there would need to be upwards reflection, so we convert our vector $\mathbf{v}$ representing the path from the source to the detector to spherical coordinates, giving us a polar angle (zenith angle) "theta-direct". With this we know that from the source the ray should propagate with an initial zenith angle lying within the angle interval 0° to theta-direct° := Ω ($\theta \in]0, \Omega]$).

Next we need to define our "observers", if you shoot a ray with the radiopropa module from a certain point at a certain angle the ray path will get simulated until it interacts with this
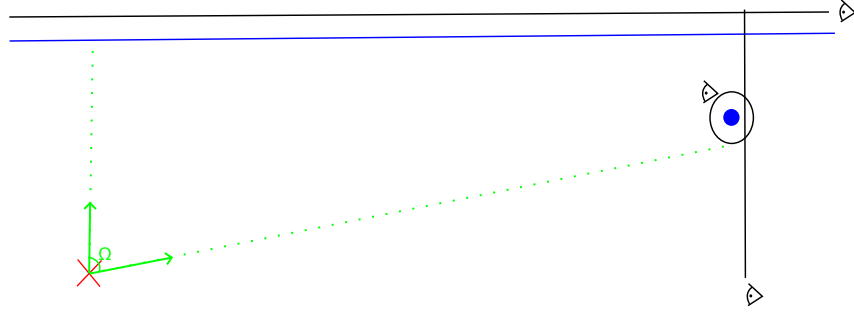
Figure 4.1: Illustration of the workings of the hybrid algorithm
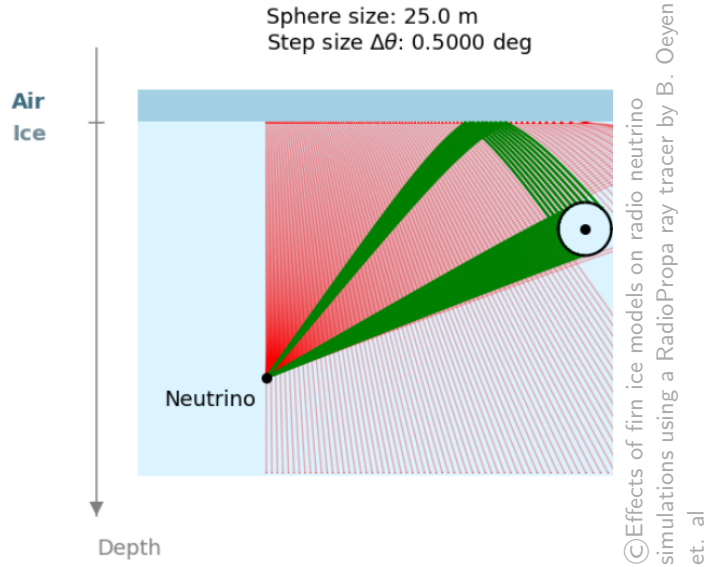
Figure 4.2: Iterative searches to find where the ray tracer ends up at the sphere, shown in green

"observer". Ideally we would like to a priori know where to shoot our ray and have the detector be an infinitesimally small observer in our simulation, but as we'll be working with general ice models this can't be done.

The algorithm of finding the possible paths is then as follows: We define a spherical observer at the location of the detector, with a radius of fair size[1]. We place an observer plane directly behind the detector with normal vector **u** (as no rays can propagate back after passing the detector) and an observer above the surface (as no rays could make it back after escaping the ice) our full setup is then what's illustrated in figure 4.1

Here the red cross is the radio source, the blue horizontal line is the ice-air boundary surface, the blue dot to the right is the detector and the green Ω indicates the range over which solutions to the problem are possible.

We start off by just iteratively guessing: given a certain angle step size $\Delta\theta$ shoot rays at the angles $\{0, \Delta\theta, 2\Delta\theta, ..., \Omega\}$ And see which ones get detected at the sphere around the detector, this process is illustrated in figure 4.2.

If 2 distinct launch regions are found, say in the regions $[\theta_1, \theta_2]$ and $[\theta_3, \theta_4]$ the rays end up on the sphere (drawn in green), then the so called *minimization* procedure will start. Using scipy's module optimize.minimize the optimal solution will be found by using the Nelder-Mead

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[1]We'll get back to how this "fair size" gets chosen
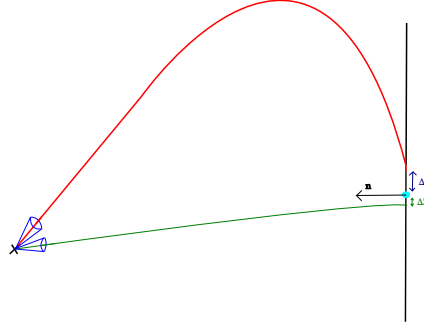
Figure 4.3: The scipy algorithm shoots rays in a direction within the blue cone angle intervals and minimizes the Δz that gets returned

method [39]. First we get rid of the spherical observer and place the vertical observer at the detector, now to be able to use the minimize module we'll need a function to minimize, for this reason we first define the function *delta_z* as, given a certain launch angle, propagating the ray onto the vertical observer and returning the distance from the point where it lands on the plane to the detector, as illustrated on figure 4.3 (i.e it returns the value Δz). The function we'll minimize is then delta_z_squared which just squares the value which delta_z returns as we want to do away with negative values (so we can minimize to $\Delta z = 0$). We use the previously found angle boundaries as the boundaries for this minimization algorithm, meaning that if the 2 zenith angle intervals $[\theta_1, \theta_2]$ and $[\theta_3, \theta_4]$ were found in the first step of the algorithm it will first minimize Δz^2 within the first angle interval and find it's solution and then within the second angle interval. With this our algorithm is done, it does have a fail-safe as well in case that the first step, finding the launch regions, doesn't find the 2 launch regions. Namely it reverts back to being the iterative ray tracer.

4.2 Performance Optimization

We wish to optimize this algorithm to make it as fast as possible. To consistently test the algorithm after every particular change in a parameter we'll be randomly generating vertex interaction positions, keeping the detector at the fixed (0,-100) value. To this end the numpy random module was used to generate random coordinates, the considered square (as there is only a z component to the ice model, the 3D problem has cylindrical symmetry and thus essentially only a 2D problem) is x:0.1km,4km and z:-0.1km,-3km[2]. Every simulated point shown in the following subsections consists of at least 500 random initial positions. As the speed of the algorithm is computer dependent the algorithm's speed is always plotted relative to the iterative ray tracer's speed, simulated with the same coordinates and under equal computer load.

Now we don't want to just achieve higher speed in our algorithm, we also want to at least have the same accuracy as the iterative ray tracer, if not even better. To this end we need to check with an "exact solution". There is only one candidate that fits this role: *the analytic ray tracer*. The plan is thus to use the exponential ice model as a testing ground for the hybrid ray tracer and solving each vertex-detector ray tracing problem with both the iterative, analytic and hybrid ray tracer. After having solved for the **propagation time** (meaning the time it takes the ray to propagate from the source to the detector) and the **arrival zenith angle** (the zenith angle the

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[2]This start at 100m depth was to get around issues concerning events that won't even trigger in a full simulation
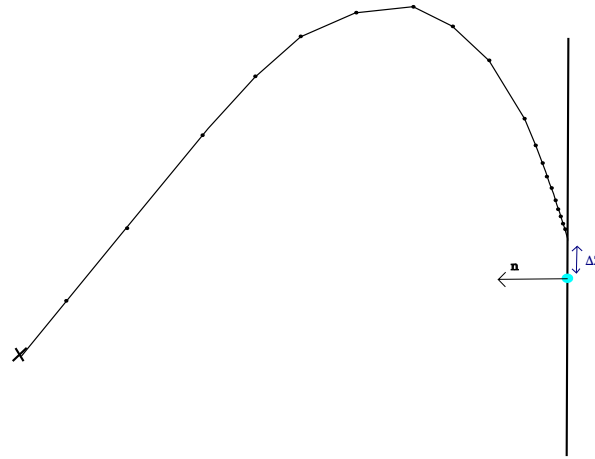
Figure 4.4: the steps taken are illustrated with the dots, the spacing reduces close to the detector. changing the normal vector changes the spacing

ray makes at the detector) for each of the algorithms we can infer the accuracy of a particular algorithm by how much it differs from the solution found through the analytic ray tracer.

4.2.1 Length of the normal vector

Whilst figuring out what was wrong with the initial *minimizer* we stumbled on the fact that radiopropa has a little weird quirk. As visually explained in figure 4.4, the size of the normal vector seems to influence how big radiopropa's ray tracer's step size is taken close to the detector. This thus influences the accuracy and total computational time taken. The results of varying the length of this normal vector, comparing the accuracy (in timing and arrival zenith) with the analytic ray tracer and the computational time with the iterative ray tracer, are shown in figures 4.5 and 4.6. Looking at these figures we can make, what would normally be rather obvious but is interesting nonetheless, a first optimization conclusion: take the normal vector length to be 1 unit in radiopropa. We can conclude this as the calculation speed seems to be minimal there (after zooming in on the graph) and the accuracy dropping rapidly after 1 meter.

4.2.2 ztol

We'll now change the *tolerance*, with this we mean when the minimization algorithm returns a Δz smaller than a certain treshold "ztol" the ray will be accepted as the solution. The results from analogous comparisons as previously discussed are shown in figures 4.7 and 4.8. There seems to be a minimum around 0.05m, looking at the accuracy for this tolerance it seems sufficient to be used. We can thus infer the second optimization conclusion: take ztol to be 0.05 m.

4.2.3 Sphere Size & Step Size

The initial rays are sent out in steps of a certain angle and with a sphere around the detector of a certain size. Varying the parameters of this first step of the algorithm (e.g the step size and sphere size) might thus have an effect on both the accuracy and the computational time. As this initial search for launch angle regions is also the slowest step in the hybrid ray tracer
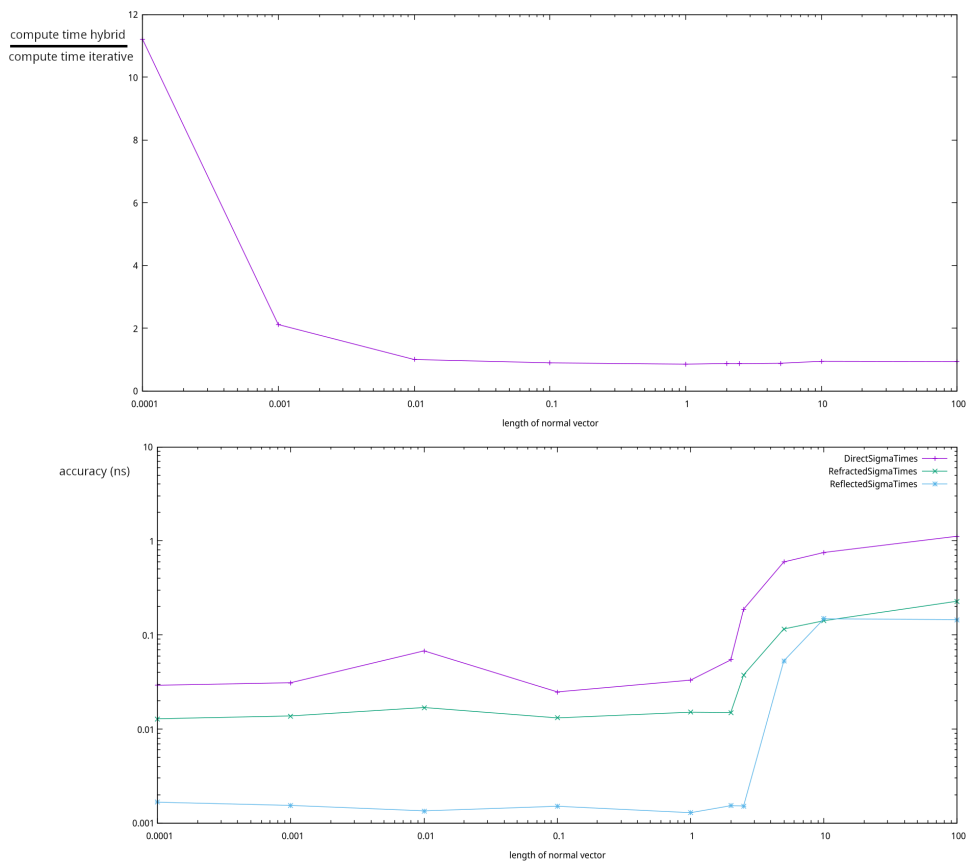
Figure 4.5: The speed lowers with larger normal vector length but the accuracy on timing gets worse after a length of 1
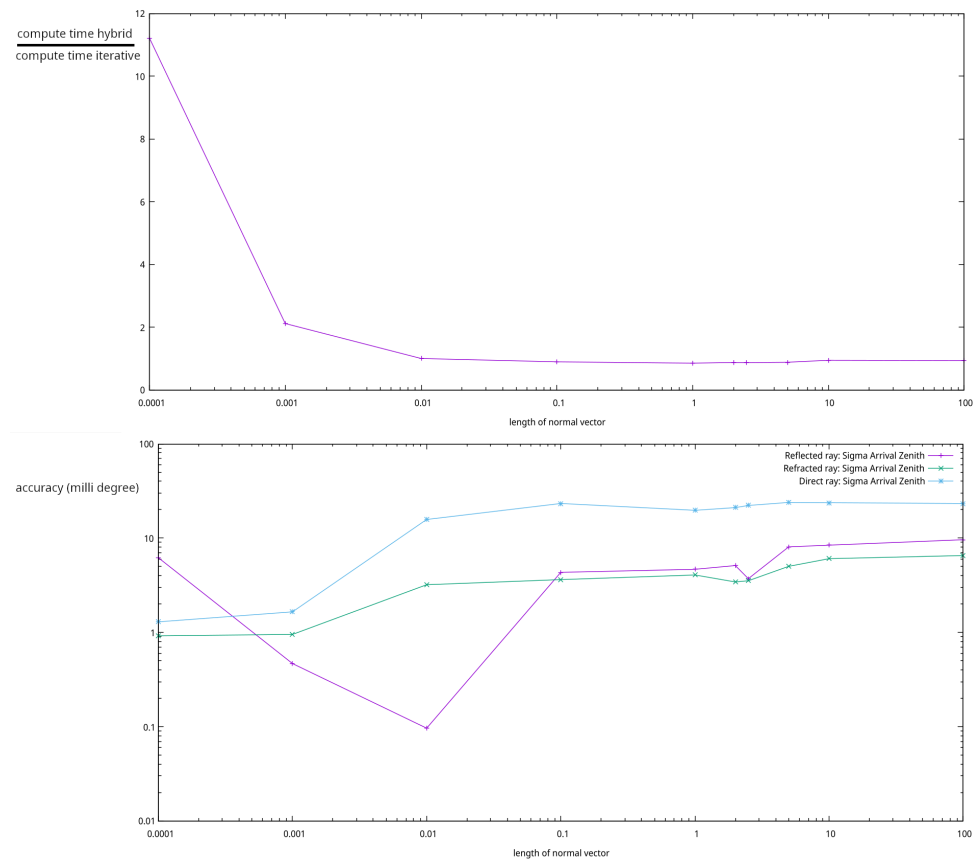
Figure 4.6: The speed lowers with larger normal vector length but accuracy stays roughly the same after 0.1
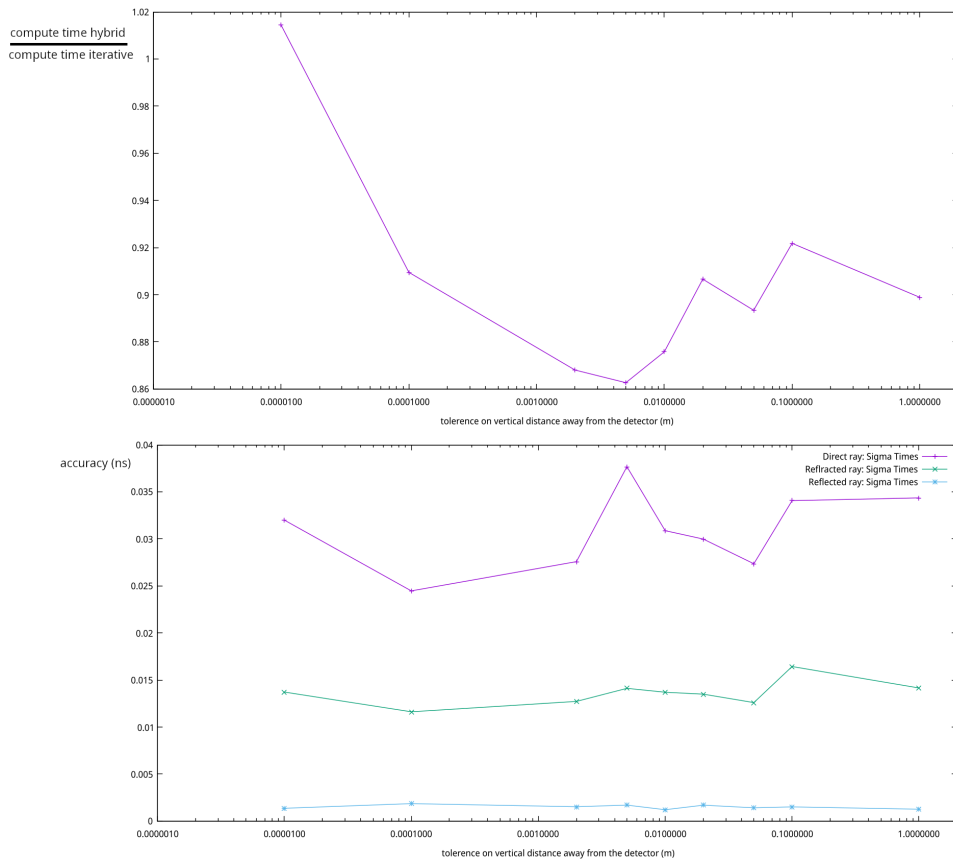
Figure 4.7: the solution seems to reach a minimal time at a tolerance of 5cm whilst the accuracy on timing stays roughly the same
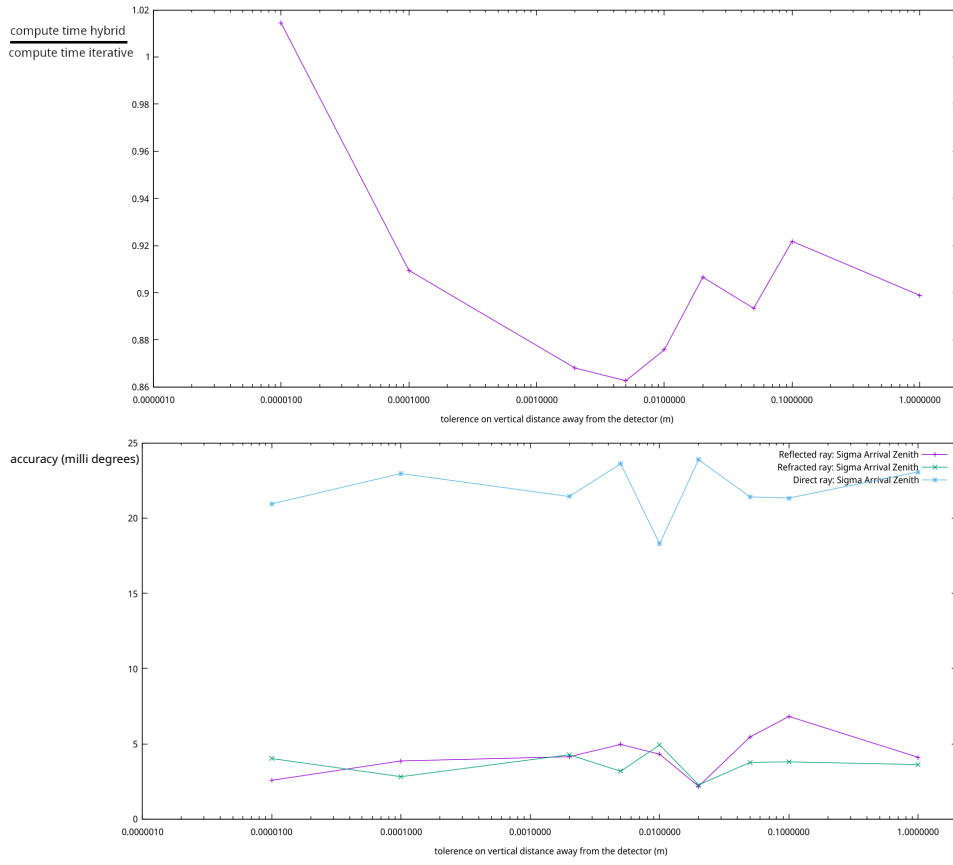
Figure 4.8: the solution seems to reach a minimal time at a tolerance of 5cm whilst the accuracy on the angle stays roughly the same
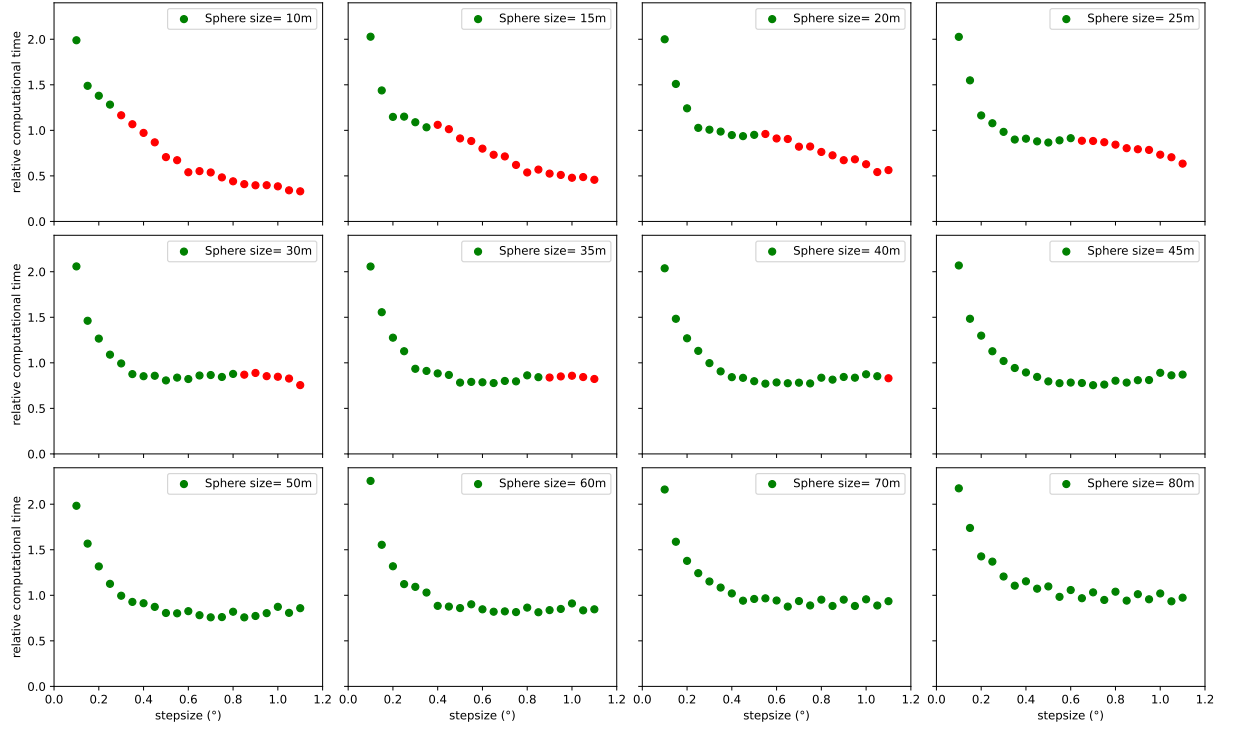
Figure 4.9: The data in green is acceptable, at high sphere size the geometric effects start to play a role and staggering is observed

(takes $\approx 57\%$ of the total computation time) it's also the most important step to optimize. The optimization procedure is as follows: change the sphere size and loop over various step sizes, recording the speed. Note that, as we have to vary 2 parameters, we can't really look at accuracy here. This isn't needed however as we'll see that after finding the optimal solution the accuracy is still sufficient, apart from one part where it is needed: **if insufficient solutions are found**, as we wish this algorithm to be better the iterative ray tracer, it'll need to at least find as many solutions as the iterative ray tracer does. If, for a particular random interaction vertex location, less solutions are found by the hybrid ray tracer than for the iterative ray tracer, this parameter choice will be thrown away (and colored differently). The results are shown in figure 4.9, the points colored red are unusable as previously discussed.

The lower on the graph the points lie, the better. If we combine all the green points into a single plot we get what is shown on figure 4.10, zooming in onto the lowest point , we see that an optimal sphere size seems to be at 45m accompanied by a step size of 0.7°, this is in contrast to the iterative ray tracer where a sphere size of 25m and stepsize of 0.5° is used. Note that changing these values for the iterative ray tracer doesn't change it's speed nor accuracy.

The programs used in making these plots can be found here under the folder "testhybrid".

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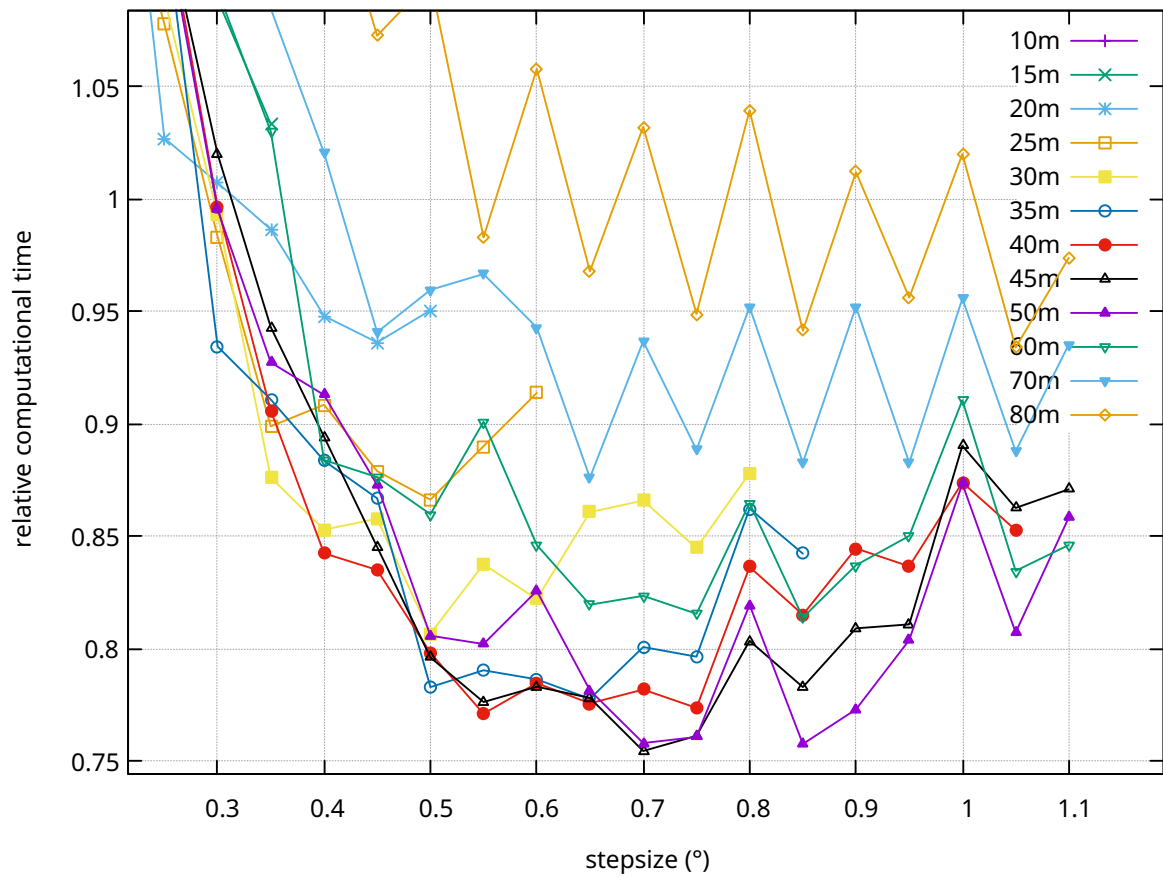
Figure 4.10: Green values in variation in sphere and angle step size, the lower the better. Max speed (lowest point on the figure) at 0.7° as step size and 45m sphere size
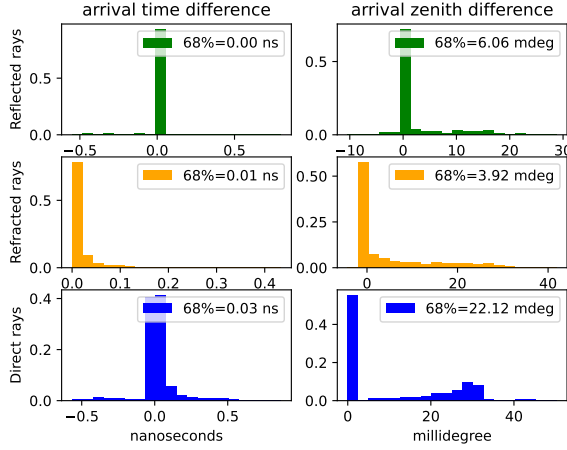
Figure 4.11: Hybrid
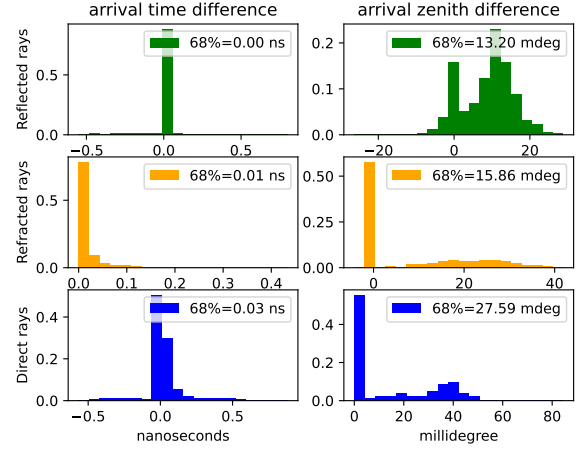
Figure 4.12: Iterative

4.2.4 Conclusion of optimization

How does the hybrid ray tracer perform relative to the iterative ray tracer if we use the previously optimized variables? After doing a simulation of 1000 random source locations (double the previous amount) with the iterative, analytic and hybrid ray tracer and comparing both the iterative to the analytic and the hybrid to the analytic we get what's shown in figures 4.11 and 4.12. Where we can clearly see that the hybrid ray tracer is more accurate, now during this simulation we also recorded the computational speed, the fractional speeds relative to the analytic ray tracer are presented below:

- iterative: 5.93×10^{-5} computations/analytic computation

- hybrid: 7.97×10^{-5} computations/analytic computation

The hybrid ray tracer is thus 33.7% faster than the iterative ray tracer. The speed difference with the analytic ray tracer might seem quite overwhelming but this can get mitigated in the future if part of the hybrid ray tracer gets re-written in a compiled language (like c++) just like the analytic ray tracer.

CHAPTER

5

WEATHER BALLOON

In this chapter we'll infer information about the ice the detectors reside in using radio signals coming from a weather balloon flying over the stations. We'll go about this by first finding the difference in timing between channels by fitting the balloon's sinusoidal signal to the data, and then doing a plane wave reconstruction, minimizing the angle the reconstruction makes with the balloon, thus finding the local index of refraction. This procedure will be explained more in depth over the following sections.

Prior to the measurements we'll need to be able to predict how accurate our findings will be, for this we'll need to run a simulation with the hybrid ray tracer. There is one change that needs to happen first to our algorithm for us to be able to simulate this: The air observer has to be removed as to make a ray tracing possible from within the air into the ice and onto the detector. The modified version of the hybrid ray tracer can be found here under the branch radiopropa/BaLLooN.

Due to the way our algorithm works the time the ray took is only from when it became a secondary[1], this information is insufficient as we want the full travel time. The propagation time from the balloon to the ice t can later be added to the time of the path in the ice by measuring the length d of the drawn line from the balloon to the beginning of the recorded path, setting the speed of radio waves in air to the speed of light c and then just adding $t = d/c$ to the time found from the algorithm.

5.1 Plane Wave Reconstruction

We want to do a plane wave reconstruction of the original position as this will make us able to infer the index of refraction between chosen channels. Example paths the weather balloon produce that end up in the deep channels is shown in figure **??**, here the balloon emits a signal which propagates straight in the air and then refracts in the ice. Locally in the ice we can assume the wave to come in as a plane wave. The arriving plane wave is shown as parallel lines in

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[1]This is a problem which also seems to hold in the iterative ray tracer, it might get fixed in the future but as secondaries weren't needed for most applications we deemed it fine for the moment
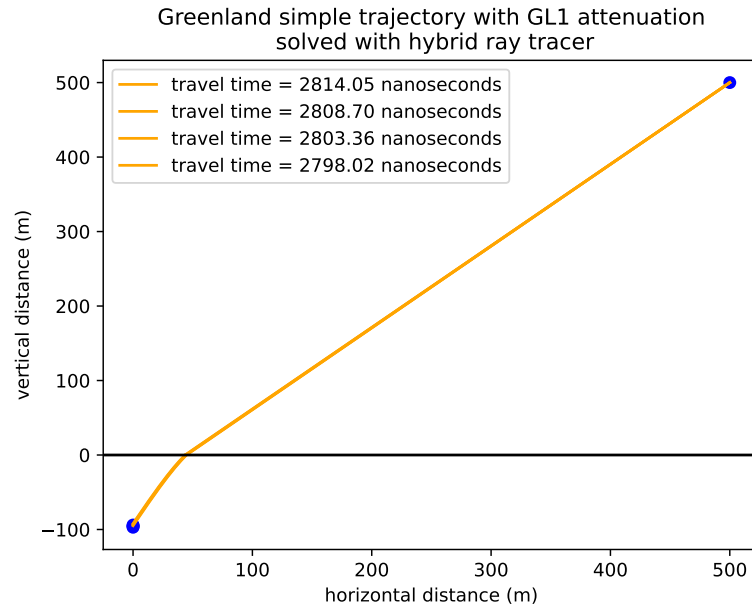
Figure 5.1: Example trajectory of rays coming from a weather balloon (blue dot top right) and going through the ice to the various detectors (blue dots bottom left)
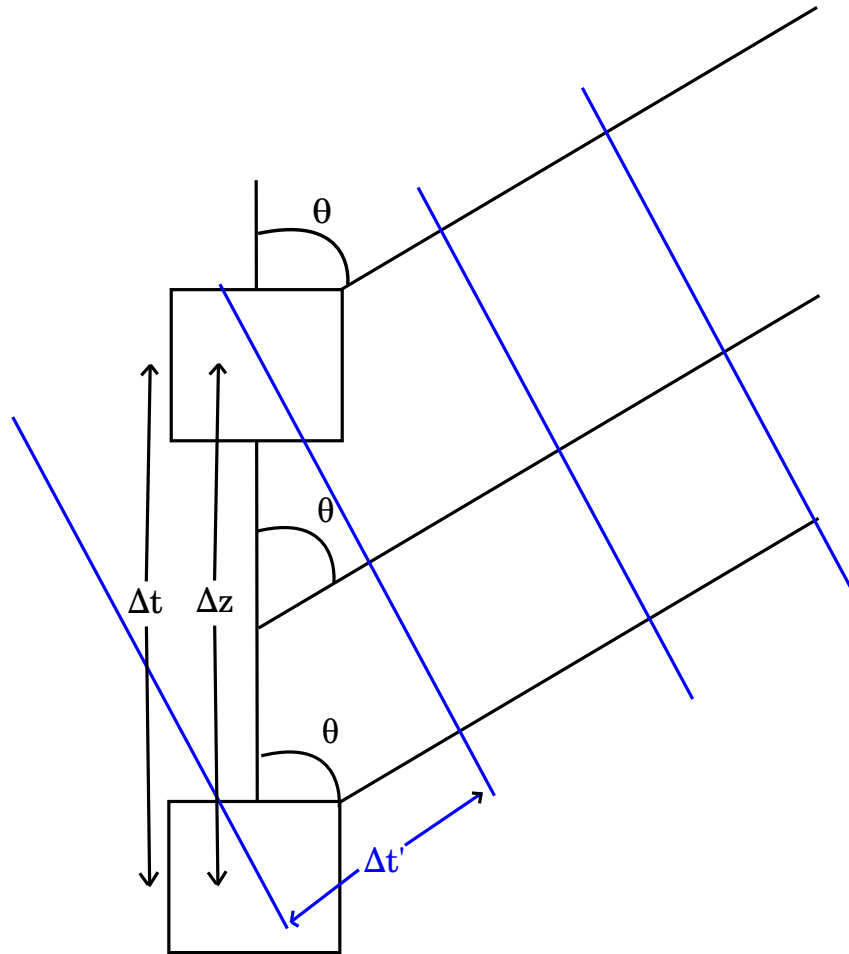

Figure 5.2: Illustration of Plane waves

blue on figure 5.2. The reconstruction can be understood by taking a closer look at this figure, the radio waves coming from the weather balloon make a certain angle with the detectors. The top detector (top box) detects the wave at a certain time t_1, the bottom detector detects it at a time t_2. After deciphering the data RNO-G recorded we'd thus see that these two detectors got a signal $\Delta t = t_1 - t_2$ seconds apart from each other. Now ideally this observed time is equal to the time it took the wave to propagate that distance (termed $\Delta t'$) which we can calculate from the geometry of the problem and dimensional analysis:

$$\Delta t' = \frac{m}{(m/s)} = (s/m) * m = v^{-1} * m = v^{-1} \cos\theta \Delta z \tag{5.1}$$

With $v = c/n$ the local speed of light, n the index of refraction at the depth in between the considered channels and Δz the distance between the channels. Thus if we know the angle θ, the time $\Delta t'$ and the distance between the channels Δz we could infer the index of refraction at a certain depth as can be seen by reforming equation 5.1:

$$n = \frac{\Delta t'}{\Delta z} \frac{c}{\cos\theta} \tag{5.2}$$

We can actually roughly guess the angle, as for a balloon flying close to the detector this incoming angle will be roughly the same as the observed angle. We expect the following function to show a minimum at that angle:

$$\eta(\theta) := \Delta t - \Delta t' = \Delta t - \frac{\cos\theta \Delta z}{v} \tag{5.3}$$

If we want to use more than 2 detectors at once however (which we'll do for the phased array), we'll need to specify various functions to minimize. E.g if we have four detectors labeled 0 to 3 we'll have to construct functions between detectors 0&1, 0&2, 0&3, 1&2, 1&3 and 2&3 . The further apart the detectors lie the larger the function values and thus the more they will weigh. This weighing of further spaced channels is what we want is these will yield a more accurate result. An example simulation of these η functions for a particular index of refraction is shown in figure 5.3. For this figure the modified hybrid ray tracing algorithm was used to simulate what the difference in timing would be.

5.1.1   simple plane wave reconstruction

As we assume the plane wave angle and the direct angle between the detector and the balloon to be nearly the same (i.e the balloon is right overhead the detector) we take $\theta = \theta_b$, the function we thus wish to minimize is the sum of the previously defined function for various detectors at an angle of θ_b:

$$f(n) := \sum_{i=\text{channel pairs}} \left(\Delta t_i - \frac{n\cos\theta_b \Delta z_i}{c} \right) \equiv \sum_{i<j} \left(\Delta t_{ij} - \frac{n\cos\theta_b \Delta z_{ij}}{c} \right) \tag{5.4}$$

where Δt_{ij} denotes the observed time difference between channels i and j, similarly Δz_{ij} denotes the distance between channels i and j. If this function f gets minimized, the n leading up to this minimzation will be the answer we are seaking: the index of refraction inbetween the detectors. To find an expression for the index, let's solve for n:

$$f(n) = \sum_{i<j} \left(\Delta t_{ij} - \frac{n\cos\theta_b \Delta z_{ij}}{c} \right) \tag{5.5}$$

$$\sum_{i<j} \frac{n\cos\theta_b \Delta z_{ij}}{c} = \sum_{i<j} \Delta t_{ij} - f(n) \tag{5.6}$$

$$n = \frac{c}{\cos(\theta_b)} \left(\frac{\sum_{i<j} \Delta t_{ij}}{\sum_{i<j} \Delta z_{ij}} - \frac{f(n)}{\sum_{i<j} \Delta z_{ij}} \right) \tag{5.7}$$
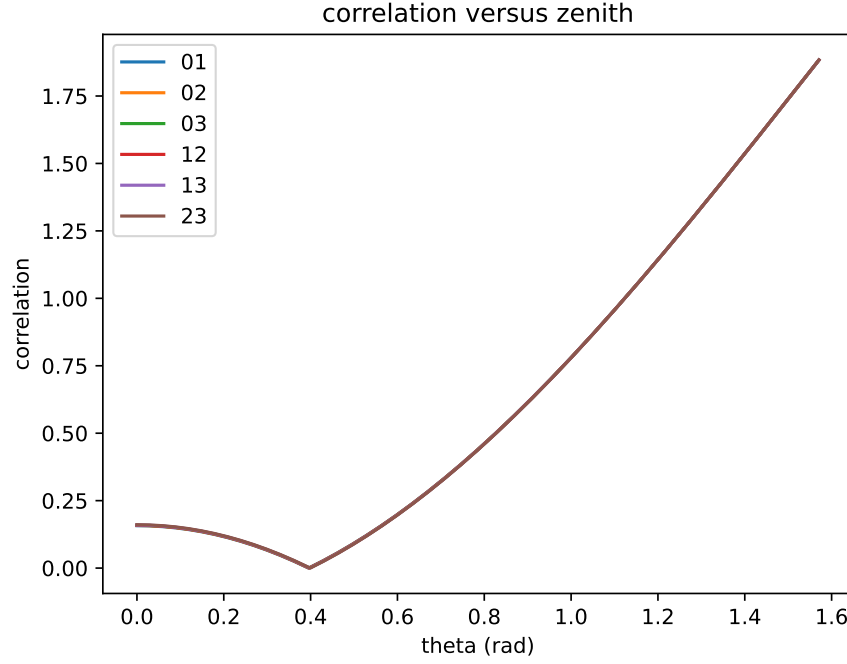
Figure 5.3: Example normed correlation functions

The error on this result can also be computed quite straightforwardly by assuming the observed propagation time to channel i has an error δt_i, implying an error of $\delta t_i + \delta t_j$ on the observed difference Δ_{ij} (which we'll find out later). For the positional accuracy we'll assume to know the detectors to within 5cm, this will imply an accuracy on Δz_{ij} of 10cm.

The error on the index we'll find is thus:

$$\delta n = \frac{c}{\cos\theta_b} \delta \left(\frac{\sum_{i<j} \Delta t_{ij}}{\sum_{i<j} \Delta z_{ij}} - \frac{f(n)}{\sum_{i<j} \Delta z_{ij}} \right) \tag{5.8}$$

$$\delta n \approx \frac{c}{\cos\theta_b} \left(\frac{\sum_{i<j}(\delta t_i + \delta t_j)}{\sum_{i<j} \Delta z_{ij}} \right) \tag{5.9}$$

As it turns out that the contribution to the total error by the observed time is way bigger than the error on the location of the detectors.

5.1.2 plane wave reconstruction using snell's law

This was one way of fitting the index of refraction, another procedure that we could do is by implementing breaking of the plane wave at the surface through the use of snell's law. For this we assume the reconstructed plane wave to behave like an actual wave and, encountering the ice-air boundary , refracting according to snell's law. This is useful for when the angle with the balloon is too big as is illustrated in figure 5.5, here you can clearly see that, even though the plane wave locally matches the incoming signal, it ends up really far from the balloon. The reconstructed plane wave follows the wave path closely until the air-ice boundary where the wave path got refracted, we thus try doing the same thing by making the plane wave refract as well.

To find the index of refraction this way we can't minimize by taking the incoming plane wave to have the same angle as the balloon, we'll need to look at the distance between the plane wave
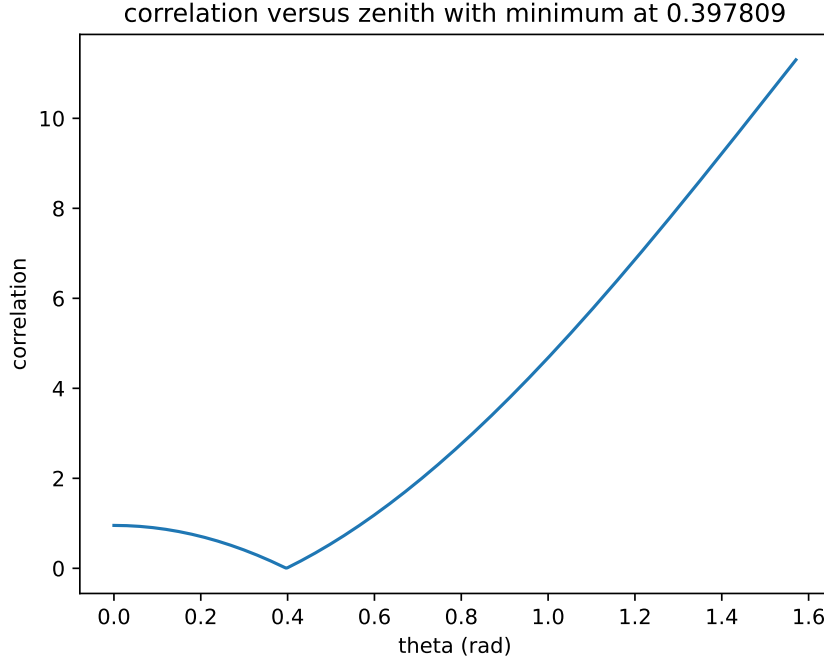
Figure 5.4: Example sum of the normed correlation functions

reconstructed ray (after also refracting at the surface) and the balloon, both at the height of the balloon. The full procedure then goes as follows: We first choose a certain index of refraction n , then we reconstruct the plane wave launch angle by minimizing the function

$$f(\theta) := \sum_{i=\text{channel pairs}} \left(\Delta t_i - \frac{n \cos \theta \Delta z_i}{c} \right) \equiv \sum_{i<j} \left(\Delta t_{ij} - \frac{n \cos \theta \Delta z_{ij}}{c} \right) \tag{5.10}$$

Such a function is illustrated in figure 5.4. This will yield a certain launch angle θ_1, we can use this angle and the height of the middle of the concerned detectors to derive the path in the ice, the outgoing zenith angle at the surface θ_2 can be calculated from Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \implies \theta_2 = \sin^{-1} \left(\frac{n_1}{n_2} \sin \theta_1 \right) \tag{5.11}$$

After doing this we have a linear function describing the path after it passed the ice-air boundary layer. If we evaluate this function at the height of the balloon we then get the distance the reconstructed ray is away from the balloon. To find the index of refraction n we record this distance and redo the procedure starting at the minimization of equation 5.10 for a different index of refraction. After iterating through a bunch of indices we then have a corresponding list of distances to the balloon. The index corresponding to the minimum in these distances is then the final result.

5.2 Is the goal feasible?

5.2.1 Simple Plane Wave

In the example reconstruction illustrated in figure 5.5 the difference in angle between direct to balloon and plane wave reconstruction is quite big ($\approx 65\%$) but as the balloon gets closer to the
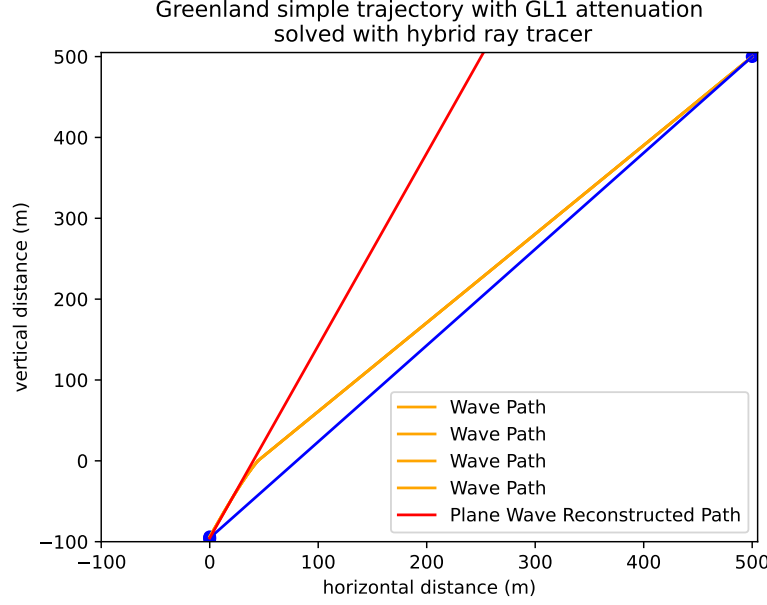
Figure 5.5: Example plane wave reconstruction of weather balloon position

detector this reduces significantly. As previously layed out, our goal is to find the local index of refraction n by using the plane wave reconstruction with the recorded timing and the positional data from the weather balloon.

Now let's ask ourselves the question, within which angles should the weather balloon fly for the data to be useful? As was previously stated, the further the weather balloon is away (in the x direction) the bigger the zenith angle with the detector the less accurate the plane wave reconstruction. So which angles are acceptable? Note that not only angle but also height will eventually play a role in the accuracy, the angle however gives a good starting point. To determine this our method works as follows:

We vary the position of the weather balloon in the x direction (keeping the height constant at 500m), simulate the ray path to the channels 0 to 3 and then fit n such that the difference between the balloon position and the plane wave at the same height is as small as possible. Then we compare the n we have fit to the one we know from the model at that position. We quantify the discrepancy between these two indices of refraction using what we here define as the *systematic error*:

$$\varepsilon \ (\%) = \frac{n_{\text{fit}} - n_{\text{exact}}}{n_{\text{exact}}} \tag{5.12}$$

Carrying this out[2] we get figure 5.6, i.e it gets exponentially shifted towards higher n as the balloon moves further away. If we wish our systematic error to be within 1%[3], the angle the balloon makes with the middle of channels 0 to 3 needs to be less than 10°.

Now what would our <10° policy entail? And is it even possible? Say we take a look at station Terianniaq (station 12) and see what our policy entails, it is located at 72.6000868058195° N -38.4962265332872° W in the global geographic coordinate system (longitudinal, latitude and elevation), this is quite difficult to work with directly. For this reason we first convert the station's location to local ENU coordinates (east, north, up) relative to the 'DISC' which is a

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[2]The code for this can be found in projects-mt/BaLLooN/simulations as plane_wave.py

[3]we want this as small as possible as to not rely on the simulation
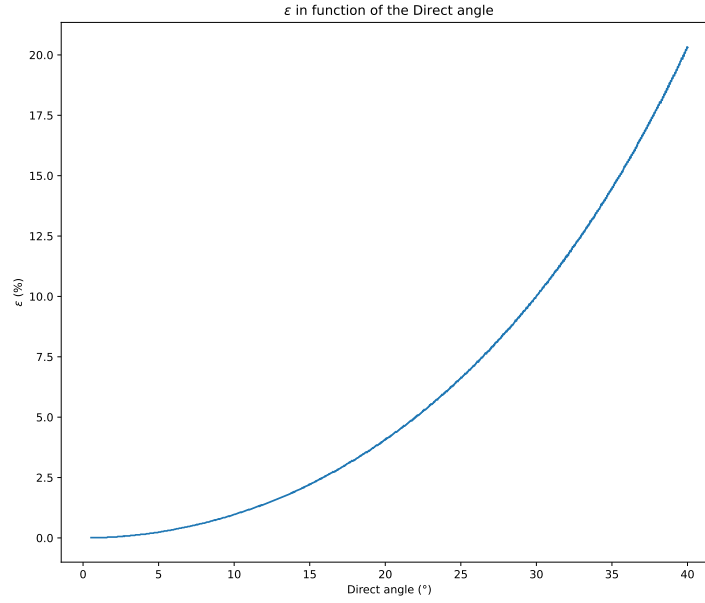
Figure 5.6: Epsilon in function of the direct angle

point in the base camp located at 72.58279265212887 latitude, -38.45581495328228 longitude and 3251.9489147560234 elevation.

After having converted station 12's position into ENU coordinates we get -137.67250176003688N 1727.5184983294744E, we then set our "up" to be -95.5m as this is the approximate location of the middle of channels 0-3. Now looking at e.g the Balloon path recorded on the 20th of august 2022 (figure 5.8) we see that the balloon crosses paths closely with detector 12, but how close was this encounter? To quantify this we can take a look at every balloon positional data entry (there are >12000 entries) individually and compute the angle the balloon makes with the detector by first converting the location of the balloon into ENU coordinates. Then calculating the lateral distance ($\sqrt{(x - x')^2 + (y - y')^2}$) then the relative vertical distance $|z - z'|$ and then from those compute the angle. Doing this and recording when the balloon gets close enough to get below the 10° mark we get the yellow part of figure 5.8. We thus see that in this example the $< 10°$ policy is viable.

Now how much data do we have that way? We'll be looking at the data recorded over the summer of 2022, more particularly 15/06/2022 - 30/09/2022. The positional data of the weather balloons was obtained from the `ftp1.esrl.noaa.gov` website using the rno-g-sonde script of the official RNO-G github page. After looping through every weather balloon gpx file recorded in the summer of 2022 and seeing when it gets within 10 degrees from any detector we get the data shown in appendix D, even though this is quite a lot of data there's still another step that we could do to broaden the amount of usable data.

5.2.2 Refraction at the surface

Up until now we have not used the property that waves refract at the surface as we didn't want to assume anything, now say that we include refraction at the surface for our plane wave reconstruction. This would mean that we'd follow analogous steps as our previous analysis, i.e doing a plane wave reconstruction from the difference in timing and trying to fit the index of
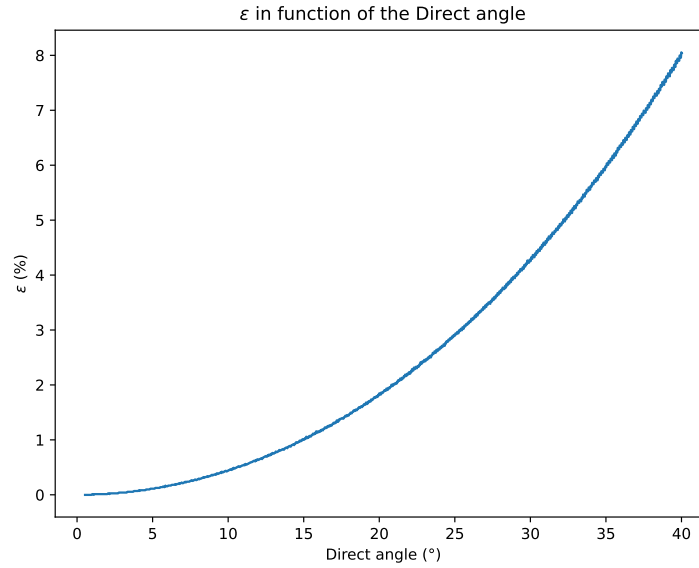
Figure 5.7: epsilon IFO possible angles from channels 0-3 with refraction at the surface

refraction, only now the plane wave abides with Snell's law at the surface, going from n=1.27 to n=1.

Doing this whilst looping over possible horizontal balloon positions, we get the result shown in figure 5.7[4] As you can see we can now go up to 15° and still have a systematic error of less than 1%! The only drawback of this method is that we need to assume the index of refraction to be 1.27 at the surface of the ice, if this isn't the case in some places our predictions won't be accurate.

5.2.3 Influence of height on Epsilon

In the previous sections we've assumed the height of the weather balloon to be 500m, does changing this height influence the behavior of ϵ in some way? The answer is, at first surprisingly, yes. As can be seen in figure 5.9 the systematic error can vary with height for the same angles. This has, as a consequence, that if we manage to get a hold on some usable data the ϵ might still be quite large (if the height is really large). Because of this we'll have to re-compute ϵ exactly for every measurement we do.

5.3 Fitting the index: Phased array

5.3.1 Station 11, Run 1034 Event number 12397

Now that we know our goal to be feasible, let's analyze some data. As we'll start by just analyzing one event, let's take a reasonably good one for our analysis. A close look at graph 5.6 shows that events under 5° at a height of 500m produce an ϵ of less than 0.22%, implying that if we measure n to be 1.7407 our systematic error will only be 0.0038. A good start will thus be finding moments when the balloon gets to within a 5% angle, note that the systematic error is height dependent so we'll have to calculate it afterwards. After looping through all the balloon

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[4]The code for this can be found in projects-mt/BaLLooN/simulations as plane_wave_with_snell.py

42
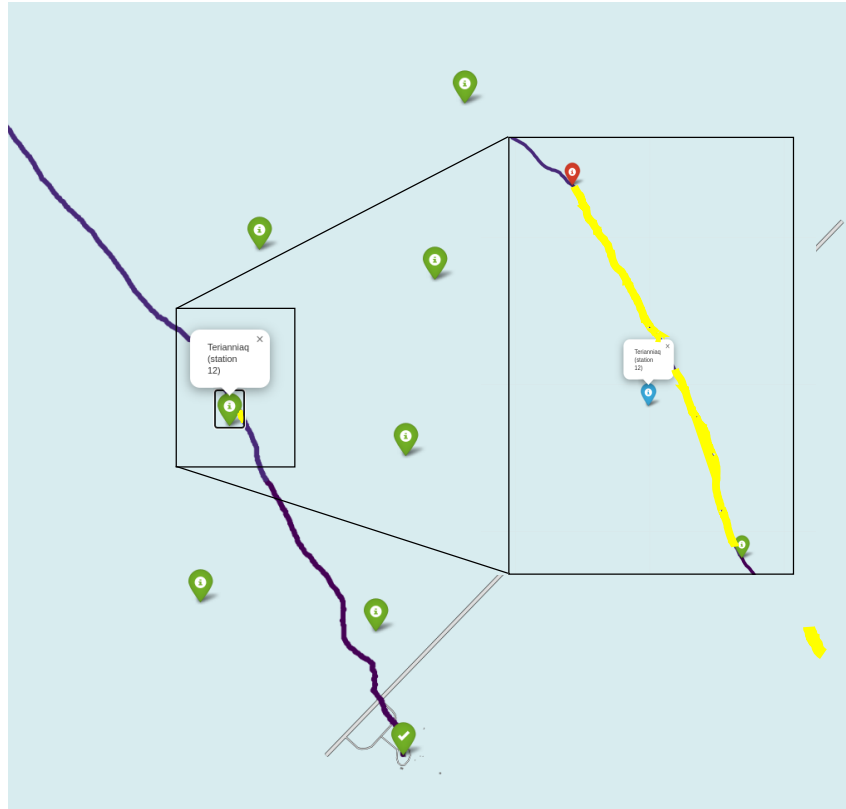
Figure 5.8: Path traced out by a weather balloon in purple released at 20/08/2022, in yellow you can see when it gets within 10° of detector 12.
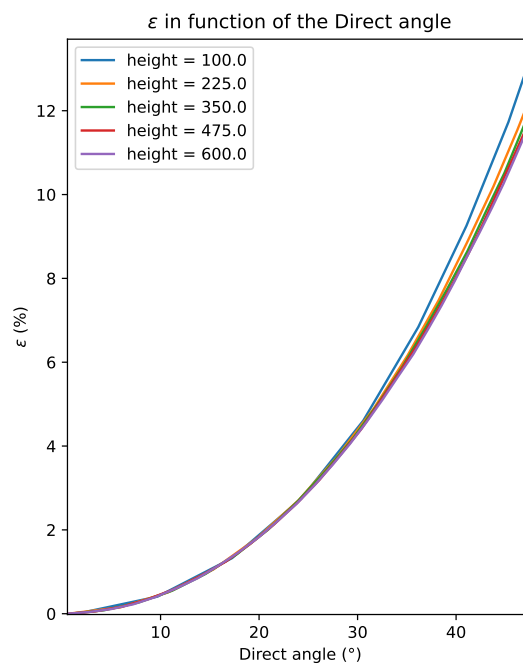
Figure 5.9: How varying the height influences ϵ over the same angles

positional files and only outputting the $< 5°$ ones we get the time frames shown in appendix C.

If we search in the DESY database [5] within the calculated time frames for the particular detectors where the balloon gets close enough to, and where the 403MHz signal coming from the balloon is detected in the deep channels, the events of the 24th of July stands out; at 23:21:53 the balloon gets quite close to detector 11 and shows a clear 403MHz signal at the phased array in channels 0,2 and 3, as shown for the channels 0 and 3 in figure 5.10. **CHANGE THIS**

Now to calculate the differences in timing for this received signal, the code we built for this is called FitN.py and stored at the repository projects-mt under BaLLooN/RealData, let's go over the full code step by step:[6]

Spatial data

The first part we'll need to concern ourselves with is determining the relative positions of everything. The balloon data file and the time when the event took place are given, from these two both the latitudinal and longitudinal position and the elevation of the balloon at the given time are determined. We convert these three measurements to the ENU coordinate frame (x,y,z with respect to reference) and store it in the array *BalloonPosition*. The next step is to get the location of the detector, for this we first instantiate a detector object

```
1  det = NuRadioReco.detector.detector.Detector(json_file="RNO_season_2022.json")
```

The RNO season 2022 json file can be found on the official RNO-G github under "analysis-tools", then we update the detector to the time of the event and get the absolute position of our detector (station 23) via the get_absolute_position module:

```
1          stationlocation = det.get_absolute_position(station_id)
```

Where at the specific station this position is doesn't matter as we'll explains shortly. Now that we have both the position of our balloon and station in ENU coordinates, let's simplify the calculations by setting the detector as the origin i.e our new balloon position will be

$$RelBalloon = BalloonPosition - StationPosition \tag{5.13}$$

And as we might want to plot this later, due to the cylindrical symmetry of the ice model, we can rotate the coordinates to get rid of our y-axis. We can do this by defining the radius:

$$r := \sqrt{RelBalloon_x^2 + RelBalloon_y^2} \tag{5.14}$$

And just setting this equal to $Balloon_x$ and setting $Balloon_y$ to zero. We don't have the position of our individual channels yet, only of the station itself, these can however easily be obtained using the get_relative_position module on our detector object. As we chose our station to be the center of the coordinate system, these relative positions are absolute positions of the channels in our frame of reference. Using these it thus doesn't matter where the position of the station was defined.

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[5]https://rnog-monitor.zeuthen.desy.de/
[6]I advise the people who will continue this work to pull up the code side-by-side with this explanation
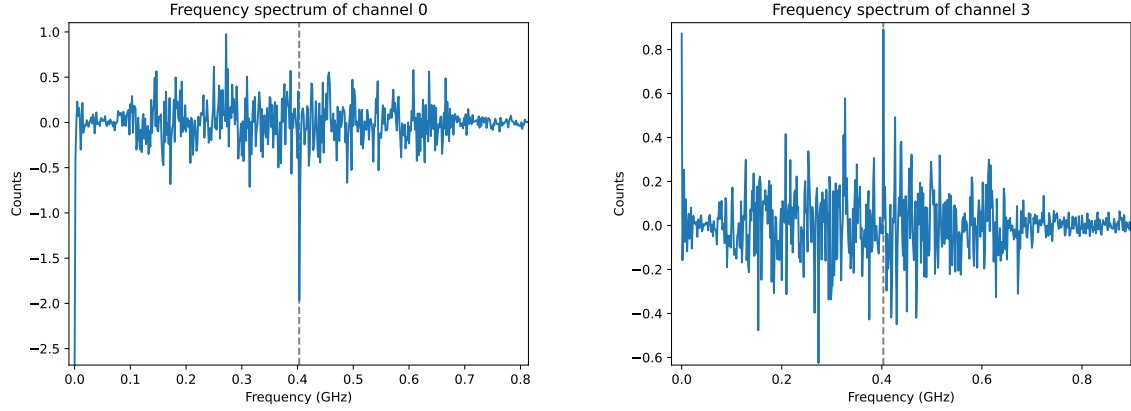
Figure 5.10: recorded frequencies on detector 23 at 2022/08/29 11:18:32

Signal analysis and initial guesses

Now that we have our geometry, let's analyze the data for the channels, the data for a particular channel is stored in a channel object. From this object we can get the recorded voltages with the get_trace() module, the recorded times with the get_times() module, the recorded frequencies with the get_frequencies() and the recorded spectrum corresponding to these frequencies with get_frequency_spectrum() , note that the last two do a FFT on our data. We know that the signal sent out by the weather balloon is a sine wave with a frequency of 403MHz; as the data is measured in nanoseconds the frequency is:

$$f = 403\text{MHz} = 403 \times 10^{-3}\frac{1}{\text{ns}} \tag{5.15}$$

The recorded spectrum of channels 0 and 3 is given in figure 5.10, for which we previously mentioned the spike at 0.403GHz. Now note that on figure 5.10 there are peaks both below 0.15GHz and above 0.6GHz, this is all non-physical noise as the Vpol antenna's range only goes from 0.15GHz to 0.6GHz [8] that's why we'll first pass this signal trough a virtual butterworth bandpass filter.

After passing the signal through the filter we'd also like to up sample the signal as to increase the resolution, this can be done using the resample() module. This resamples the trace to a new sampling rate , and we'll up sample towards 10GHz increasing our timely accuracy from 0.3125ns to 0.1ns. After filtering and up sampling we have some voltage response as shown for channel 0 in figure 5.11, we wish to find a sine wave coming from the weather balloon in this signal. **CHANGE THIS**

To find a sine wave herein we'll use radiotools' helper module get_normalized_xcorr which indirectly uses scipys signal correlation function. But before using that we'll need a template to correlate with the data. The template we'll be choosing is of course the sine function but it's important to notice that the channel has a certain sampling rate, namely now after up sampling, 10GHz.

Our template sine which we'll correlate to the data will also need to have this sampling rate, meaning that it needs to be step wise defined with spaces of 0.1ns. Next we'll also need to give the sine a certain amplitude, as we don't have a system for finding this yet let's for now assume an amplitude $A = 0.007$ (this shouldn't impact the correlation). Our template thus looks like this:

$$\mathcal{S} = A \cdot \sin(\omega t) \tag{5.16}$$

45
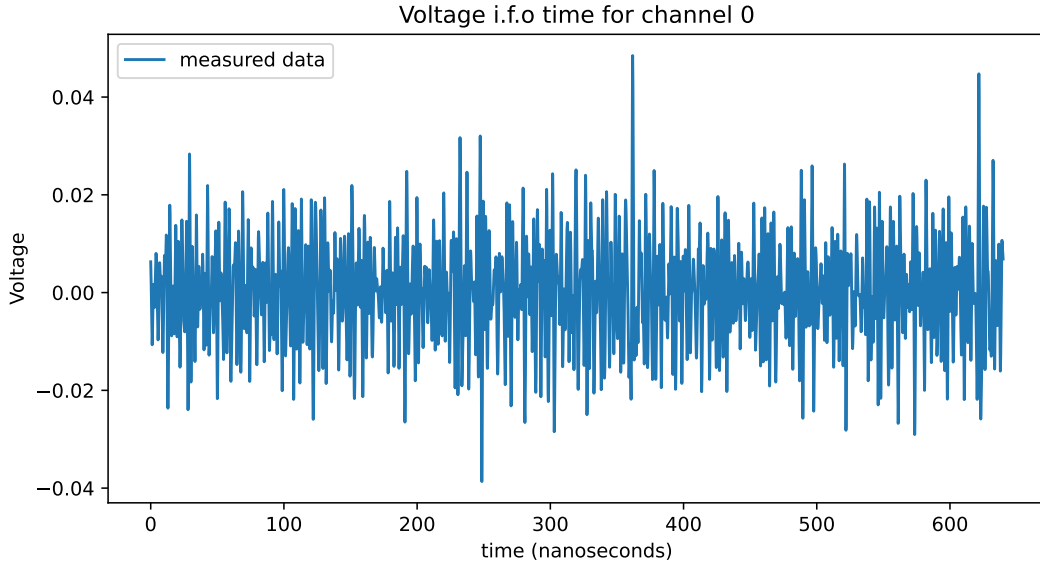
Figure 5.11: Recorded voltage i.f.o time in vpol antenna 0 after up sampling and passing through the butterworth filter

with

$$\omega = 2\pi f \tag{5.17}$$

Herein t is an array going from 0 to $3/f$ as to be able to fit 3 periods with intervals of 0.1ns. This template gets automatically shifted by the radiotools correlation module with steps of 0.1ns and each time the correlation with the data gets computed as is illustrated in figure 5.12. In real life the data is a bit less perfect and after doing this correlation procedure on the real data we get what's (partially) shown in figure **CHANGE THIS** 5.13. Herein the peaks represent the maximal correlation, if we now do the same for channel 3 we have two correlation functions, if we correlate these with each other we'll get the difference in timing between the channels. This is easy to comprehend after taking a look at the illustration shown in figure **??**. This cross correlation is shown in figure **CHANGE THIS ??**, the negative offset is caused by accounting for cable delay. Note that multiple peak correlations are present, to thus find out which one is the right one we'll do a simple simulation using our modified hybrid ray tracer from which we know what the approximate time difference is and search in this neighborhood.

Fitting n and finding it's error

Now that we have the differences in timing between the individual channels we'll loop over the local (middle of the detectors) indices of refraction, each yielding a function $\eta'(\theta) = \text{norm}(\Delta t - \Delta t(\theta))$. Every time we minimize this function we find a certain launch angle θ which we can use to do a plane wave reconstruction (also using Snell's law at the surface) and finally recording the distance from the reconstructed wave to the balloon at the height of the balloon in an array **differences**. Doing this for every index of refraction in our specified range we have a list **n** and a corresponding list **differences**, if we find the minimal difference in the **differences** list then the corresponding n in the list **n** is our anwser, note however that there are multiple minima, so we'll be choosing the one lying in the middle.

We now wish to estimate the error which is additional to the *systematic error* ϵ, for this we'll plot the index of refraction on the x axis and the inverse difference on the y axis as shown in
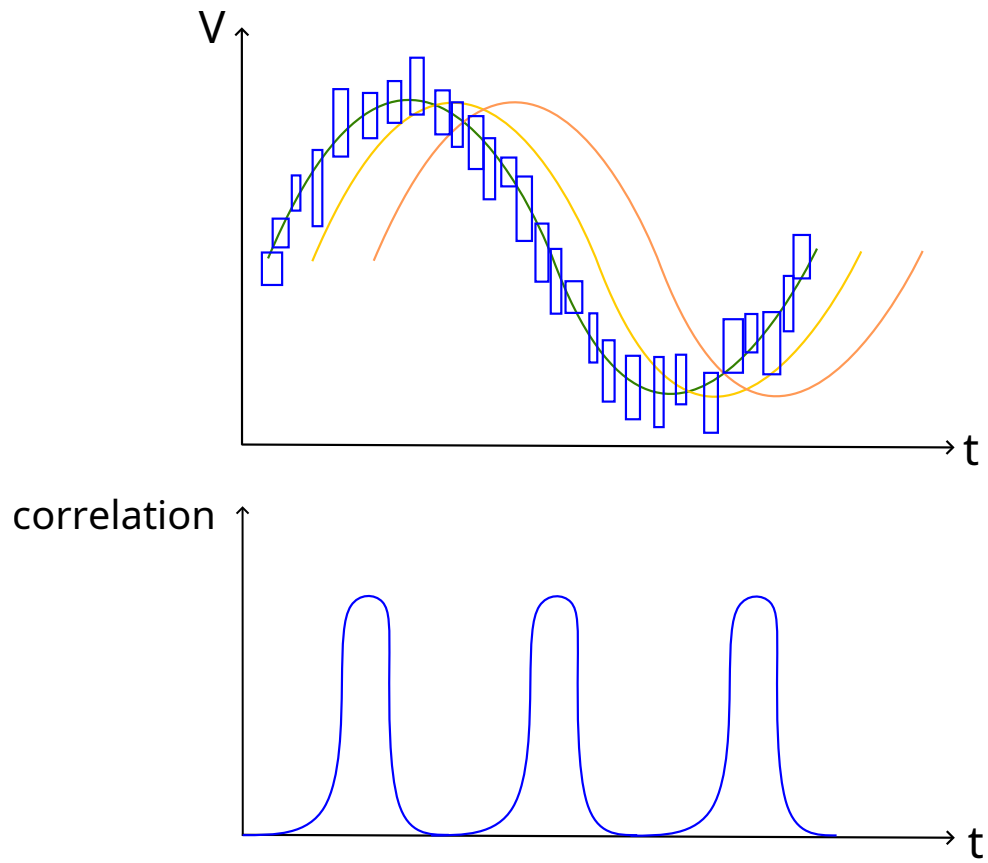
Figure 5.12: How correlating a sine with data leads to periodic peaks in the correlation function
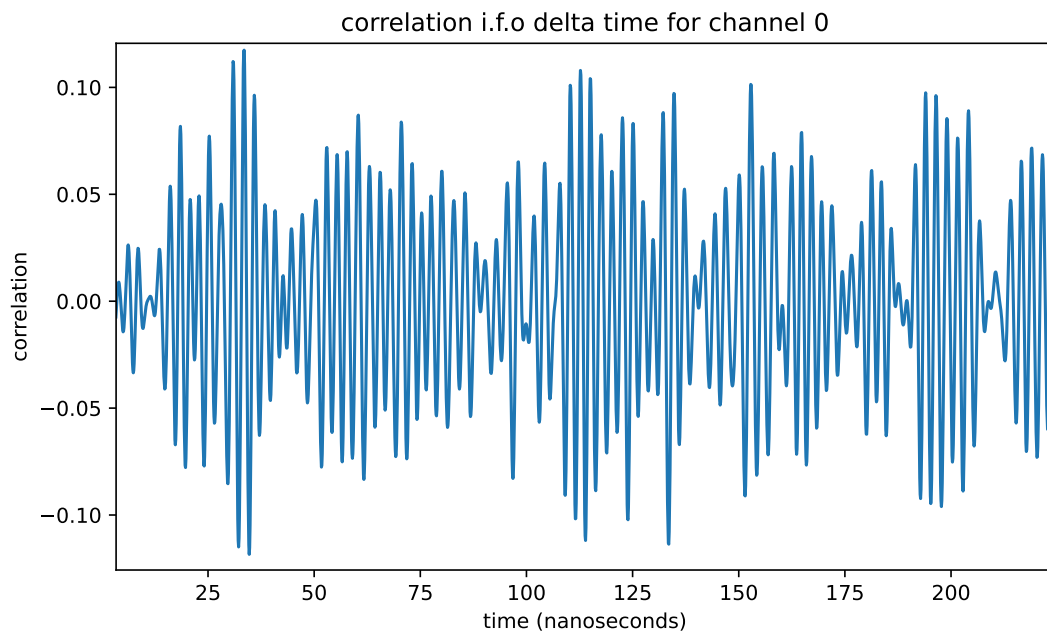
Figure 5.13: Zoom on the correlation i.f.o the time for channel 0
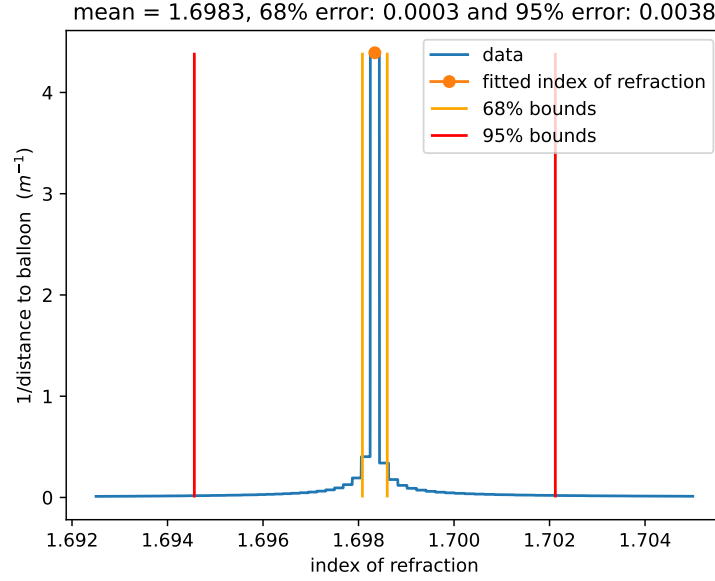
Figure 5.14: Fit of the index on Event 12397, the peak is very narrow

figure 5.14. A first idea was to Gaussian to this curve of the form [26]

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left\{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}\right\} \tag{5.18}$$

but as the data isn't really gaussian this fit wasn't great and underestimated the error. To estimate the error we think that using integration gives a good estimate, i.e we integrate over the full data (defined within a certain interval of the solution) and then again symmetrically outwards from the middle of the peak. If the ratio of these two is 68% then the interval this corresponds to is the one sigma error on our fit, analogously for 95%. If we carry this out we get the orange and red vertical lines which are shown on figure 5.14. Let's now add the systematic error which we computed to the error from this fit as the total error, finally we get:

Depth (m)	Station id	channels	Run:Event	$n_{exponential}$	$n_{fit}(68\%)$
-94.518	11	0&2&3	1034:12397	1.7397	1.7045 ± 0.006

And with 95% certainty:

Depth (m)	Station id	channels	Run:Event	$n_{exponential}$	$n_{fit}(95\%)$
-94.518	11	0&2&3	1034:12397	1.7397	1.7045 ± 0.01

Where the 68% fit lies is visually shown in figure 5.15. In both certainties the fit shows a clear discrepency with the exponential model. Note that this result is less dependent on the assumptions inherent to the ice model used in the simulation due to the small correction factor ($\epsilon \approx 0.36\%$). If we take a look at the density data and convert a measurement of roughly the same depth to the index using Shytt's equation ($n(z) \approx 1 + 0.845\rho(z)$) of roughly 1.733 which also isn't in agreement with this result. This might be caused by one of the following reasons:

- The density measurements aren't correct

- The index isn't fully linear at every depth
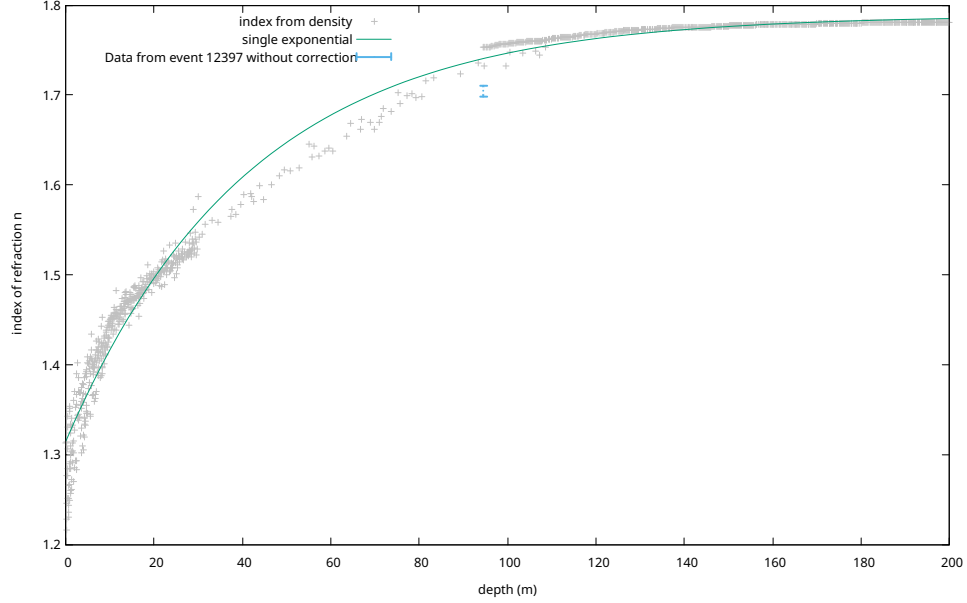
Figure 5.15: Event 12397 shows itself as a clear outlier hinting at the need to investigate the index-depth relation further

The density measurements do actually show quite a lot of spread for nearly the same values so there might be a problem there (there are also not that many recorded measurements and no reported uncertainties).

As for the linearity of the index, if we take a look at the index-depth relation found in the south polar firn [36]:

$$n(z) = 1.324 - 5.2854z - 21.865z^2 - 39.058z^3 \tag{5.19}$$

This would predict an index of 1.66, in stark disagreement with the exponential model. So either the coupling of the density with the index isn't fully linear or the density-depth relation in Greenland might be slightly different than in the south pole.

5.4 Channels 5,6 and 7

A very interesting depth is in between channels 5 and 7 as, looking at the difference between the index computed from the density and the single exponential model as shown in figure 5.15 this is where the largest deviations between both is observed. We'll take a look at this depth with channels 5,6 and 7 but note that these will be way less reliable (difficult to quantify how unreliable) than the phased array as the channels are spaced further apart.

The event we'll be using is recorded in detector 21 at the 26th of July 11:18:41 and falls within the $< 5°$ mark, doing analogous analyses as in the previous section we get figures B.2-B.4 which can be summarized in a table as shown below:

Depth (m)	Station id	channels	Run:Event	$n_{exponential}$	ϵ	$n_{fit}(68\%)$
-48.155	21	6&7	1441:117	1.6400	-0.02%	1.631 ± 0.001
-58.38	21	5&7	1441:117	1.6736	-0.23%	1.6650 ± 0.004
-68.2	21	5&6	1441:117	1.6983	0.02%	1.6919 ± 0.0006

Note that all of the indices that are found have a value below the exponential model's.

5.5 Guide for further analysis

CHANGE THIS Here I'll give a quick guide on how to continue this work, as a phased array measurement with small error hasn't been found yet. First off you'll need to install the NuRadioMC fork from my github located here and checkout the branch radiopropa/BaLLooN. Then go to `https://rnog-monitor.zeuthen.desy.de/` and search for events mentioned in appendix C (within those time frames), looking at the frequency spectrum of the phased array to see if the 0.403GHz signal gets detected. If such an event gets found write the run and event number down and also the exact date and time.

Now download this run file, the exact procedure is explained on the rno-g internal wiki under "analysis" but after you have installed everything my "getrnorun.sh" script located here might come in handy.

Now download all the balloon positional files (.gpx files) with the rno-g-sonde script located here and in this find the balloon file relevant for the event time, e.g a file named "SMT_20230315_111501.gpx" was launched the 15th of march in 2023 at 11:15:01.

Now the preparations are done, download the program used for fitting called "FitN.py" located here under BaLLooN. If you take a look at it's source code the first few variables (station_id, event_id, gpx_file,...) are what need to be changed to the previously found values. Run this with n_cut=None and then look at a good cut for the index of refraction (over which range you want to do the error analysis, examples are shown in appendix B) and rerun the program.

CONCLUSION

The hybrid ray tracer developed over the course of this thesis and reported in chapter 4 was a success, not only is it more accurate than it's predecessors, as shown in figures 4.11 and 4.12, but it's also faster by about 34%. The accuracy of the ray tracer also makes it perfectly suitable for very fine precision simulations as used within the Balloon radio wave measurements.

The use of weather balloons to estimate the index of refraction as was reported in 5 was also done successfully yielding the following data:

Depth (m)	Station id	channels	Run:Event	$n_{exponential}$	n_{fit}
-94.518	11	0&2&3	1034:12397	1.7397	1.7045 ± 0.006

And visually shown as the data in blue on figure 5.15, it clearly shows a big discrepancy with the exponential model. We reason that this clearly shows that there's a need to investigate the index-depth relation further as the wave propagation, and thus neutrino reconstruction, are heavily dependent on the ice model.

Note that there was only one event in the phased array that was analysed, this is because the occasions of when a balloon passes close enough to a detector and when the signal is measurable in the deep array are very few.

As there are a multitude of events (as can be found in appendices C and D but only finite time to analyze each and every one, this code is also made public here as to make it easy to improve on this work. Especially interesting might be events where ϵ is negligible (the balloon is really close) at the phased array and as such is the plane wave reconstruction a near perfect representation of the actual wave.

As this method seems to be a viable way of measuring the index of refraction, it might be a good idea to have a more controllable radio wave source fly closer to the detectors to make more accurate measurements, e.g an autonomous[7] drone with an antenna strapped to it or just some form of stationed antenna.

It might also be a good idea to make the signal easier to fit, as the currently used signal has quite a short wavelength (0.403GHz) we have to guess when the signal roughly arrives. If we have, say an AM signal, we wouldn't have to assume the rough arrival time of the signal, thus reducing the possible error on timing.

In the ideal case, as has been done in the South Polar firn [36], we'd want some immobile close source and a phased array which we'll move down every couple of measurements, thus obtaining an index-depth profile using direct measurements. This might be carried out e.g during deployment of a new station's power string.

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[7]as to not have it need a radio controller, causing RF interference on top of the one coming from the engine and also as autonomous GNSS positioning is always more accurate than human steering

APPENDIX

A

LIST OF ABBREVIATIONS

- **AM**: **A**mplitude **M**odulated

- **AGN**: **A**ctive **G**alactic **N**ucleus

- **CMB**: **C**osmic **M**icrowave **B**ackground

- **DAQ**: **D**ata **AQ**uisition system

- **DnR**: **D**irect a**N**d **R**efracted

- **DSNB**: **D**iffuse **S**upernova **N**eutrino **B**ackground

- **FFT** **F**ast **F**ourrier **T**ransform

- **GRBs**: **G**amma-**R**ay **B**ursts

- **RADIANT**: **RA**dio **DI**gitizer and **A**uxiliary **N**eutrino **T**rigger

- **RNO-G**: **R**adio **N**eutrino **O**bservatory in **G**reenland

- **RF**: **R**adio **F**requency

- **UHE**: **U**ltra **H**igh **E**nergy

- **UHECRs**: **U**ltra **H**igh **E**nergy **C**osmic **R**ay**s**

B

EXTRA FIGURES
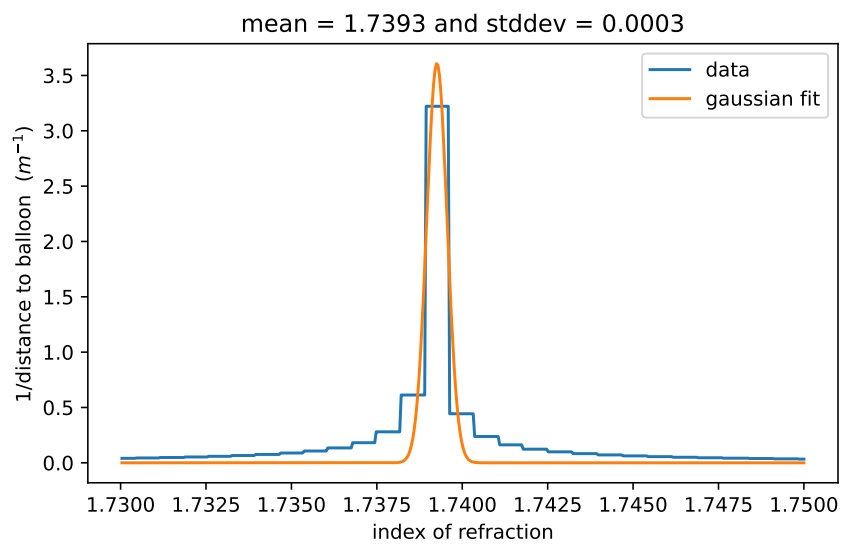
Figure B.1: gaussian fit doesn't perfectly align with the data
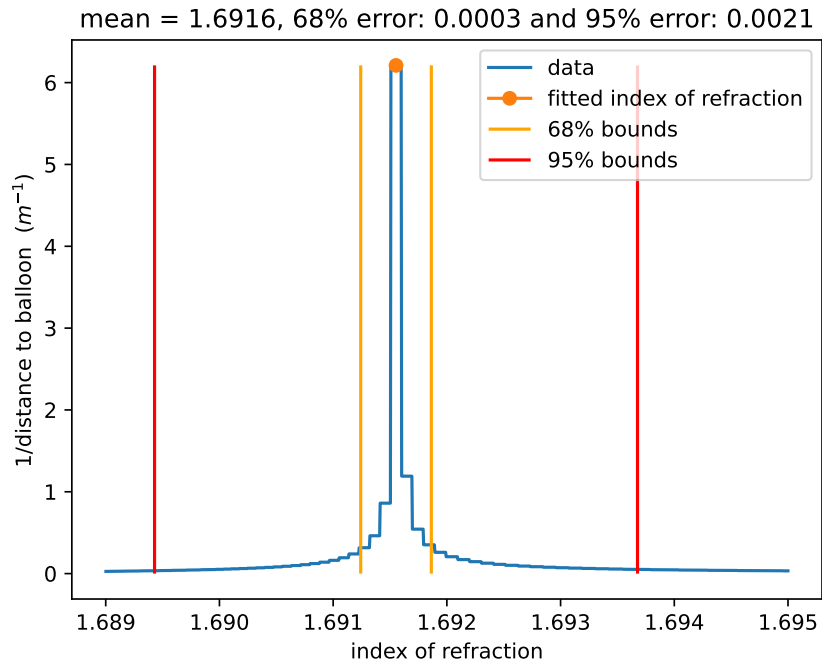
Figure B.2: Fit of channels 5 and 6
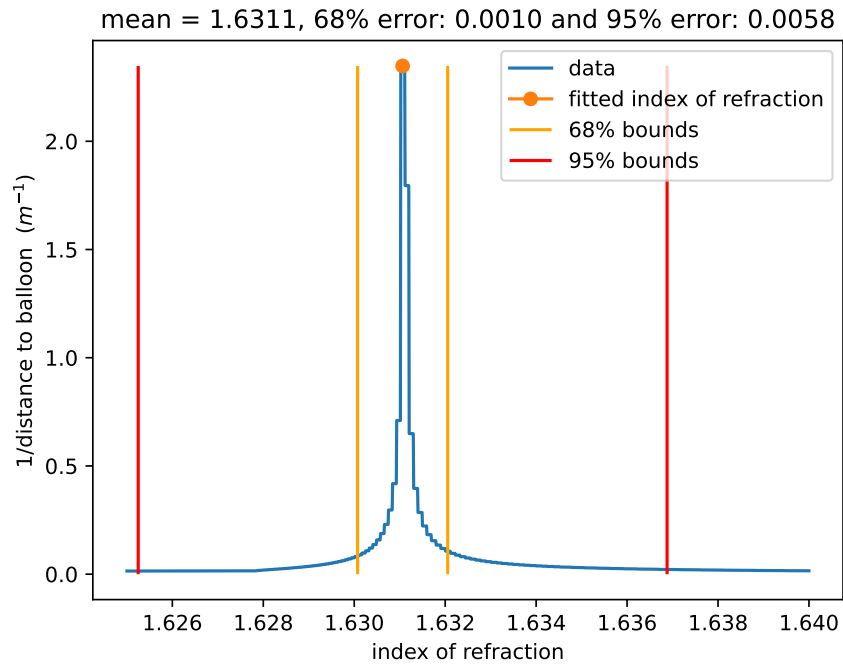
Figure B.3: Fit of channels 6 and 7
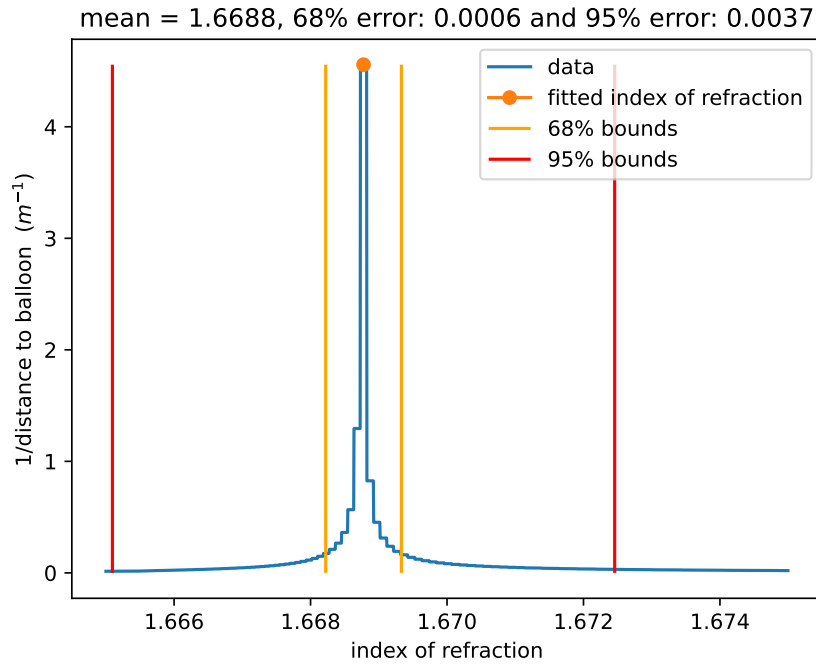
Figure B.4: Fit of channels 5 and 7

C

BALLOON PASSBYS UNDER 5°
IN THE SUMMER OF 2022

Balloon filename (gpx)	station	expected timeframe
SMT_20220907_112500.gpx	23.00	2022-09-07 11:28:47+00:00 till 2022-09-07 11:28:49+00:00
SMT_20220728_112143.gpx	12.00	2022-07-28 11:36:42+00:00 till 2022-07-28 11:37:44+00:00
SMT_20220728_112143.gpx	11.00	2022-07-28 11:34:00+00:00 till 2022-07-28 11:35:37+00:00
SMT_20220728_112143.gpx	13.00	2022-07-28 11:38:18+00:00 till 2022-07-28 11:39:13+00:00
SMT_20220723_231622.gpx	21.00	2022-07-23 23:25:19+00:00 till 2022-07-23 23:27:24+00:00
SMT_20220723_231622.gpx	22.00	2022-07-23 23:31:22+00:00 till 2022-07-23 23:33:50+00:00
SMT_20220930_231507.gpx	13.00	2022-09-30 23:19:22+00:00 till 2022-09-30 23:19:23+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220904_111459.gpx	21.00	2022-09-04 11:17:00+00:00 till 2022-09-04 11:17:49+00:00
SMT_20220904_111459.gpx	22.00	2022-09-04 11:21:12+00:00 till 2022-09-04 11:21:29+00:00
SMT_20220726_111605.gpx	21.00	2022-07-26 11:18:31+00:00 till 2022-07-26 11:18:47+00:00
SMT_20220726_111605.gpx	23.00	2022-07-26 11:27:32+00:00 till 2022-07-26 11:28:24+00:00
SMT_20220726_111605.gpx	24.00	2022-07-26 11:34:42+00:00 till 2022-07-26 11:40:36+00:00
SMT_20220826_113003.gpx	21.00	2022-08-26 11:32:14+00:00 till 2022-08-26 11:32:30+00:00
SMT_20220826_113003.gpx	13.00	2022-08-26 11:38:18+00:00 till 2022-08-26 11:39:04+00:00
SMT_20220714_231645.gpx	11.00	2022-07-14 23:30:57+00:00 till 2022-07-14 23:31:40+00:00
SMT_20220701_111515.gpx	11.00	2022-07-01 11:22:57+00:00 till 2022-07-01 11:25:30+00:00
SMT_20220725_112511.gpx	12.00	2022-07-25 11:29:41+00:00 till 2022-07-25 11:30:12+00:00
SMT_20220703_111803.gpx	24.00	2022-07-03 11:47:29+00:00 till 2022-07-03 11:50:43+00:00
SMT_20220820_111609.gpx	12.00	2022-08-20 11:24:37+00:00 till 2022-08-20 11:25:33+00:00
SMT_20220623_231633.gpx	13.00	2022-06-23 23:29:52+00:00 till 2022-06-23 23:30:59+00:00
SMT_20220623_231633.gpx	22.00	2022-06-23 23:23:50+00:00 till 2022-06-23 23:25:39+00:00
SMT_20220703_231627.gpx	21.00	2022-07-04 00:21:36+00:00 till 2022-07-04 00:42:14+00:00
SMT_20220703_231627.gpx	12.00	2022-07-04 00:32:03+00:00 till 2022-07-04 00:45:17+00:00
SMT_20220703_231627.gpx	11.00	2022-07-04 00:32:02+00:00 till 2022-07-04 00:47:35+00:00
SMT_20220703_231627.gpx	22.00	2022-07-04 00:21:47+00:00 till 2022-07-04 00:40:30+00:00
SMT_20220703_231627.gpx	23.00	2022-07-04 00:26:31+00:00 till 2022-07-04 00:34:55+00:00
SMT_20220624_231528.gpx	24.00	2022-06-25 00:29:26+00:00 till 2022-06-25 00:35:21+00:00
SMT_20220916_231807.gpx	22.00	2022-09-16 23:21:25+00:00 till 2022-09-16 23:21:49+00:00
SMT_20220908_111450.gpx	12.00	2022-09-08 11:20:23+00:00 till 2022-09-08 11:21:08+00:00
SMT_20220908_111450.gpx	13.00	2022-09-08 11:23:08+00:00 till 2022-09-08 11:23:54+00:00
SMT_20220817_111600.gpx	21.00	2022-08-17 11:31:37+00:00 till 2022-08-17 11:33:56+00:00
SMT_20220729_112533.gpx	11.00	2022-07-29 12:26:35+00:00 till 2022-07-29 12:31:35+00:00
SMT_20220907_231621.gpx	24.00	2022-09-07 23:24:23+00:00 till 2022-09-07 23:24:51+00:00
SMT_20220630_231835.gpx	21.00	2022-07-01 00:18:16+00:00 till 2022-07-01 00:32:45+00:00
SMT_20220630_231835.gpx	12.00	2022-07-01 00:25:19+00:00 till 2022-07-01 00:38:40+00:00
SMT_20220630_231835.gpx	11.00	2022-07-01 00:24:24+00:00 till 2022-07-01 00:37:58+00:00
SMT_20220630_231835.gpx	13.00	2022-07-01 00:30:30+00:00 till 2022-07-01 00:37:06+00:00
SMT_20220630_231835.gpx	22.00	2022-07-01 00:22:24+00:00 till 2022-07-01 00:34:12+00:00
SMT_20220826_231852.gpx	23.00	2022-08-26 23:27:09+00:00 till 2022-08-26 23:27:51+00:00
SMT_20220826_231852.gpx	24.00	2022-08-26 23:29:02+00:00 till 2022-08-26 23:29:48+00:00
SMT_20220624_111844.gpx	13.00	2022-06-24 11:33:51+00:00 till 2022-06-24 11:34:42+00:00
SMT_20220624_111844.gpx	22.00	2022-06-24 11:31:46+00:00 till 2022-06-24 11:32:35+00:00
SMT_20220707_112434.gpx	21.00	2022-07-07 12:31:12+00:00 till 2022-07-07 12:48:00+00:00
SMT_20220707_112434.gpx	12.00	2022-07-07 12:37:07+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	11.00	2022-07-07 12:36:00+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	13.00	2022-07-07 12:41:38+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	22.00	2022-07-07 12:34:46+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	23.00	2022-07-07 12:41:33+00:00 till 2022-07-07 12:48:09+00:00
SMT_20220829_111459.gpx	23.00	2022-08-29 11:18:46+00:00 till 2022-08-29 11:18:58+00:00
SMT_20220829_111459.gpx	24.00	2022-08-29 11:19:52+00:00 till 2022-08-29 11:20:10+00:00
SMT_20220727_232120.gpx	21.00	2022-07-27 23:24:53+00:00 till 2022-07-27 23:25:26+00:00
SMT_20220719_231514.gpx	11.00	2022-07-19 23:23:48+00:00 till 2022-07-19 23:26:06+00:00
SMT_20220807_231525.gpx	11.00	2022-08-07 23:18:35+00:00 till 2022-08-07 23:19:02+00:00
SMT_20220725_231505.gpx	13.00	2022-07-26 00:41:45+00:00 till 2022-07-26 00:53:49+00:00
SMT_20220725_231505.gpx	22.00	2022-07-25 23:22:13+00:00 till 2022-07-25 23:23:48+00:00
SMT_20220725_231505.gpx	23.00	2022-07-25 23:26:39+00:00 till 2022-07-26 00:48:25+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220725_231505.gpx	23.00	2022-07-25 23:26:39+00:00 till 2022-07-26 00:48:25+00:00
SMT_20220725_231505.gpx	24.00	2022-07-26 00:35:23+00:00 till 2022-07-26 00:49:53+00:00
SMT_20220928_111604.gpx	11.00	2022-09-28 11:34:13+00:00 till 2022-09-28 11:35:36+00:00
SMT_20220808_231507.gpx	11.00	2022-08-08 23:18:40+00:00 till 2022-08-08 23:19:08+00:00
SMT_20220816_232314.gpx	22.00	2022-08-16 23:34:34+00:00 till 2022-08-16 23:35:09+00:00
SMT_20220704_231605.gpx	21.00	2022-07-04 23:23:47+00:00 till 2022-07-04 23:27:33+00:00
SMT_20220630_112143.gpx	21.00	2022-06-30 12:26:56+00:00 till 2022-06-30 12:38:03+00:00
SMT_20220630_112143.gpx	12.00	2022-06-30 12:31:57+00:00 till 2022-06-30 12:44:25+00:00
SMT_20220630_112143.gpx	11.00	2022-06-30 12:31:26+00:00 till 2022-06-30 12:42:23+00:00
SMT_20220630_112143.gpx	13.00	2022-06-30 12:34:40+00:00 till 2022-06-30 12:44:06+00:00
SMT_20220630_112143.gpx	22.00	2022-06-30 12:28:56+00:00 till 2022-06-30 12:39:23+00:00
SMT_20220630_112143.gpx	23.00	2022-06-30 12:33:15+00:00 till 2022-06-30 12:37:09+00:00
SMT_20220704_112103.gpx	21.00	2022-07-04 11:49:20+00:00 till 2022-07-04 11:55:43+00:00
SMT_20220704_112103.gpx	11.00	2022-07-04 11:45:32+00:00 till 2022-07-04 11:51:31+00:00
SMT_20220704_112103.gpx	13.00	2022-07-04 12:10:16+00:00 till 2022-07-04 12:11:52+00:00
SMT_20220704_112103.gpx	22.00	2022-07-04 11:52:45+00:00 till 2022-07-04 12:02:35+00:00
SMT_20220704_112103.gpx	23.00	2022-07-04 11:58:37+00:00 till 2022-07-04 12:16:54+00:00
SMT_20220704_112103.gpx	24.00	2022-07-04 12:06:21+00:00 till 2022-07-04 12:25:28+00:00
SMT_20220720_111442.gpx	23.00	2022-07-20 11:46:26+00:00 till 2022-07-20 11:50:05+00:00
SMT_20220720_111442.gpx	24.00	2022-07-20 11:50:53+00:00 till 2022-07-20 12:03:52+00:00
SMT_20220829_231438.gpx	22.00	2022-08-29 23:16:33+00:00 till 2022-08-29 23:16:38+00:00
SMT_20220829_231438.gpx	23.00	2022-08-29 23:17:45+00:00 till 2022-08-29 23:17:58+00:00
SMT_20220921_231851.gpx	12.00	2022-09-22 10:46:18+00:00 till 2022-09-22 10:46:19+00:00
SMT_20220821_111511.gpx	21.00	2022-08-21 12:39:53+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	12.00	2022-08-21 12:51:06+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	11.00	2022-08-21 12:51:32+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	13.00	2022-08-21 12:52:27+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	22.00	2022-08-21 12:40:26+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	23.00	2022-08-21 12:43:03+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220724_231539.gpx	11.00	2022-07-24 23:20:04+00:00 till 2022-07-24 23:21:11+00:00
SMT_20220827_111534.gpx	24.00	2022-08-27 11:23:00+00:00 till 2022-08-27 11:23:07+00:00
SMT_20220625_111630.gpx	21.00	2022-06-25 12:27:31+00:00 till 2022-06-25 12:35:22+00:00
SMT_20220625_111630.gpx	12.00	2022-06-25 12:30:09+00:00 till 2022-06-25 12:39:40+00:00
SMT_20220625_111630.gpx	11.00	2022-06-25 12:32:45+00:00 till 2022-06-25 12:37:21+00:00
SMT_20220625_111630.gpx	13.00	2022-06-25 12:30:42+00:00 till 2022-06-25 12:40:11+00:00
SMT_20220625_111630.gpx	22.00	2022-06-25 12:27:03+00:00 till 2022-06-25 12:37:11+00:00
SMT_20220625_111630.gpx	23.00	2022-06-25 12:28:31+00:00 till 2022-06-25 12:37:18+00:00

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BALLOON PASSBYS UNDER 10°
IN THE SUMMER OF 2022

Balloon filename (gpx)	station	expected timeframe
SMT_20220719_231514.gpx	21	2022-07-19 23:19:46+00:00 till 2022-07-19 23:20:41+00:00
SMT_20220719_231514.gpx	11	2022-07-19 23:22:44+00:00 till 2022-07-19 23:27:19+00:00
SMT_20220831_111419.gpx	11	2022-08-31 11:16:20+00:00 till 2022-08-31 11:16:26+00:00
SMT_20220625_111630.gpx	21	2022-06-25 12:22:22+00:00 till 2022-06-25 12:40:57+00:00
SMT_20220625_111630.gpx	12	2022-06-25 12:25:55+00:00 till 2022-06-25 12:45:40+00:00
SMT_20220625_111630.gpx	11	2022-06-25 12:25:58+00:00 till 2022-06-25 12:45:09+00:00
SMT_20220625_111630.gpx	13	2022-06-25 12:26:44+00:00 till 2022-06-25 12:45:40+00:00
SMT_20220625_111630.gpx	22	2022-06-25 12:22:25+00:00 till 2022-06-25 12:42:40+00:00
SMT_20220625_111630.gpx	23	2022-06-25 12:24:10+00:00 till 2022-06-25 12:43:09+00:00
SMT_20220625_111630.gpx	24	2022-06-25 12:26:32+00:00 till 2022-06-25 12:42:24+00:00
SMT_20220826_113003.gpx	21	2022-08-26 11:32:04+00:00 till 2022-08-26 11:32:42+00:00
SMT_20220826_113003.gpx	13	2022-08-26 11:37:48+00:00 till 2022-08-26 11:39:40+00:00
SMT_20220626_112912.gpx	11	2022-06-26 11:35:52+00:00 till 2022-06-26 11:37:32+00:00
SMT_20220808_231507.gpx	11	2022-08-08 23:18:27+00:00 till 2022-08-08 23:19:24+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220724_231539.gpx	11	2022-07-24 23:19:27+00:00 till 2022-07-24 23:21:58+00:00
SMT_20220724_231539.gpx	13	2022-07-25 00:19:35+00:00 till 2022-07-25 00:32:09+00:00
SMT_20220829_231438.gpx	22	2022-08-29 23:16:29+00:00 till 2022-08-29 23:16:42+00:00
SMT_20220829_231438.gpx	23	2022-08-29 23:17:39+00:00 till 2022-08-29 23:18:04+00:00
SMT_20220829_231438.gpx	24	2022-08-29 23:18:59+00:00 till 2022-08-29 23:19:22+00:00
SMT_20220916_231807.gpx	21	2022-09-16 23:19:09+00:00 till 2022-09-16 23:19:17+00:00
SMT_20220916_231807.gpx	22	2022-09-16 23:21:13+00:00 till 2022-09-16 23:22:03+00:00
SMT_20220816_232314.gpx	22	2022-08-16 23:33:11+00:00 till 2022-08-16 23:37:34+00:00
SMT_20220907_112500.gpx	23	2022-09-07 11:28:37+00:00 till 2022-09-07 11:28:59+00:00
SMT_20220907_112500.gpx	24	2022-09-07 11:29:35+00:00 till 2022-09-07 11:29:53+00:00
SMT_20220628_231514.gpx	12	2022-06-28 23:19:37+00:00 till 2022-06-28 23:20:55+00:00
SMT_20220630_112143.gpx	21	2022-06-30 12:21:02+00:00 till 2022-06-30 12:46:53+00:00
SMT_20220630_112143.gpx	12	2022-06-30 12:26:35+00:00 till 2022-06-30 12:48:30+00:00
SMT_20220630_112143.gpx	11	2022-06-30 12:25:33+00:00 till 2022-06-30 12:48:30+00:00
SMT_20220630_112143.gpx	13	2022-06-30 12:28:56+00:00 till 2022-06-30 12:48:30+00:00
SMT_20220630_112143.gpx	22	2022-06-30 12:23:21+00:00 till 2022-06-30 12:47:42+00:00
SMT_20220630_112143.gpx	23	2022-06-30 12:26:20+00:00 till 2022-06-30 12:47:25+00:00
SMT_20220630_112143.gpx	24	2022-06-30 12:30:34+00:00 till 2022-06-30 12:46:14+00:00
SMT_20220725_231505.gpx	21	2022-07-25 23:17:47+00:00 till 2022-07-26 00:53:39+00:00
SMT_20220725_231505.gpx	12	2022-07-26 00:38:19+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220725_231505.gpx	11	2022-07-26 00:45:41+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220725_231505.gpx	13	2022-07-26 00:34:56+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220725_231505.gpx	22	2022-07-25 23:21:41+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220725_231505.gpx	23	2022-07-25 23:25:16+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220725_231505.gpx	24	2022-07-26 00:25:43+00:00 till 2022-07-26 00:55:04+00:00
SMT_20220703_111803.gpx	22	2022-07-03 11:40:24+00:00 till 2022-07-03 11:42:55+00:00
SMT_20220703_111803.gpx	23	2022-07-03 11:42:26+00:00 till 2022-07-03 11:49:33+00:00
SMT_20220703_111803.gpx	24	2022-07-03 11:45:29+00:00 till 2022-07-03 11:52:37+00:00
SMT_20220820_111609.gpx	21	2022-08-20 11:19:36+00:00 till 2022-08-20 11:21:16+00:00
SMT_20220820_111609.gpx	12	2022-08-20 11:24:02+00:00 till 2022-08-20 11:26:23+00:00
SMT_20220624_231528.gpx	12	2022-06-25 00:33:09+00:00 till 2022-06-25 00:40:51+00:00
SMT_20220624_231528.gpx	13	2022-06-25 00:28:45+00:00 till 2022-06-25 00:40:56+00:00
SMT_20220624_231528.gpx	22	2022-06-25 00:31:15+00:00 till 2022-06-25 00:34:40+00:00
SMT_20220624_231528.gpx	23	2022-06-25 00:24:52+00:00 till 2022-06-25 00:40:56+00:00
SMT_20220624_231528.gpx	24	2022-06-25 00:23:18+00:00 till 2022-06-25 00:40:56+00:00
SMT_20220701_111515.gpx	11	2022-07-01 11:21:58+00:00 till 2022-07-01 11:26:31+00:00
SMT_20220930_111518.gpx	12	2022-09-30 11:19:46+00:00 till 2022-09-30 11:20:04+00:00
SMT_20220821_111511.gpx	21	2022-08-21 12:30:15+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	12	2022-08-21 12:37:45+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	11	2022-08-21 12:37:28+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	13	2022-08-21 12:39:39+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	22	2022-08-21 12:31:58+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	23	2022-08-21 12:33:47+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220821_111511.gpx	24	2022-08-21 12:39:51+00:00 till 2022-08-21 12:56:06+00:00
SMT_20220813_112235.gpx	21	2022-08-13 11:12:14+00:00 till 2022-08-13 11:12:14+00:00
SMT_20220714_231645.gpx	12	2022-07-14 23:33:22+00:00 till 2022-07-14 23:38:49+00:00
SMT_20220714_231645.gpx	11	2022-07-14 23:27:54+00:00 till 2022-07-14 23:35:34+00:00
SMT_20220714_231645.gpx	13	2022-07-14 23:37:48+00:00 till 2022-07-14 23:46:03+00:00
SMT_20220723_231622.gpx	21	2022-07-23 23:21:03+00:00 till 2022-07-23 23:30:26+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220723_231622.gpx	21	2022-07-23 23:21:03+00:00 till 2022-07-23 23:30:26+00:00
SMT_20220723_231622.gpx	22	2022-07-23 23:30:12+00:00 till 2022-07-23 23:35:27+00:00
SMT_20220723_231622.gpx	23	2022-07-23 23:33:26+00:00 till 2022-07-23 23:37:57+00:00
SMT_20220723_231622.gpx	24	2022-07-23 23:36:33+00:00 till 2022-07-23 23:39:18+00:00
SMT_20220701_231934.gpx	22	2022-07-01 23:08:19+00:00 till 2022-07-01 23:08:19+00:00
SMT_20220701_231934.gpx	23	2022-07-01 23:08:19+00:00 till 2022-07-01 23:08:19+00:00
SMT_20220830_231921.gpx	12	2022-08-30 23:22:15+00:00 till 2022-08-30 23:22:31+00:00
SMT_20220706_231615.gpx	22	2022-07-07 00:34:24+00:00 till 2022-07-07 00:35:15+00:00
SMT_20220706_231615.gpx	23	2022-07-07 00:33:30+00:00 till 2022-07-07 00:35:15+00:00
SMT_20220706_231615.gpx	24	2022-07-07 00:33:50+00:00 till 2022-07-07 00:35:15+00:00
SMT_20220728_112143.gpx	12	2022-07-28 11:36:04+00:00 till 2022-07-28 11:38:16+00:00
SMT_20220728_112143.gpx	11	2022-07-28 11:32:06+00:00 till 2022-07-28 11:36:28+00:00
SMT_20220728_112143.gpx	13	2022-07-28 11:37:48+00:00 till 2022-07-28 11:39:49+00:00
SMT_20220716_111633.gpx	21	2022-07-16 12:05:05+00:00 till 2022-07-16 12:20:22+00:00
SMT_20220716_111633.gpx	12	2022-07-16 12:10:53+00:00 till 2022-07-16 12:24:07+00:00
SMT_20220716_111633.gpx	11	2022-07-16 12:08:23+00:00 till 2022-07-16 12:25:43+00:00
SMT_20220716_111633.gpx	22	2022-07-16 12:09:06+00:00 till 2022-07-16 12:18:35+00:00
SMT_20220715_231621.gpx	21	2022-07-16 00:08:58+00:00 till 2022-07-16 00:12:03+00:00
SMT_20220726_111605.gpx	21	2022-07-26 11:18:19+00:00 till 2022-07-26 11:19:03+00:00
SMT_20220726_111605.gpx	12	2022-07-26 12:20:14+00:00 till 2022-07-26 12:21:53+00:00
SMT_20220726_111605.gpx	13	2022-07-26 12:06:52+00:00 till 2022-07-26 12:30:56+00:00
SMT_20220726_111605.gpx	22	2022-07-26 11:21:46+00:00 till 2022-07-26 11:24:39+00:00
SMT_20220726_111605.gpx	23	2022-07-26 11:26:09+00:00 till 2022-07-26 12:22:24+00:00
SMT_20220726_111605.gpx	24	2022-07-26 11:31:17+00:00 till 2022-07-26 12:25:10+00:00
SMT_20220726_231510.gpx	11	2022-07-26 23:31:39+00:00 till 2022-07-26 23:43:04+00:00
SMT_20220724_111936.gpx	11	2022-07-24 11:24:45+00:00 till 2022-07-24 11:27:03+00:00
SMT_20220724_111936.gpx	13	2022-07-24 12:23:16+00:00 till 2022-07-24 12:33:48+00:00
SMT_20220724_111936.gpx	24	2022-07-24 12:12:44+00:00 till 2022-07-24 12:29:27+00:00
SMT_20220820_231751.gpx	13	2022-08-20 23:41:03+00:00 till 2022-08-20 23:45:01+00:00
SMT_20220820_231751.gpx	22	2022-08-20 23:39:20+00:00 till 2022-08-20 23:41:29+00:00
SMT_20220820_231751.gpx	23	2022-08-20 23:39:47+00:00 till 2022-08-20 23:42:41+00:00
SMT_20220703_231627.gpx	21	2022-07-03 23:58:58+00:00 till 2022-07-04 00:51:57+00:00
SMT_20220703_231627.gpx	12	2022-07-04 00:19:47+00:00 till 2022-07-04 00:52:09+00:00
SMT_20220703_231627.gpx	11	2022-07-04 00:19:37+00:00 till 2022-07-04 00:52:09+00:00
SMT_20220703_231627.gpx	13	2022-07-04 00:22:04+00:00 till 2022-07-04 00:52:07+00:00
SMT_20220703_231627.gpx	22	2022-07-04 00:14:09+00:00 till 2022-07-04 00:50:28+00:00
SMT_20220703_231627.gpx	23	2022-07-04 00:17:51+00:00 till 2022-07-04 00:48:29+00:00
SMT_20220703_231627.gpx	24	2022-07-04 00:23:40+00:00 till 2022-07-04 00:42:26+00:00
SMT_20220816_111548.gpx	11	2022-08-16 11:19:06+00:00 till 2022-08-16 11:20:08+00:00
SMT_20220704_231605.gpx	21	2022-07-04 23:21:14+00:00 till 2022-07-04 23:29:47+00:00
SMT_20220704_231605.gpx	22	2022-07-05 00:45:35+00:00 till 2022-07-05 00:46:21+00:00
SMT_20220704_231605.gpx	23	2022-07-05 00:44:35+00:00 till 2022-07-05 00:46:21+00:00
SMT_20220704_231605.gpx	24	2022-07-05 00:44:08+00:00 till 2022-07-05 00:46:21+00:00
SMT_20220921_231851.gpx	12	2022-09-22 10:46:18+00:00 till 2022-09-22 10:46:20+00:00
SMT_20220921_231851.gpx	13	2022-09-22 10:46:21+00:00 till 2022-09-22 10:46:22+00:00
SMT_20220630_231835.gpx	21	2022-07-01 00:11:25+00:00 till 2022-07-01 00:39:49+00:00
SMT_20220630_231835.gpx	12	2022-07-01 00:19:34+00:00 till 2022-07-01 00:45:51+00:00
SMT_20220630_231835.gpx	11	2022-07-01 00:17:35+00:00 till 2022-07-01 00:45:17+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220630_231835.gpx	13	2022-07-01 00:23:23+00:00 till 2022-07-01 00:45:28+00:00
SMT_20220630_231835.gpx	22	2022-07-01 00:17:04+00:00 till 2022-07-01 00:40:11+00:00
SMT_20220630_231835.gpx	23	2022-07-01 00:21:11+00:00 till 2022-07-01 00:39:32+00:00
SMT_20220630_231835.gpx	24	2022-07-01 00:26:47+00:00 till 2022-07-01 00:37:45+00:00
SMT_20220807_231525.gpx	11	2022-08-07 23:18:24+00:00 till 2022-08-07 23:19:22+00:00
SMT_20220727_232120.gpx	21	2022-07-27 23:24:29+00:00 till 2022-07-27 23:25:46+00:00
SMT_20220727_232120.gpx	22	2022-07-27 23:27:22+00:00 till 2022-07-27 23:27:30+00:00
SMT_20220727_232120.gpx	23	2022-07-27 23:31:39+00:00 till 2022-07-27 23:32:39+00:00
SMT_20220727_232120.gpx	24	2022-07-27 23:33:29+00:00 till 2022-07-27 23:36:31+00:00
SMT_20220707_112434.gpx	21	2022-07-07 12:23:11+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	12	2022-07-07 12:31:06+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	11	2022-07-07 12:28:16+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	13	2022-07-07 12:34:19+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	22	2022-07-07 12:26:02+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	23	2022-07-07 12:32:01+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220707_112434.gpx	24	2022-07-07 12:37:10+00:00 till 2022-07-07 12:49:22+00:00
SMT_20220617_231459.gpx	22	2022-06-17 23:17:36+00:00 till 2022-06-17 23:17:58+00:00
SMT_20220826_231852.gpx	23	2022-08-26 23:26:43+00:00 till 2022-08-26 23:28:19+00:00
SMT_20220826_231852.gpx	24	2022-08-26 23:28:41+00:00 till 2022-08-26 23:30:12+00:00
SMT_20220828_111632.gpx	22	2022-08-28 11:21:14+00:00 till 2022-08-28 11:23:09+00:00
SMT_20220828_111632.gpx	23	2022-08-28 11:24:07+00:00 till 2022-08-28 11:25:44+00:00
SMT_20220828_111632.gpx	24	2022-08-28 11:26:44+00:00 till 2022-08-28 11:28:09+00:00
SMT_20220623_231633.gpx	13	2022-06-23 23:29:11+00:00 till 2022-06-23 23:31:38+00:00
SMT_20220623_231633.gpx	22	2022-06-23 23:23:06+00:00 till 2022-06-23 23:26:51+00:00
SMT_20220807_111547.gpx	12	2022-08-07 11:22:02+00:00 till 2022-08-07 11:22:59+00:00
SMT_20220807_111547.gpx	13	2022-08-07 11:26:06+00:00 till 2022-08-07 11:27:55+00:00
SMT_20220624_111844.gpx	12	2022-06-24 11:33:01+00:00 till 2022-06-24 11:33:33+00:00
SMT_20220624_111844.gpx	13	2022-06-24 11:33:25+00:00 till 2022-06-24 11:35:11+00:00
SMT_20220624_111844.gpx	22	2022-06-24 11:31:13+00:00 till 2022-06-24 11:33:06+00:00
SMT_20220929_111540.gpx	12	2022-09-29 11:19:52+00:00 till 2022-09-29 11:20:48+00:00
SMT_20220720_111442.gpx	21	2022-07-20 11:28:20+00:00 till 2022-07-20 11:34:28+00:00
SMT_20220720_111442.gpx	22	2022-07-20 11:32:55+00:00 till 2022-07-20 11:49:29+00:00
SMT_20220720_111442.gpx	23	2022-07-20 11:37:02+00:00 till 2022-07-20 12:04:15+00:00
SMT_20220720_111442.gpx	24	2022-07-20 11:44:43+00:00 till 2022-07-20 12:12:56+00:00
SMT_20220829_111459.gpx	21	2022-08-29 11:15:53+00:00 till 2022-08-29 11:15:59+00:00
SMT_20220829_111459.gpx	23	2022-08-29 11:18:35+00:00 till 2022-08-29 11:19:05+00:00
SMT_20220829_111459.gpx	24	2022-08-29 11:19:44+00:00 till 2022-08-29 11:20:20+00:00
SMT_20220705_113009.gpx	21	2022-07-05 12:48:04+00:00 till 2022-07-05 12:53:24+00:00
SMT_20220705_113009.gpx	11	2022-07-05 12:50:13+00:00 till 2022-07-05 12:53:24+00:00
SMT_20220817_111600.gpx	21	2022-08-17 11:20:21+00:00 till 2022-08-17 11:35:09+00:00
SMT_20220817_111600.gpx	11	2022-08-17 11:27:50+00:00 till 2022-08-17 11:30:32+00:00
SMT_20220904_111459.gpx	21	2022-09-04 11:16:45+00:00 till 2022-09-04 11:18:39+00:00
SMT_20220904_111459.gpx	22	2022-09-04 11:20:46+00:00 till 2022-09-04 11:21:55+00:00
SMT_20220904_111459.gpx	23	2022-09-04 11:22:57+00:00 till 2022-09-04 11:24:53+00:00
SMT_20220904_111459.gpx	24	2022-09-04 11:24:58+00:00 till 2022-09-04 11:25:49+00:00
SMT_20220928_111604.gpx	12	2022-09-28 11:37:02+00:00 till 2022-09-28 11:38:16+00:00
SMT_20220928_111604.gpx	11	2022-09-28 11:33:16+00:00 till 2022-09-28 11:36:59+00:00
SMT_20220930_231507.gpx	13	2022-09-30 23:19:10+00:00 till 2022-09-30 23:19:35+00:00

Balloon filename (gpx)	station	expected timeframe
SMT_20220904_231730.gpx	24	2022-09-04 23:22:54+00:00 till 2022-09-04 23:23:14+00:00
SMT_20220921_111527.gpx	12	2022-09-21 11:27:31+00:00 till 2022-09-21 11:29:09+00:00
SMT_20220921_111527.gpx	11	2022-09-21 11:25:37+00:00 till 2022-09-21 11:27:09+00:00
SMT_20220921_111527.gpx	13	2022-09-21 11:29:18+00:00 till 2022-09-21 11:30:46+00:00
SMT_20220725_112511.gpx	12	2022-07-25 11:29:27+00:00 till 2022-07-25 11:30:29+00:00
SMT_20220907_231621.gpx	23	2022-09-07 23:22:59+00:00 till 2022-09-07 23:23:40+00:00
SMT_20220907_231621.gpx	24	2022-09-07 23:24:09+00:00 till 2022-09-07 23:25:07+00:00
SMT_20220827_111534.gpx	24	2022-08-27 11:22:30+00:00 till 2022-08-27 11:23:43+00:00
SMT_20220615_231713.gpx	12	2022-06-15 23:21:29+00:00 till 2022-06-15 23:22:47+00:00
SMT_20220908_111450.gpx	12	2022-09-08 11:20:02+00:00 till 2022-09-08 11:21:40+00:00
SMT_20220908_111450.gpx	13	2022-09-08 11:22:39+00:00 till 2022-09-08 11:24:21+00:00
SMT_20220616_231523.gpx	11	2022-06-16 23:17:55+00:00 till 2022-06-16 23:18:16+00:00
SMT_20220729_112533.gpx	21	2022-07-29 12:19:23+00:00 till 2022-07-29 12:33:04+00:00
SMT_20220729_112533.gpx	12	2022-07-29 12:26:18+00:00 till 2022-07-29 12:36:15+00:00
SMT_20220729_112533.gpx	11	2022-07-29 12:21:20+00:00 till 2022-07-29 12:37:29+00:00
SMT_20220704_112103.gpx	21	2022-07-04 11:46:05+00:00 till 2022-07-04 12:00:57+00:00
SMT_20220704_112103.gpx	12	2022-07-04 11:48:49+00:00 till 2022-07-04 12:35:14+00:00
SMT_20220704_112103.gpx	11	2022-07-04 11:41:27+00:00 till 2022-07-04 11:58:58+00:00
SMT_20220704_112103.gpx	13	2022-07-04 11:56:33+00:00 till 2022-07-04 12:40:36+00:00
SMT_20220704_112103.gpx	22	2022-07-04 11:49:29+00:00 till 2022-07-04 12:25:01+00:00
SMT_20220704_112103.gpx	23	2022-07-04 11:54:52+00:00 till 2022-07-04 12:33:48+00:00
SMT_20220704_112103.gpx	24	2022-07-04 11:59:40+00:00 till 2022-07-04 12:34:54+00:00
SMT_20220825_112057.gpx	12	2022-08-25 11:25:22+00:00 till 2022-08-25 11:25:43+00:00
SMT_20220712_111713.gpx	11	2022-07-12 12:29:00+00:00 till 2022-07-12 12:30:52+00:00
SMT_20220628_111612.gpx	11	2022-06-28 11:19:17+00:00 till 2022-06-28 11:19:27+00:00
SMT_20220702_231622.gpx	21	2022-07-03 00:14:37+00:00 till 2022-07-03 00:47:11+00:00
SMT_20220702_231622.gpx	12	2022-07-03 00:22:20+00:00 till 2022-07-03 00:52:30+00:00
SMT_20220702_231622.gpx	11	2022-07-03 00:29:05+00:00 till 2022-07-03 00:52:25+00:00
SMT_20220702_231622.gpx	13	2022-07-03 00:21:33+00:00 till 2022-07-03 00:52:30+00:00
SMT_20220702_231622.gpx	22	2022-07-03 00:11:26+00:00 till 2022-07-03 00:50:35+00:00
SMT_20220702_231622.gpx	23	2022-07-03 00:14:24+00:00 till 2022-07-03 00:51:28+00:00
SMT_20220702_231622.gpx	24	2022-07-03 00:16:28+00:00 till 2022-07-03 00:51:10+00:00
SMT_20220706_112237.gpx	21	2022-07-06 12:48:26+00:00 till 2022-07-06 12:48:49+00:00
SMT_20220803_232212.gpx	21	2022-08-03 23:23:53+00:00 till 2022-08-03 23:23:54+00:00
SMT_20220803_232212.gpx	22	2022-08-03 23:26:19+00:00 till 2022-08-03 23:27:55+00:00
SMT_20220803_232212.gpx	23	2022-08-03 23:29:46+00:00 till 2022-08-03 23:34:09+00:00
SMT_20220803_232212.gpx	24	2022-08-03 23:34:19+00:00 till 2022-08-03 23:38:20+00:00

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