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Can electromagnetic emission from glacier movements mimic signal in radio neutrino detectors?

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Several experiments in ice-covered regions are instrumenting balloons or mountain tops with antennas to look for a radio signal from ultra-high-energy neutrinos skimming the Earth's surface. In addition to the well known "mystery events" observed while ANITA flew over Antarctica, the mountain-top experiment TAROGE-M has recorded an anomalous cluster of radio signals from a nearby glacier from where no human-made backgrounds had been expected at first. There are many observations of radio emission associated with the fracture of ice and other solid materials. The available reports span across different disciplines and consequently focus on frequency ranges and sampling rates below what is relevant for radio neutrino detection. For this contribution we made an inventory of the available literature and attempted to measure radio emission from cracking ice in the laboratory. We intend to alert the radio neutrino community on the possibility that fracture of glacial ice may constitute a background for radio-neutrino experiments.

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1. Introduction

Several experimental approaches have been proposed, are in the prototyping state, or under construction to detect ultra-high energy neutrinos (> 10 PeV). A number of them have used or plan to use the radio emission (roughly 100 MHz - 1 GHz) following neutrino interactions in the polar ice caps, such as the in-air experiments ANITA [1], PUEO [2], and TAROGE [3], as well as in-ice experiments, such as ARA [4], ARIANNA [5], and RNO-G [6]. So far, all experiments have only reported the detection of background and not signal. Most backgrounds can be related to wind or human activity, but some have escaped a simple explanation. Most notably the *the ANITA mystery events* [1, 7, 8]. While showing the expected neutrino signature, the reconstructed arrival directions of these events are in strong tension to existing limits by IceCube and would require changes to the Standard Model of Particle Physics to be reconcilable with upward going particles, having traveled through the Earth [9]. None of the so far proposed explanations comes without reservations. TAROGE-M, installed on a mountain range in Antarctica, has also observed several impulsive events that raised questions. The three events arrived within a relatively short time from the direction of a nearby glacier [3]. They were identified as highly signal-like. While modestly clustered in time ($\Delta t = 23\,\mathrm{s}$), these events are not classified as tribo-electric background due to low wind-conditions at the site. The original publication stated no human activity at the origin, however, as reported at this conference [10] in the mean-time a Global Navigation Satellite System (GNSS) permanent station was identified as likely cause. Nonetheless, the origin on a glacier has motivated us to look at whether glaciers are known emitters of electromagnetic emission (EM) and can mimic neutrino signals.

2. Details of the observed signatures

Neutrino and cosmic ray signals are characterized by non-repeating nanosecond scale pulses that show a very smooth frequency spectrum, from the low MHz-regime to GHz frequencies. However, building an instrument that can resolve the entire frequency content of the pulse is essentially impossible, given bandwidth limitations in the receiving hardware. Air shower arrays typically choose the 30 – 80 MHz range and for neutrino detection most experiments use roughly the band from 100 MHz to 1.5 GHz. Most experiments use rather sophisticated triggering strategies to find potential cosmic rays and neutrino signals, since the data is currently never recorded continuously, but only snapshots of less than a microsecond are taken. The analysis of the recorded signals generally starts by removing known backgrounds such as continuous wave signals, instrument artifacts or vetoing arrival directions of known noise sources. This is then often followed by complex searches looking for single impulsive events (e.g. [1, 5]). Publications describing the analysis and data selection approach often state sentences like: *"This [other] event has a waveform quite different from all other cosmic rays, and has the lowest SNR of any cosmic ray observed. Both of these events are excluded from these analyses."* [1] Searching for a certain signature from glaciers therefore requires access to the raw data and Monte Carlo simulations of an instrument. To summarize, one needs a mechanism that generates signals with the following properties: (1) short and impulsive signals with frequency content up high MHz frequencies; (2) isolated pulses (in the MHz–GHz frequency range), as opposed to long-pulse trains, which would result in multiple-triggers failing various cluster cuts; (3) signals strong enough to be observed in at least $\mathcal{O}(\mathrm{km})$ distance; (4) polarized

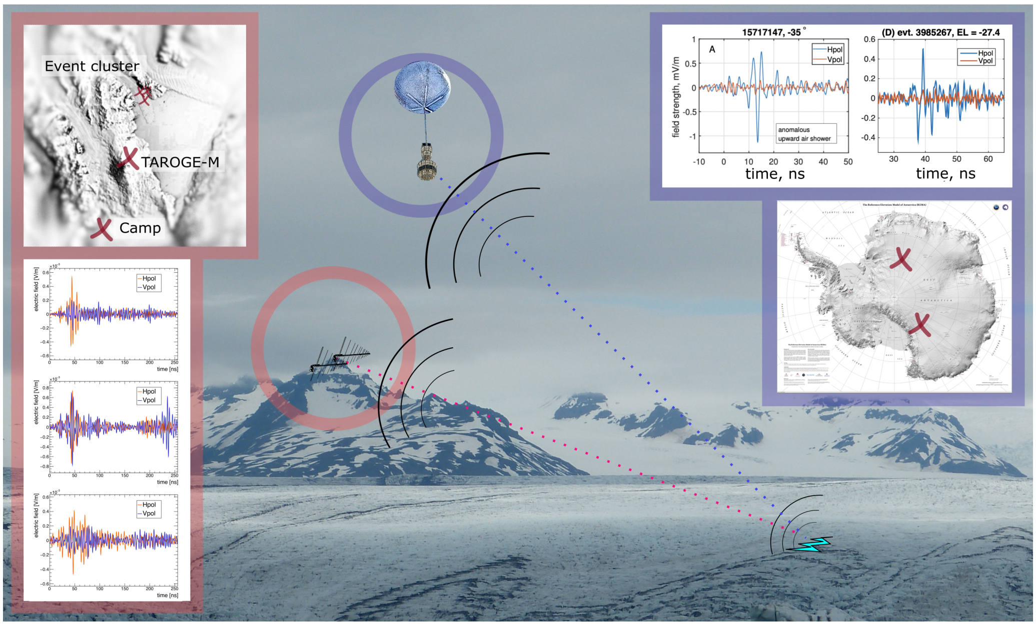

Figure 1: Composite overview figure of event signatures observed in TAROGE-M [3] (left) and ANITA I/III [1] (right). The illustration hypothetically connects them to ice fracture.

signals with a clear directionality. Furthermore, we are looking at processes that do no occur often or at least only generate these types of signals relatively rarely. Recall that in four flights of ANITA, each lasting for tens of days, less than 10 of these events have been observed. So either the process itself has to be rare or the process can be often, but detecting it is suppressed by instrument, trigger, or event selection characteristics, only allowing a rarely occurring tail of a distribution to pass.

3. Experimental evidence in glaciology and geophysics

We have reviewed literature across disciplines that make it seem plausible that EM from an ice mass could create a measurable signal. *Fractoemission* describes "the emission of particles and photons, before, during, and following the propagation of a crack in a stressed material" [11]. This is a wide definition describing similar phenomena addressed in different terms, such as *mechanoluminescence* or *triboluminescence* for light emission. The number of reports of emission after mechanical stress is almost endless, many include the emission of EM (e.g. [12–14]). Since all glaciers move and crack and crevasses are observed in moving glacial ice as result of brittle failure of ice under tension, this provides the necessary mechanical stress for potentially relevant fractoemission. Crevasses typically penetrate to a depth of $\sim$30 m in temperate glaciers, but fracturing can sometimes even go significantly deeper [15].

3.1 Field experiments in glaciers and ice sheets

EM has been reported in the deformation and cracking of glacial, lake, and sea ice. Although the comprehensive review of electromechanical phenomena observed in ice by Petrenko [16] was written almost three decades ago, the experimental findings have not changed much since. Non-stationary measurements of EM have been attempted early-on with low-altitude flights over and

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icebreaker passage through [17, 18] regions of sea ice with varying ice cover and thickness, and under different wind conditions. Here, the presence of high winds induces load on the sea ice resulting in cracking and hummocking. Both attempts reported significantly higher signal amplitudes in regions where more cracking was expected. Stationary measurements of the cracking process are easier and allow for a coincident measurement of acoustic and seismic signals together with the EM. Hammer-and-plate shots have been used to actively induce cracks in ice. Through this method it was e.g. possible to measure seismoelectric signals originating from a 22 m deep dry-wet interface layer in glacial ice [19]. EM has also been recorded when the cracking occurs naturally through temperature changes [16, 20]. Electroseismic signals have been recorded in the horizontal cracking of sea ice, where the salinity gradient leads to a frozen-in electric field [16]. However, seismoelectric emission is also observed in cracks of freshwater ice [16], where no material interfaces nor frozen-in electric field gradients are present. EM has also been observed in snow avalanches [18]. While cracking can contribute to the signal generation also here, electrification through friction similar to the triboelectric signals observed during high wind periods in radio neutrino experiments [21] may also generate the signal. Interestingly, a temperature dependence on the frictional charging using a ski sliding [22] has been observed, which could be tested with more detailed analysis in order to better characterize the triboelectric backgrounds in radio neutrino experiments. All of these geophysical experiments concentrated on measuring the EM at much lower frequencies and longer time-scales, typically employing kHz-antennas and resolutions of seconds.

3.2 Ice fracturing in lab

Out in the field, it is quite complex to control the origin of the signals. In literature, a number of experiments in the laboratory are described that use ice. EM from cracks has been measured in compression experiments in the laboratory [23, 24], with field probes embedded near the crack tip [25], as well as in the breaking of ice rods with embedded electrodes, and scouring of ice surfaces [24]. There has been an attempt to classify the different types of radio signals observed in the ice [26], and the observed power-law statistics of pulse amplitudes, pauses, and fractal character of the signals indicates the presence of long-range correlation in the dislocation pile-ups [27, 28] during critical failure. All of the ice measurements were again taken at much lower frequencies. We have, therefore, attempted to measure high-frequency emission in the laboratory, using different amplifiers and antennas. However, our access to large volumes of ice was limited, so small blocks of $10 \times 10 \times 5$ cm frozen to -40°C were used. Fracturing was simply induced by hammering on the ice blocks. By carefully moderating the applied force, we tried to preferentially induce singular crack surfaces rather than smashing the blocks. In the most suitable set-up, a bi-cone antenna, sensitive to 30 MHz – 1 GHz and a broad-band amplifier with 30 dB amplification was used. The antenna was placed at a distance of 0.5 m to the block in a shielded-chamber in order to mitigate the ubiquitous noise at MHz frequencies present in university buildings. The read-out was performed via an oscilloscope. An EM field probe was added as a second channel covering frequencies down to 1 MHz. The acoustic signal was recorded at 0.4 m distance limiting the acoustic delay to $\lesssim 1.2$ ms. A time window of 0.02 s around the acoustic trigger on a 16 ns sample interval, and a longer 20 s window with 16 ms sample interval were probed. In both cases, no significant excess of signals was measured in comparison to hammering on the table without the ice-block. We did not run comprehensive statistical tests, since the results would have anyway been dominated by systematic

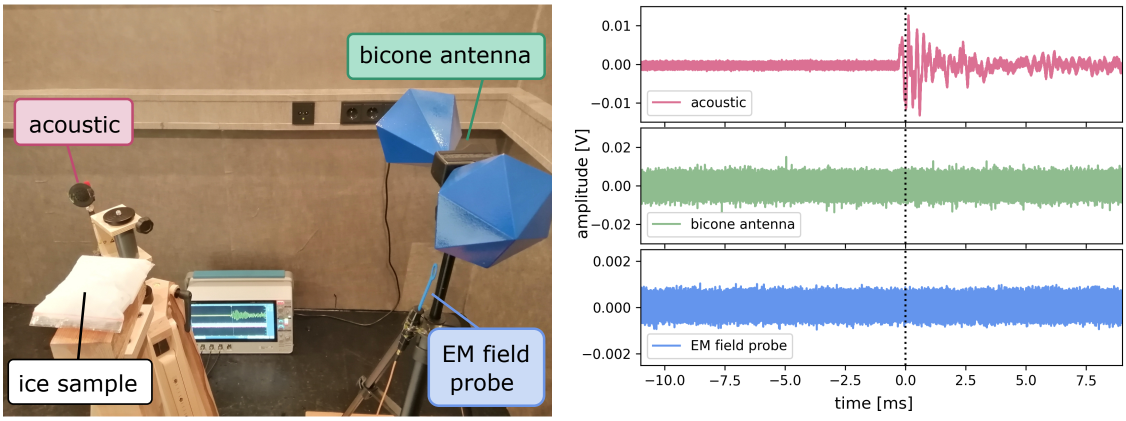

Figure 2: *Left:* Lab setup used in attempt to measure radio emission from cracks in the ice sample. *Right:* Recorded signals with the oscilloscope for the acoustic trigger channel and the two radio signal channels.

uncertainties in our simple set-up. Since we were unable to confirm the existence of high-frequency emission in our set-up, we can least exclude fracto-emission at MHz frequencies as a dominant emission which would be easy to detect. However, given the experimental limitations we also cannot rule out, that high frequency emission can be emitted. In a future experiment, kHz and MHz frequency signals should be measured together to reproduce the findings of previous studies as baseline .

3.3 Lab experiments using rock

From a geological perspective, glacial ice can be considered as a mono-mineralic metamorphic rock made from H_20. While glacial flows show features comparable to rocks in active mountain belts, the deformation rates of ice are several orders of magnitude higher, since ice temperatures are always close to the melting point [29]. Compared to ice there has been more activity towards measuring EM during crack forming in rock samples and crystalline materials. There are records of a broad range of electromagnetic signals, with readout sampling spanning intervals from seconds to microseconds in the laboratory [13, 30–34]. One key observation is that the EM signal precedes the acoustic cracking, and is attributed to the generation of new surfaces during micro-cracking before the main fault [35]. Solid rock samples are tested far below their melting point, which makes the test setup less delicate compared to ice. There is little interest in trying to measure EM emission from rocks close to their melting point, because they tend to get ductile, which precludes cracking. Ice is special in that regard, as it shows brittle behavior up to close to the melting point [36]. Since measurements were generally not performed below microsecond timescales, one central question is whether it is plausible that cracks form fast enough to generate a strong enough and coherent signal. For high frequency emission, instantaneous formation of the crack is required implying the material to show brittle rather than ductile behavior. One intriguing experiment used a neutron probe to monitor the failure of marble and granite samples under compression [37]. It was reported that only granite showed a strong increase in neutron monitor rate at the time of failure, which the authors attributed to the piezonuclear 'fusion' transition of embedded iron, $Fe^{30}_{26} \rightarrow 2\,Al^{14}_{13}$+2n.

For the transition to take place, a release time of the stored energy is derived to be $\lesssim$0.5 ns, only achievable – if at all – in materials with sufficient brittleness to show snap-back behavior, but not in ductile materials where the energy release is slow. This would imply that catastrophic failure processes might occur on nanosecond timescales in brittle materials, including ice, which is at least the correct timescale.

3.4 Electromagnetic emission in coincidence with earthquakes

EM in strained and fracturing rock has also been measured on length scales beyond the laboratory. The combined measurement of acoustic and electromagnetic emission during crack formation in mining [38], confirms the finding that the EM precedes acoustic emission, and is attributed to the early phase when small cracks are formed in the material prior to macroscopic failure. There have been also several reports of an observed EM from the rock fracture process in real time in geologically active regions [39–41]. The radio signal has been observed in coincidence with earthquakes at $O(100\,\mathrm{km})$ distance from the epicenter in regions of large seismic and volcanic activity, such as in Greece and near the Dead Sea Transform [40, 41]. A field experimental network has been installed for recording EM as precursors to earthquakes in Greece. As part of this network, one telemetric station, has been operating on Zante Island (Greece) in a region with low EM background. The instrumental setup included vertically polarized electric dipole antennas sensitive at 41, 54, and 135 MHz, respectively in addition to loop antennas. The time series were continuously sampled with a sampling rate of 1 Hz [40]. As a general feature, the emission is already observed in the hours prior to the signal in seismometers [40] and is studied for early warning. Although the formation of natural earthquakes is not understood to full detail, the general consensus is that it is a result of shear faulting. The precursor EM is thought to occur when new surfaces form through small scale cracking in the material during the nucleation phase [42]. In the final stage, the pre-cracked surfaces join to the main fault. This last stage may not be very efficient in creating new surfaces, which could explain the relative silence of EM emission in that stage. Overall, the experimental evidence for the co-existence of EM and ice movements is overwhelming in the literature. However, there is no (firm) evidence for MHz or even GHz emission. From the literature, it is unclear whether it really does not exist, or whether there were simply no measurements conducted.

4. Theoretical arguments and models for electromagnetic emission in ice

For EM to occur during the fracture process, moving charges are required. The most straightforward natural explanation how such moving charges would be generated on larger surfaces is through charge separation along the cracked surface. It is claimed that the normal hexagonal structure of pure ice due to its' symmetry by itself cannot exhibit piezo-electricity [24]. In only a small and confined region around the crack tip, the rupture of bonds which occurs during the cracking process can lead to a charge separation and radial emission [24]. A piece of ice can acquire electrical polarization if either a gradient in temperature or concentration of ions and impurities is present parallel to the newly generated surfaces (cf. the horizontal cracking of sea ice). Furthermore, when ice grains grow in natural (non-pure) ice, impurities get pushed out by the phase boundary, such that impurities get trapped near ice grain boundaries. This is because the solubility of foreign ions/atoms in ice is lower in the solid phase compared to the liquid phase. This generates an intrinsic electrical field in ice, oscillating from grain to grain in the ice bulk. The formation of micro-cracks may result from dislocation pile-up or grain boundary sliding [43]. At high strain rates, transgranular cracks dominate [44]. This involves the breaking of the bonds which link ice crystals in the matrix. Fracturing would thus move the cracked grain boundaries relative to each other, effectively resulting in a movement of charges. The models put forward have usually relied on charge separation along the cracked surface. The necessity of charge separation was always a weak point of these models, since it is only expected in media with large salinity gradients, not plausible in glacial ice sheets. A simplistic theoretical model that works without charge separation tries to explain EM emission using surface oscillations [45]. The model is not limited to certain parameter values, thus in principle allowing also EM emission above $O(100\,\mathrm{MHz})$ and we have been able to produce signals in this model similar to neutrino signals. Parameters needed to explain the events via this model correspond to time constants for the crack formation and the exponential decay of $\lesssim 10\,\mathrm{ns}$. We note that scaling is arbitrary at this point as parameters like distance, size of the emission region, etc. are not included in the model. Overall, the existing theoretical work is less compelling. However, the modeling itself requires to understand so many parameters of the cracking from microscopic to macroscopic length scales, that is it likely that only improved experimental evidence will bring progress.

5. Future work and Conclusions

There are plenty of measurements from the geophysical community, however, we have been unable to find measurements of the MHz range in clear temporal correlation to a newly formed crack, which is the missing key evidence. So it would be useful to install one of the neutrino radio receivers at a site where seismic measurements are conducted regularly (such as e.g. [46–48]) to correlate the known signals at kHz with MHz signals. As every experimenter knows, the devil will be in the details, which will make it no small feat, but it seems to be the most efficient way forward. The scaling to necessary signal power for distant receivers will still be needed, however, in direct collaboration with geophysicists scaling arguments may simplify to known sizes and processes of glacier movements. On the other hand, neutrino experiments should think about ideas to make them more robust against these potential backgrounds. Compared to ANITA, its successor PUEO will carry several improvements which might help to clarify potential future mystery events. While ANITA used 4-fold buffering, PUEO essentially has no dead-time. There is a non-negligible chance that ANITA may have missed clusters of events. This will not be the case for PUEO. According to design specifications, PUEO will be equipped with a lower frequency antenna that may help in signal identification. For both experiments, PUEO and TAROGE-M, it may also be beneficial to consider adding a kHz antenna that records almost continuously. Due to the low data rate, it should not add a lot of overhead in data volume. Also, as long as it is experimentally not clear how kHz and MHz emission are related, it may be hard to draw solid conclusions. In particular, because kHz emission will not allow for an angular resolution comparable to that at MHz frequencies.

We hope to have succeeded in alerting the astroparticle community to the fact that electromagnetic emission from geophysical processes may pose a background to radio neutrino experiments, although the evidence is currently too circumstantial and additional (cross-disciplinary) experiments with dedicated high frequency receivers in coincidence with seismic measurements are needed.

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