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Brief communication: Precision measurement of the index of refraction of deep glacial ice at radio frequencies at Summit Station, Greenland

Christoph Welling[1] **and The RNO-G Collaboration**[+]

[1]Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics,
University of Chicago, Chicago, IL 60637, USA
[+]A full list of authors appears at the end of the paper.

Correspondence: Christoph Welling (christophwelling@uchicago.edu, authors@rno-g.org)

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Abstract. We report on the measurement of the index of refraction of glacial ice at radio frequencies at Summit Station, Greenland. This measurement is of particular importance for the Radio Neutrino Observatory Greenland, an experiment currently under construction at Summit Station that seeks to detect radio signals from ultra-high-energy neutrino interactions in the ice. By correlating radio reflections in the bulk ice with features in the conductivity measurements from ice cores, we determine the index of refraction as $n = 1.778 \pm 0.006$.

1 Introduction

The Radio Neutrino Observatory Greenland (RNO-G) is an experiment for the detection of ultra-high-energy neutrinos (Aguilar et al., 2021) currently under construction near Summit Station, Greenland. It aims to discover the first astrophysical neutrinos with energies $> 10\,\mathrm{PeV}$ via radio signals from particle showers that are produced by the interactions of neutrinos in glacial ice. Doing so requires a good understanding of the optical properties of the ice at radio frequencies. We use the connection between radio echoes from within the ice and abrupt changes in ice conductivity, which has been demonstrated for the site of the Greenland Ice Core Project (GRIP) (Hempel et al., 2000) to measure the index of refraction of the bulk ice, similar to the method employed by Winter et al. (2017). The index of refraction of ice plays an important role in the radio detection of neutrinos, specifically in determining the Cherenkov angle, i.e. the direction in which the radio signal is emitted.

2 Radio echo measurements

The radio echo measurements used in this paper were taken in the summer of 2022 at Summit Station, near the GISP2 borehole. They are a follow-up to measurements taken in 2021 with the goal of measuring the radio attenuation of the ice (Aguilar et al., 2022a, b). The setup is almost identical to the previous one, with the main change being the replacement of the log-periodic dipole antennas with horn antennas and the measurements being taken near the GISP2 hole.

Signals were produced by a pulse generator and split into two outputs, one of which was used as a trigger signal. The other was fed into a 145 MHz high-pass filter and then into one of the horn antennas, which together restrict the signal to a 145–500 MHz band. The signal from the receiving horn antenna was fed into an amplifier of the same type as used by the shallow component of RNO-G and then recorded by an oscilloscope. Both antennas were placed on opposing sides of the GISP2 borehole, at a distance of about 51 m from the hole. To reduce noise, 12 000 individual waveforms were averaged. Additional radio echo measurements were taken about 550 m from the GISP2 borehole, near the so-called "Bally Building". While the use of a more powerful pulser allowed us to observe radio reflections from deeper in the ice, the distance from the GISP2 hole made the measurements unsuitable for the index of refraction measurement. They did,

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however, confirm that the observed correlation between radio reflectors and DEP data holds to greater depths.

3 Index of refraction measurement

We measure the index of refraction of the bulk ice by associating radio echoes with reflective layers identified at known depths through dielectric profiling (DEP). While the direct current (DC) conductivity has been measured for both the GISP2 and GRIP cores, alternating current (AC) conductivity measurements are only available from GRIP (Greenland Ice Core Project, 1994; Wolff et al., 1995), which is located roughly 28 km from Summit. As the DC conductivity of both ice cores is very similar (Taylor et al., 1993) and most internal layers have been shown to be continuous between the two sites (Jacobel and Hodge, 1995), we use the DEP data from GRIP and correct for the difference in layer depths using Rasmussen et al. (2014), Seierstad et al. (2014), and Centre for Ice and Climate, Niels Bohr Institute (2014).

The relation between the layer depth z and the signal propagation time t is given by

$$z = \frac{1}{2} \cdot \frac{c_0}{n} \cdot (t - \Delta T), \tag{1}$$

where c_0 is the vacuum speed of light, n is the index of refraction, and ΔT is a free parameter used to account for time offsets due to cable delays, the different index of refraction in the firn, and a possible offset between our antennas and the 0 m mark of the ice core.

We average the ice conductivity over a 5 m sliding window and calculate the root mean square of the deviation of the conductivity from this mean over a 2 m sliding window as an indicator of the change in conductivity. We also correct our radio echo measurements for signal attenuation using Aguilar et al. (2022a) and calculate the return power in a sliding 10 ns window. The index of refraction is then determined by converting the return times to depths using Eq. (1) and calculating the correlation between radio echo and conductivity data for different values of n and ΔT.

The result (Fig. 1) shows a clear maximum at $n = 1.778$. Plotting the radio return power over the DEP measurements (Fig. 2) shows that most abrupt changes in conductivity are matched with a radio echo, though there are a few exceptions. Similar inconsistencies between DEP data and radio echoes have also been noted by other measurements (Eisen et al., 2003).

4 Uncertainty estimation

The uncertainty of the index of refraction measurement consists of the uncertainties in the radio echo propagation times and the depths of the associated reflective layers. The first radio reflectors used for this measurement are at a depth of roughly 200 m, well below the transition between firn and

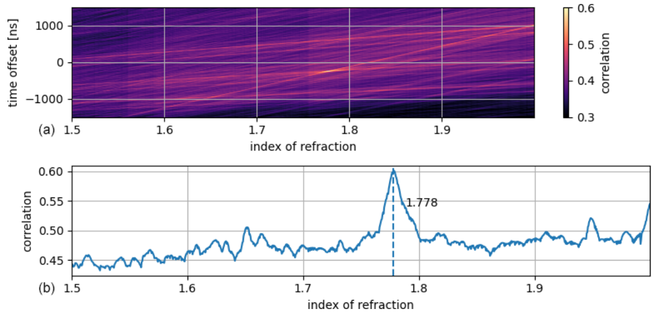

Figure 1. (a) Correlations between radio return power and RMS$(\sigma_\infty - \sigma_{\mathrm{avg}})$ for a given combination of index of refraction and time offset values. **(b)** Maximum correlation between radio return power and ice conductivity as a function of the index of refraction.

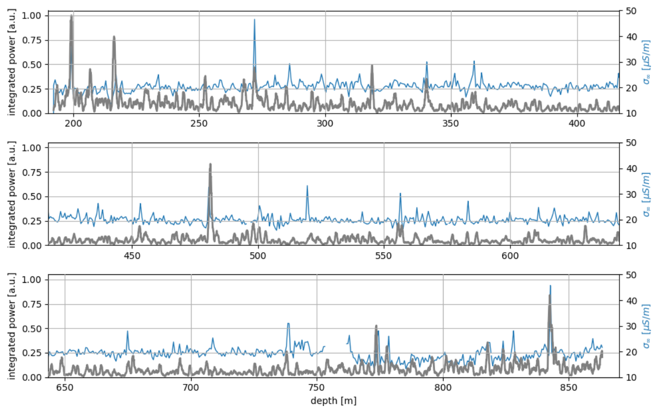

Figure 2. Radio return power as a function of the corresponding reflector depth, calculated using the reconstructed index of refraction n and the time offset ΔT (thick grey line), overlaid with the AC conductivity of the ice (thin blue line).

ice, which occurs at 75–77 m (Gow et al., 1997). Including a global time offset as a free parameter removes uncertainties from the index of refraction of the firn, cable delays, and the height of the antennas relative to the 0 m mark of the GISP2 ice core, as these affect all reflectors equally. The dominant uncertainty in Δt is the 10 ns window over which the return power was integrated. The first and last radio echoes that can be clearly associated with a specific DEP feature are at about 2.5 µs (195 m) and 10.2 µs (845 m), resulting in a relative uncertainty of $\sigma_t = 0.1\,\%$.

The uncertainty in the depth of the GISP2 conductivity data is given as 2 to 3 m at 3 km (Greenland Ice Core Project, 1994). We take this as an upper limit, though over the ~ 650 m range in depth we are looking at, the true uncertainty is likely much smaller. The uncertainty in the matching between the GISP2 and GRIP ice cores is given as 0.5 m (Seierstad et al., 2014). Thus, the conservative 2 m uncertainty on the GISP2 depth scale is the dominant uncertainty. Over a depth range of 650 m, this yields a relative uncertainty of $\sigma_z = 0.3\,\%$.

Quadratically adding the relative uncertainties in Δz and Δt results in a relative uncertainty of $\sigma_n = 0.3\,\%$, or $\sigma_{n,\mathrm{abs}} = 0.006$ in absolute terms.

5 Conclusion and outlook

We report on the observation of reflective layers in the ice sheet near Summit Station, Greenland, and compare them to conductivity measurements from the GRIP ice core. We show that most radio echoes can be attributed to features in the ice conductivity and use this relationship to measure the index of refraction of the bulk ice as $n = 1.778 \pm 0.006$.

Code and data availability. The code and data used for this paper are available under https://doi.org/10.5281/zenodo.12734887 (Welling, 2024).

Team list. Juan A. Aguilar (Université Libre de Bruxelles, Science Faculty CP230, 1050 Brussels, Belgium), Patrick Allison (Dept. of Physics, Center for Cosmology and AstroParticle Physics, Ohio State University, Columbus, OH 43210, USA), Dave Z. Besson (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA), Abigail Bishop (Wisconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), Olga Botner (Uppsala University, Dept. of Physics and Astronomy, Uppsala, 752 37, Sweden), Sjoerd Bouma (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Stijn Buitink (Vrije Universiteit Brussel, Astrophysical Institute, Pleinlaan 2, 1050 Brussels, Belgium), Whitmaur Castiglioni (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Maddalena Cataldo (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Brian A. Clark (Department of Physics, University of Maryland, College Park, MD 20742, USA), Alan Coleman (Uppsala University, Dept. of Physics and Astronomy, Uppsala, 752 37, Sweden), Kenneth Couberly (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA), Zachary Curtis-Ginsberg (Wisconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), Paramita Dasgupta (Université Libre de Bruxelles, Science Faculty CP230, 1050 Brussels, Belgium), Simon de Kockere (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium), Krijn D. de Vries (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium), Cosmin Deaconu (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Michael A. DuVernois (Wisconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), Anna Eimer (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Christian Glaser (Uppsala University, Dept. of Physics and Astronomy, Uppsala, 752 37, Sweden), Allan Hallgren (Uppsala University, Dept. of Physics and Astronomy, Uppsala, 752 37, Sweden), Steffen Hallmann (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany), Jordan C. Hanson (Whittier College, Whittier, CA 90602, USA), Bryan Hendricks (Dept. of Physics, Dept. of Astronomy and Astrophysics, Penn State University, University Park, PA 16801, USA), Jacob Henrichs (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany; Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Nils Heyer (Uppsala University, Dept. of Physics and Astronomy, Uppsala, 752 37, Sweden), Christian Hornhuber (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA), Kaeli Hughes (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA; Dept. of Physics, Dept. of Astronomy and Astrophysics, Penn State University, University Park, PA 16801, USA), Timo Karg (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany), Albrecht Karle (Wisconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), John L. Kelley (Wisconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), Michael Korntheuer (Université Libre de Bruxelles, Science Faculty CP230, 1050 Brussels, Belgium), Marek Kowalski (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany; Institut für Physik, Humboldt-Universität zu Berlin, 12489 Berlin, Germany), Ilya Kravchenko (Dept. of Physics and Astronomy, Univ. of Nebraska-Lincoln, NE 68588, USA), Ryan Krebs (Dept. of Physics, Dept. of Astronomy and Astrophysics, Penn State University, University Park, PA 16801, USA), Robert Lahmann (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Paul Lehmann (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Uzair Latif (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium), Philipp Laub (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Chao-Hsuan Liu (Dept. of Physics and Astronomy, Univ. of Nebraska-Lincoln, NE 68588, USA), Joseph Mammo (Dept. of Physics and Astronomy, Univ. of Nebraska-Lincoln, NE 68588, USA), Matthew J. Marsee (Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA), Zachary S. Meyers (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany; Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Kelli Michaels (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Katahrine Mulrey (Dept. of Astrophysics/IMAPP, Radboud University, P.O. Box 9010, 6500 GL, the Netherlands), Marco Muzio (Dept. of Physics, Dept. of Astronomy and Astrophysics, Penn State University, University Park, PA 16801, USA), Anna Nelles (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany; Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Alexander Novikov (Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA), Alisa Nozdrina (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS

66045, USA), Eric Oberla (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Bob Oeyen (Ghent University, Dept. of Physics and Astronomy, 9000 Gent, Belgium), Ilse Plaisier (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany; Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany), Noppadol Punsuebsay (Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA), Lilly Pyras (Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany; Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Dirk Ryckbosch (Ghent University, Dept. of Physics and Astronomy, 9000 Gent, Belgium), Felix Schlüter (Université Libre de Bruxelles, Science Faculty CP230, 1050 Brussels, Belgium), Olaf Scholten (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium; Kapteyn Institute, University of Groningen, Groningen, the Netherlands), David Seckel (Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA), Mohammad F. H. Seikh (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA), Daniel Smith (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Jethro Stoffels (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium), Daniel Southall (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Karen Terveer (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Simona Toscano (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Delia Tosi (isconsin IceCube Particle Astrophysics Center (WIPAC) and Dept. of Physics, University of Wisconsin-Madison, Madison, WI 53703, USA), Dieder J. Van Den Broeck (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium; Vrije Universiteit Brussel, Astrophysical Institute, Pleinlaan 2, 1050 Brussels, Belgium), Nick van Eijndhoven (Vrije Universiteit Brussel, Dienst ELEM, 1050 Brussels, Belgium), Abigail G. Vieregg (Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA), Janna Z. Vischer (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany), Dawn R. Williams (Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA), Stephanie Wissel (Dept. of Physics, Dept. of Astronomy and Astrophysics, Penn State University, University Park, PA 16801, USA), Robert Young (University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA), and Adrian Zink (Erlangen Center for Astroparticle Physics (ECAP), Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany)

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