Modulation of Neutrino-Induced Radio Signals by Evolving Polar Ice

Alex Kyriacou - akyriacou@ku.edu
Department of Astronomy and Physics
University of Kansas

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UHEN Detection in Ice

Polar ice sheets are ideal detection media for ultra-high energy neutrinos (**UHE-ν**) $E_\nu > 10$ PeV

- **Transparent to radio waves in the MHz – GHz regime** - attenuation length $L_\alpha = O(1\text{ km})$ at 100 MHz to 500 MHz
- Allows for large volumes of ice to be instrumented
- Antennas are also far cheaper than optical modules

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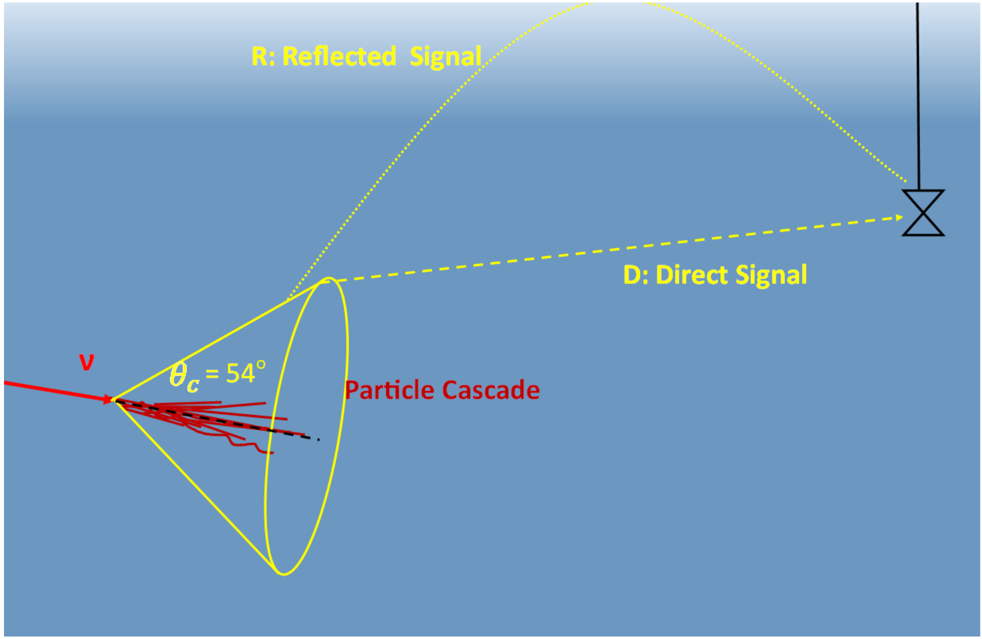

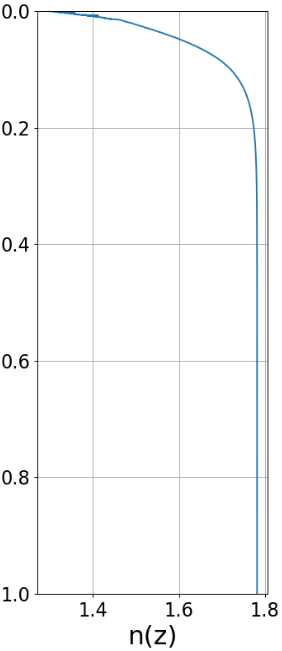

Askaryan emission

- Build-up of excess negative charge in the medium
- Coherent radio emission produced at the Cherenkov angle θ_C to the cascade direction defined by the refractive index ($\theta_C = 56$)

- Experiments searching for in-ice Askaryan: RICE, ARA, RNO-G, ARIANNA, ANITA, PUEO, IceCube-Gen2 Radio

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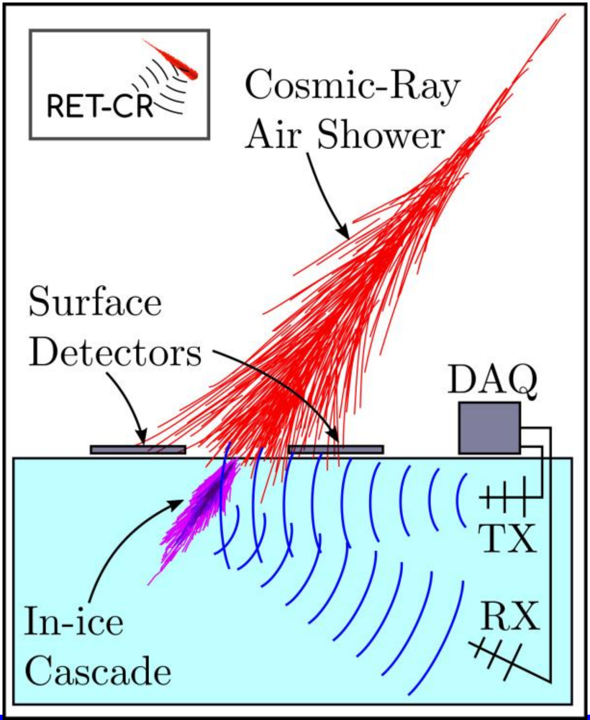


Radar-Echo method:

- Ionization trail persists briefly after UHE-ν cascade →acts as a reflective object for in-ice radar.
- Method is currently being tested in the field using UHE cosmic rays: Radar Echo Telescope for Cosmic Rays (RET-CR)
- Verification of the method in nature will facilitate the development of a future RET-N
- See Dylan Frikken's talk - HE Astro / Gravitational Waves II (08/26)

Firn Layer

RET-CR & In-Ice Askaryan Detectors have antennas within or immediately below the ‘firn layer’

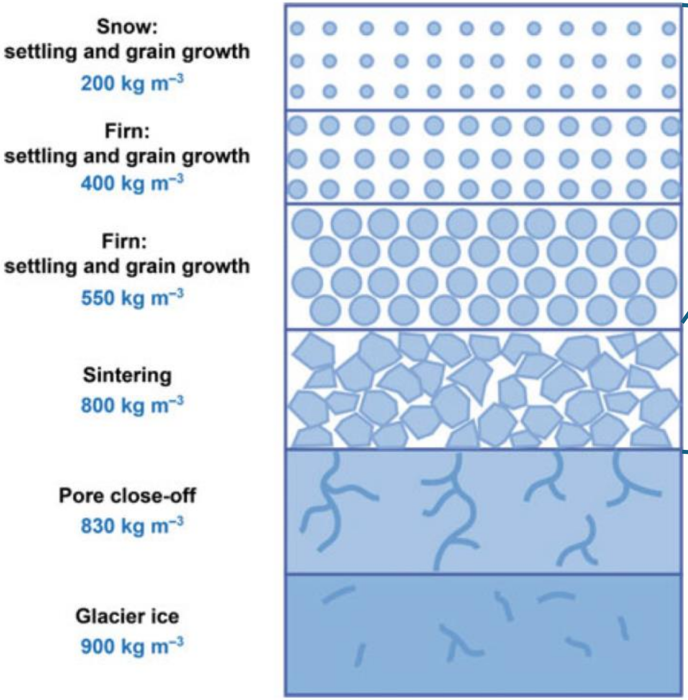
Firn: intermediate stage between fresh fallen snow and glacial ice

- 100 – 150 m deep in Greenland and Antactic ice caps
- Assuming constant accumulation and temperature:

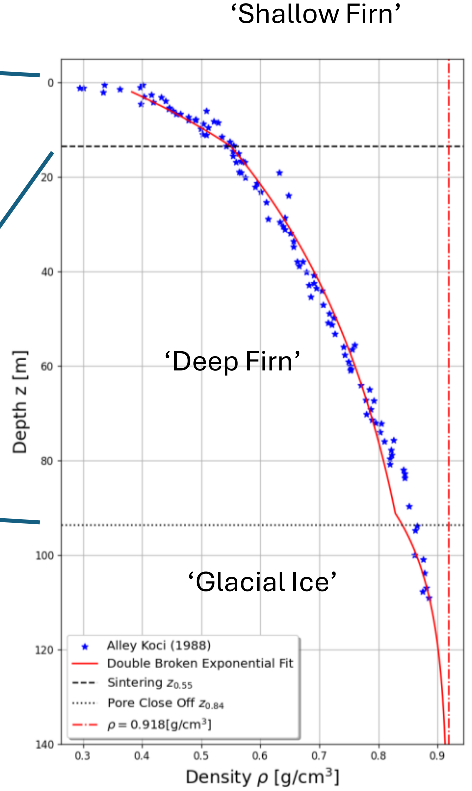
$$\rho(z) = \rho_i + \Delta\rho\, e^{-kz}$$

- Densification rate k changes due to different dominant process
  - $0 < z < z_{550}$ – ‘Shallow Firn’
  - $Z_{550} < z < z_{800}$ – ‘Deep Firn’
  - $z > z_{800}$ – ‘Glacial Ice’
- The refractive index was found empirically to be linearly proportional to the firn density [Kovacs et al. 1994]:

$$n = 1 + A(\rho[g/cm^3])$$



Buizert & Helsen, Glaciers and Ice Sheets in the Climate System, Chapter 11 (Springer)



Firn density profile at Site A, Greenland (1988) – Alley & Koci (1988) – Annals of Glaciology.

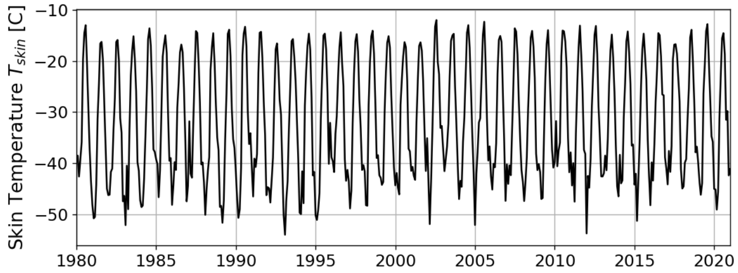
Firn Variation and Evolution

This simple description of Firn is complicated by seasonal fluctuations in temperature:

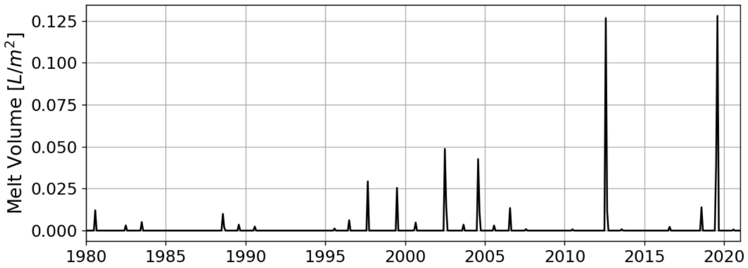
- Temperature variation leads to fluctuations in firn density
- Episodic surface melting events & rainfall

These lead to the formation of refrozen ice layers & density fluctuations → Strongest in the shallow firn layer (z < 15 m at Summit)

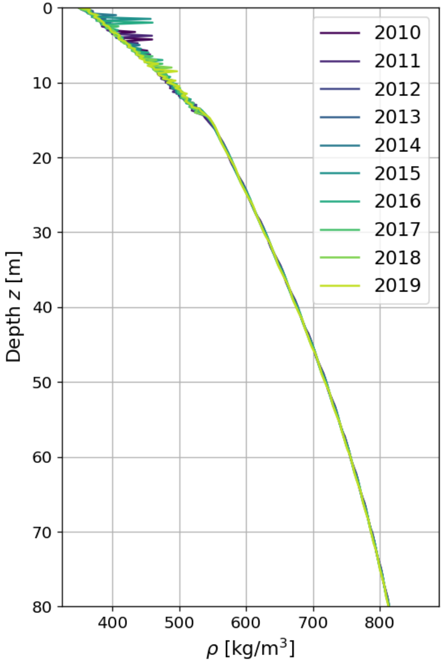
Monthly surface air temperature at Summit, Greenland



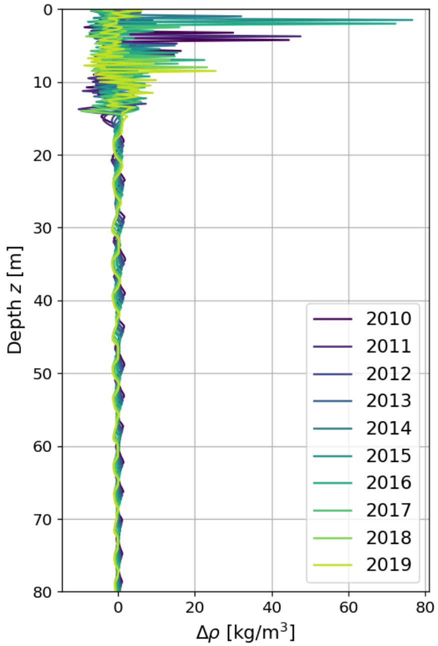
Surface Melt Events



Predicted Density from Community Firn Model



Variation of Density



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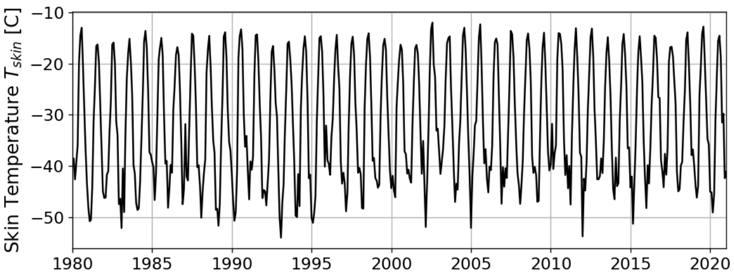

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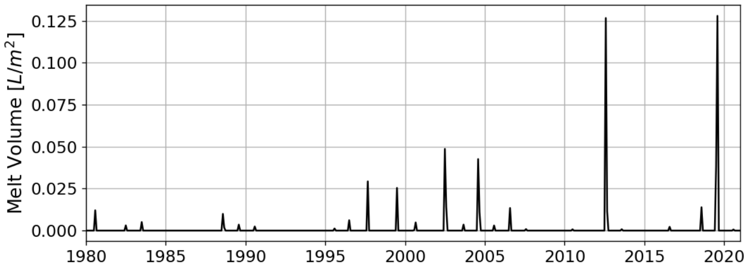

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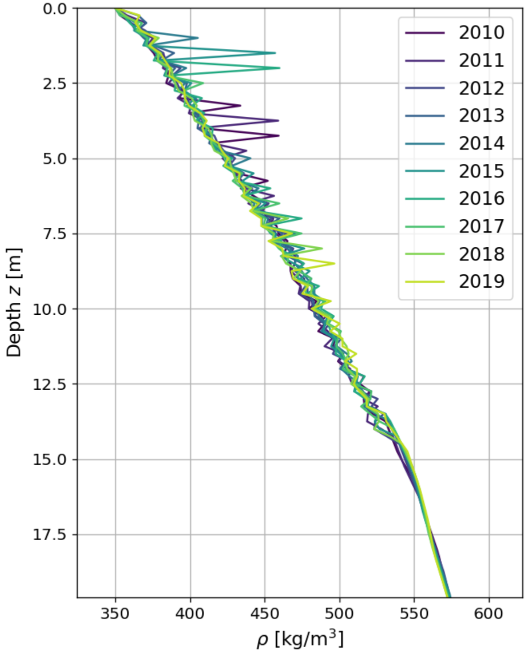

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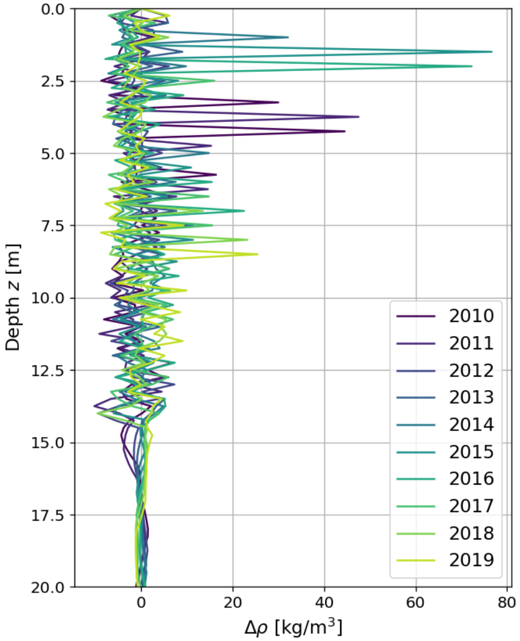

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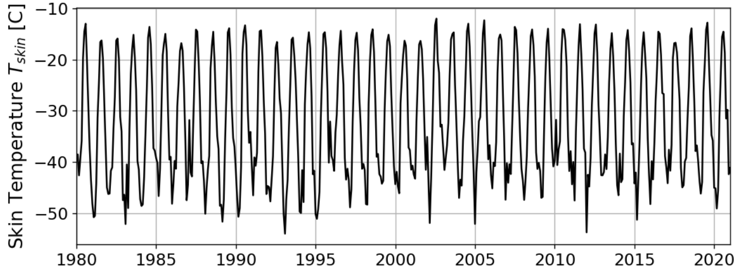

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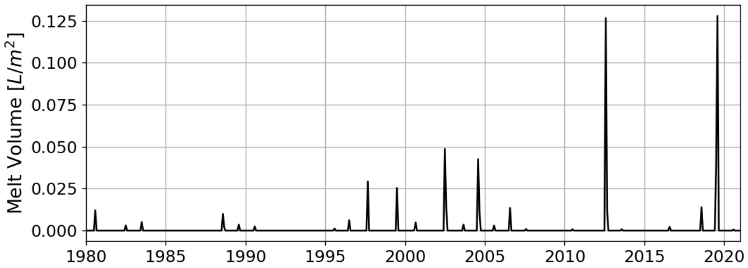

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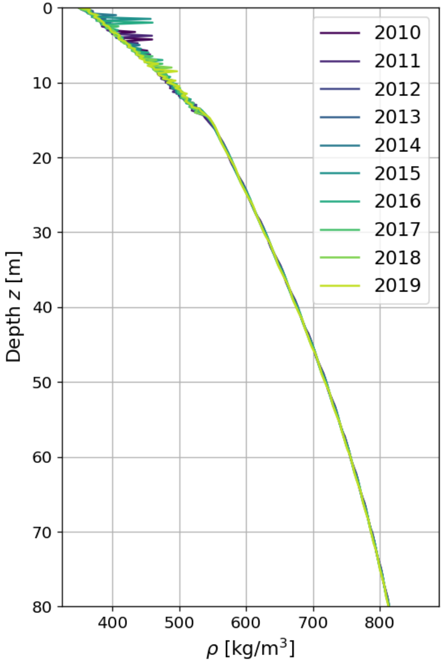
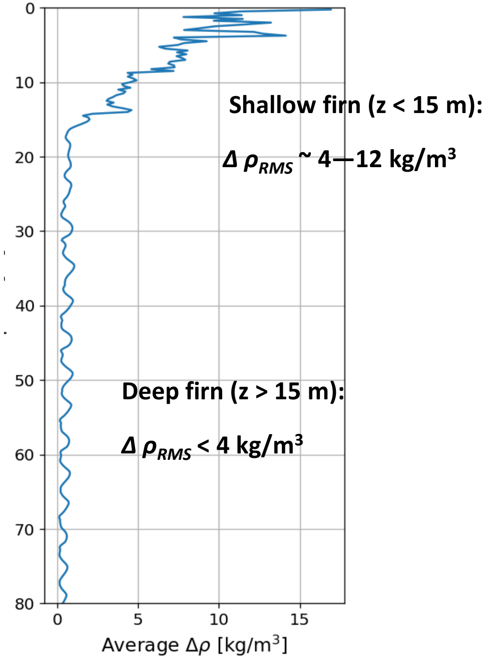


Average Variation of Density [2010-2019]



Shallow firn (z < 15 m):

$\Delta\rho_{RMS}$ ~ 4—12 kg/m³

Deep firn (z > 15 m):

$\Delta\rho_{RMS} < 4$ kg/m³

Simulation Study: Summit, Greenland

Variable firn density over time may change the properties of neutrino-induced radio signals

To investigate this effect, we use the firn layer at Summit, Greenland as a case study.

Goal: Simulate radio propagation from a deep source to a set of receivers at depths 0 m < z < 200 m, for a geometry of 1km depth x 1km radius (comparable to the attenuation length!)
→ Quantify variation in out E-field trace at RX - $\boldsymbol{E_{RX}}(\boldsymbol{t})$ **for n(z) profiles from different times**

Analysis parameters:

- Peak amplitude: $E_{RX,max}$ for direct (D) and reflected/refracted (R) signal
- Time delay between D and R signal: $\Delta t_{DR} = t_R - t_D$
- Fluence: $\phi^E_{RX} = \epsilon c \int E^2_{RX}(t) dt$

Radio Simulation Codes (see backup slides for more details):

- **MEEP**: Direct solution of Maxwell's equations in a geometric grid (FDTD method)
  - Most accurate method but computationally expensive (requires grid resolution Δx ≤ λ/10)
- **paraProp:** Parabolic-wave approximation of Maxwell's equation within cylindrically symmetry volume
  - Accurate within 'paraxial angle' to the horizontal direction → computationally efficient

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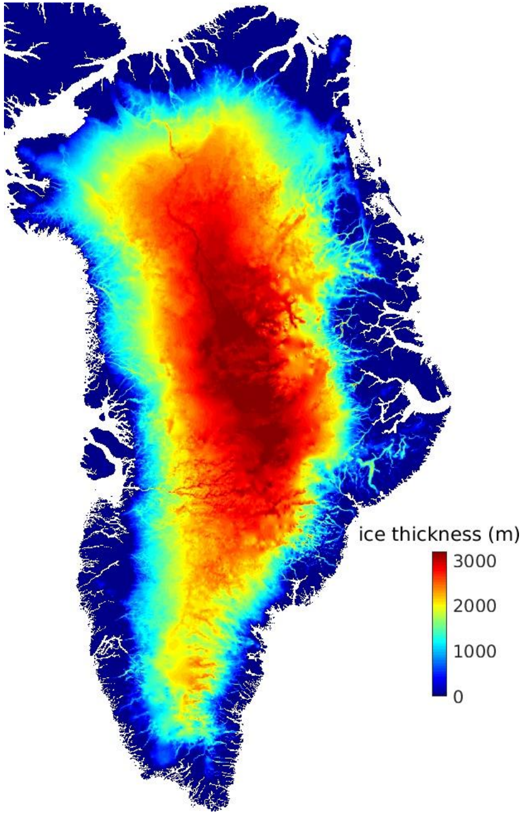
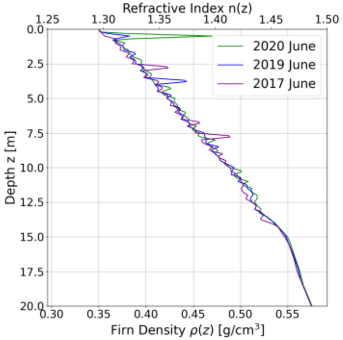


Simulation Chain

Refractive Index:

Community Firn Model (CFM)

- Density profiles derived using glaciological modelling software:
- Community Firn Model → based on climate data from Summit
- Depth grid size: 10 cm
- Outputs from each month from 1980 to 2020



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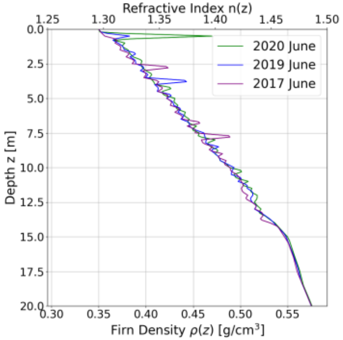

Source signal:

Analytical model of Askaryan pulse from 10^{18} eV hadronic shower

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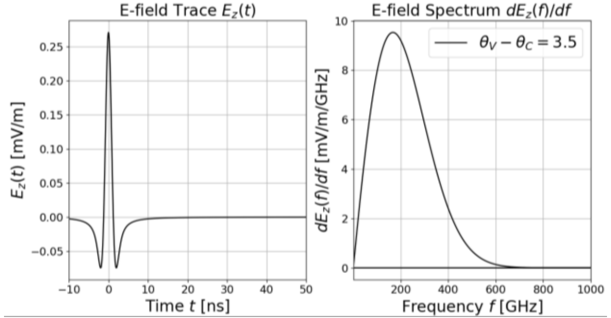

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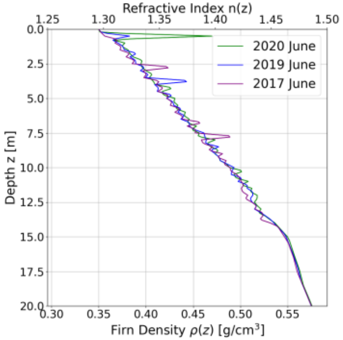

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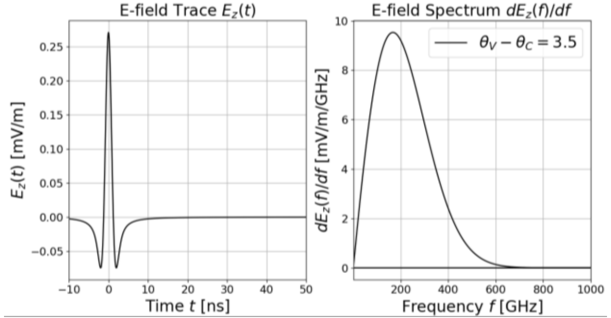
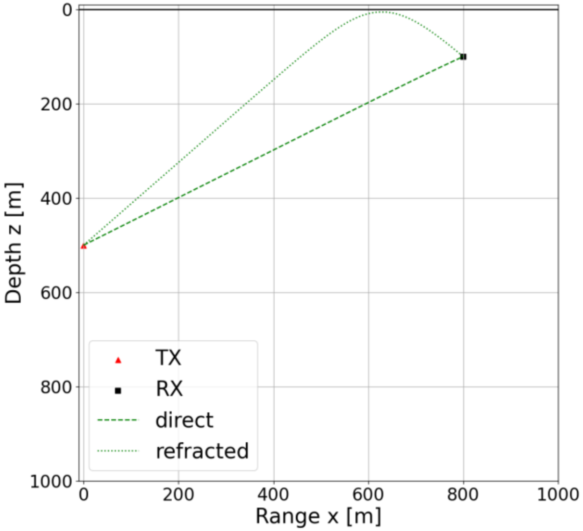


Radio Propagation Simulation

paraProp & MEEP

- Define source at x=0 within the ice (i.e. z = 500 m)
- Propagate Askaryan pulse through throughout geometry
- 1000 m radius x 1000 m depth



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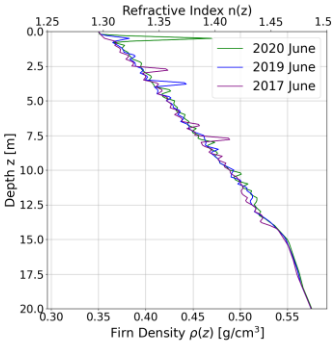

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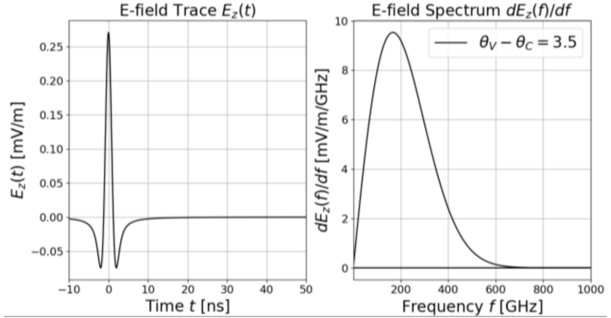

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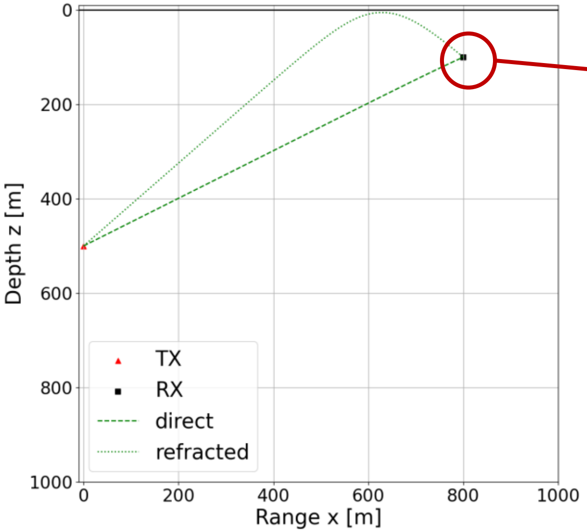
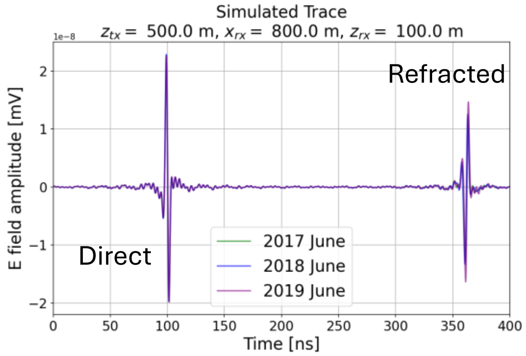


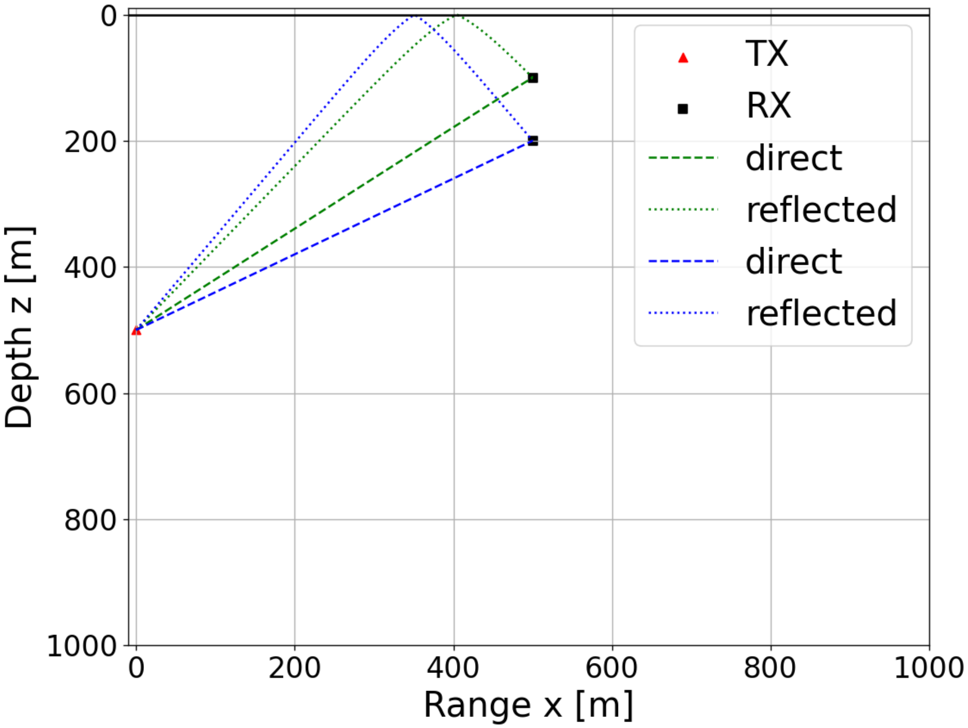
Output

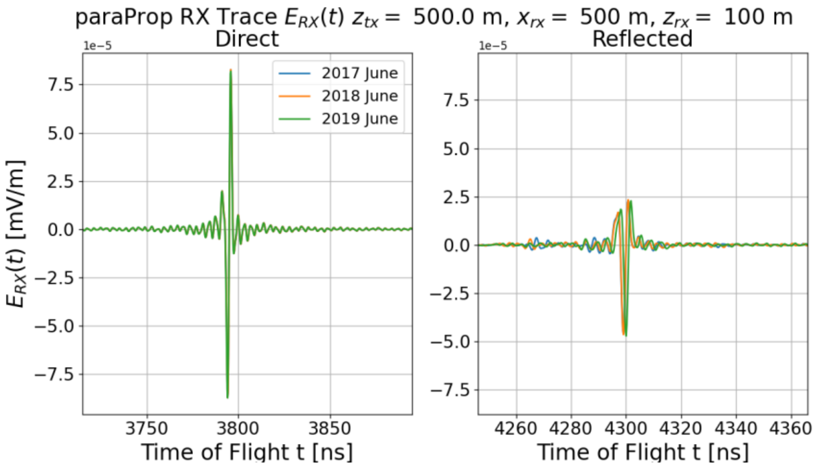
- Sample radio signal at a set of receivers (RX)
- Compare outputs for ref-index at different times
- Is possible to add antenna & detector response functions + noise

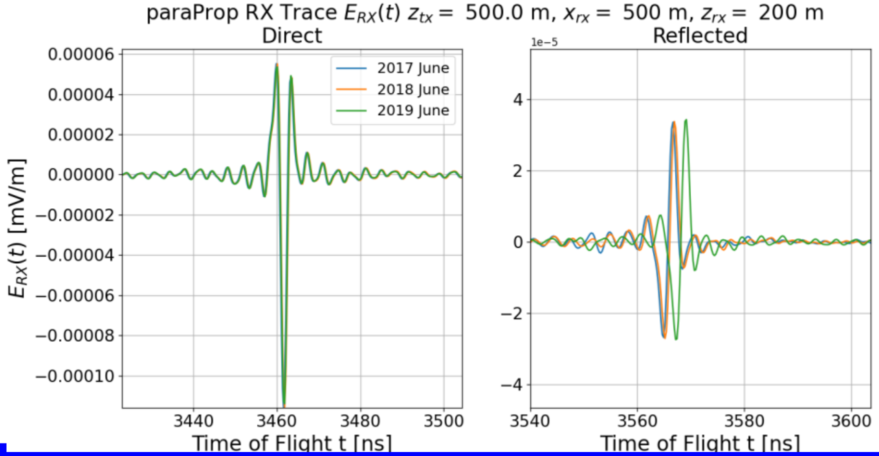


paraProp Results (z_{TX} = 500 m)

Paths of direct, reflected, and refracted signals from 500 m source to RX at 100 m and 200 m (calculated with NuRadioMC)
$|\theta_V - \theta_c| = 5$







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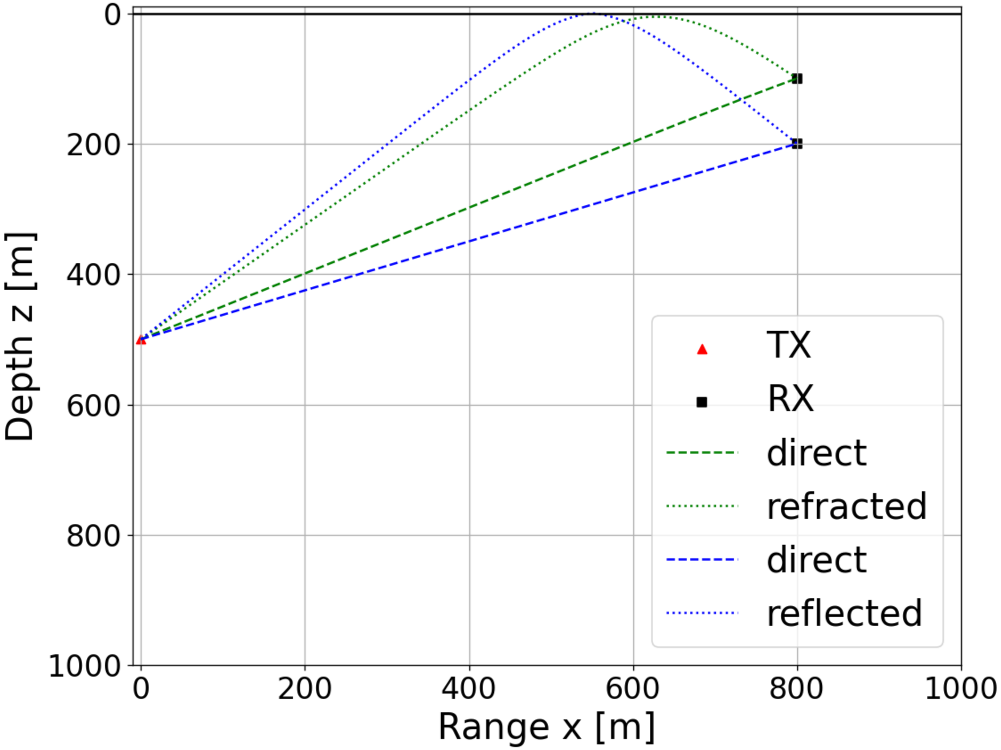
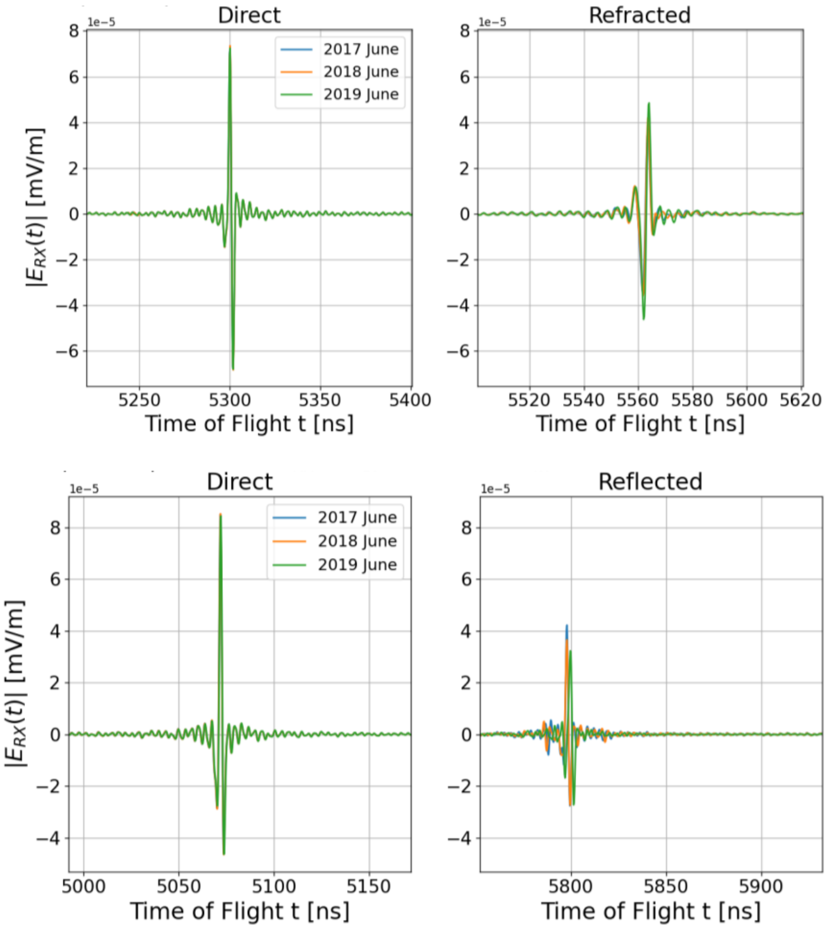




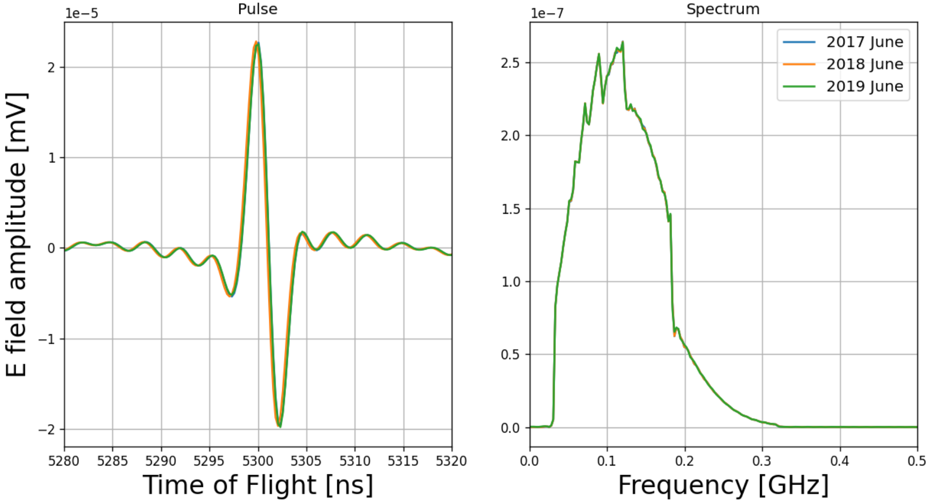
paraProp Results ($z_{TX} = 500$ m)

Only the reflected/refracted paths traverse through the shallow firn layer

- Amplitude modulation of the R-signal is an order of magnitude higher than for D-signals
- No significant variation of Δt_{DR}

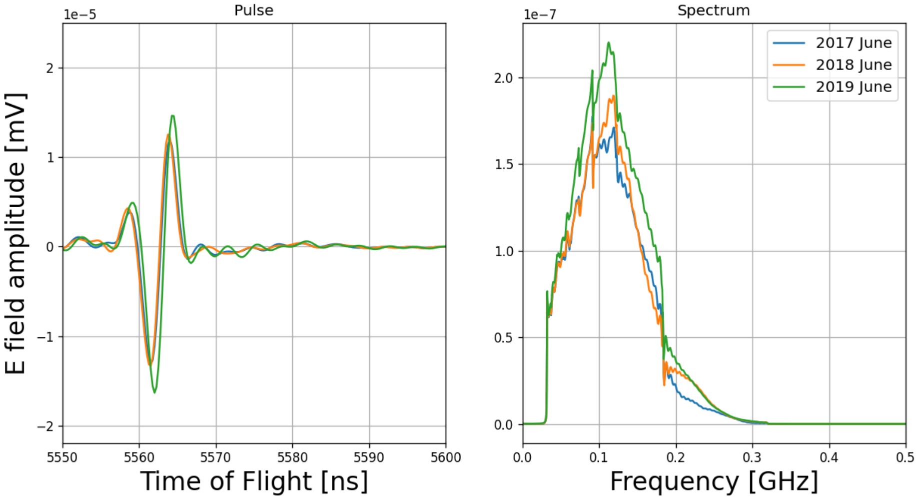
Direct signal trace at $z_{RX} = 100$ m

- $\frac{\Delta E_{max}}{E_{max}} < \sim 10^{-3}$

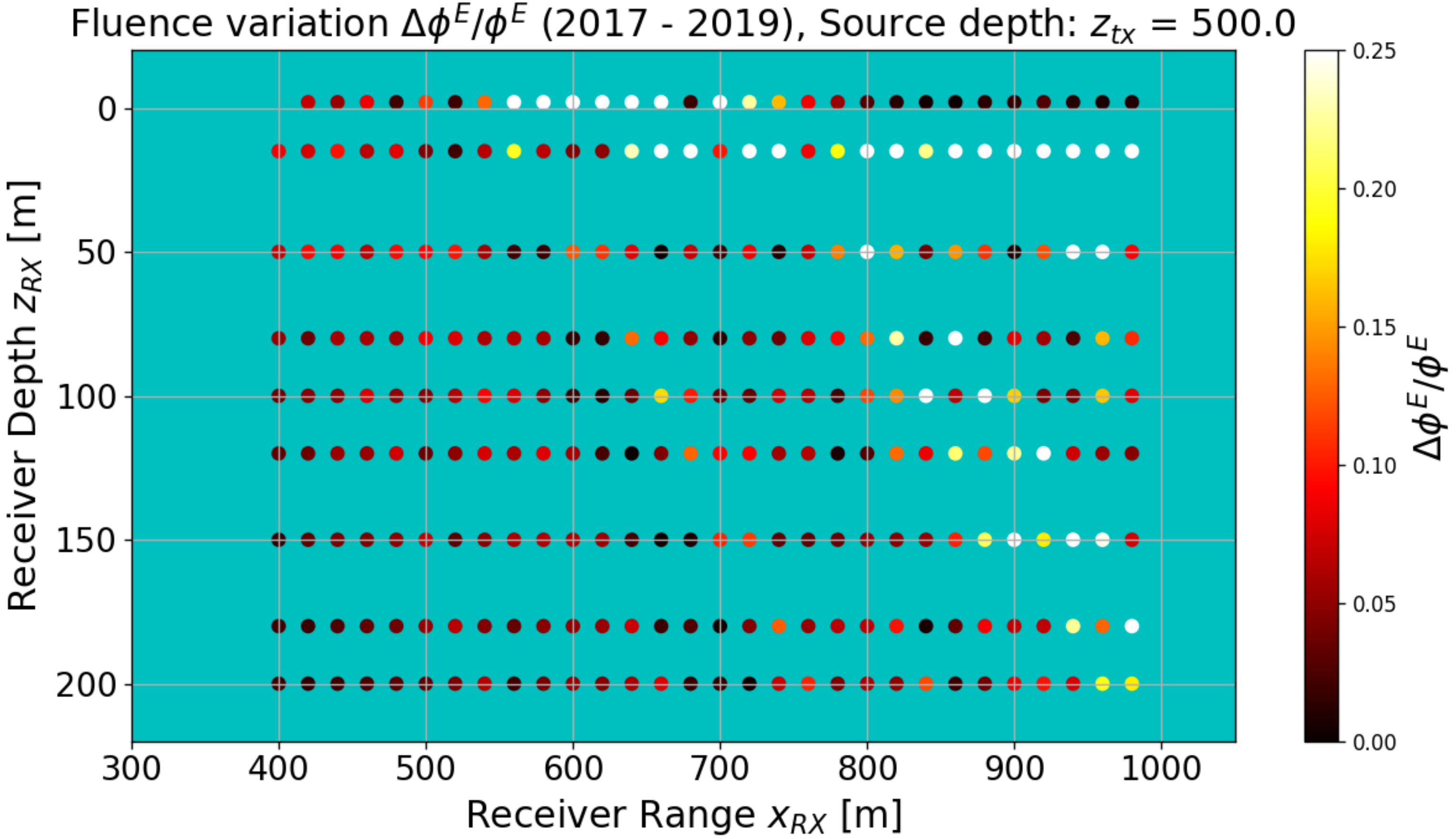


Refracted trace at $z_{RX} = 100$ m

- $\frac{\Delta E_{max}}{E_{max}} < \sim 10^{-1}$



Variation of Fluence (2017 vs 2019)



A. Kyriacou - akyriacou@ku.edu

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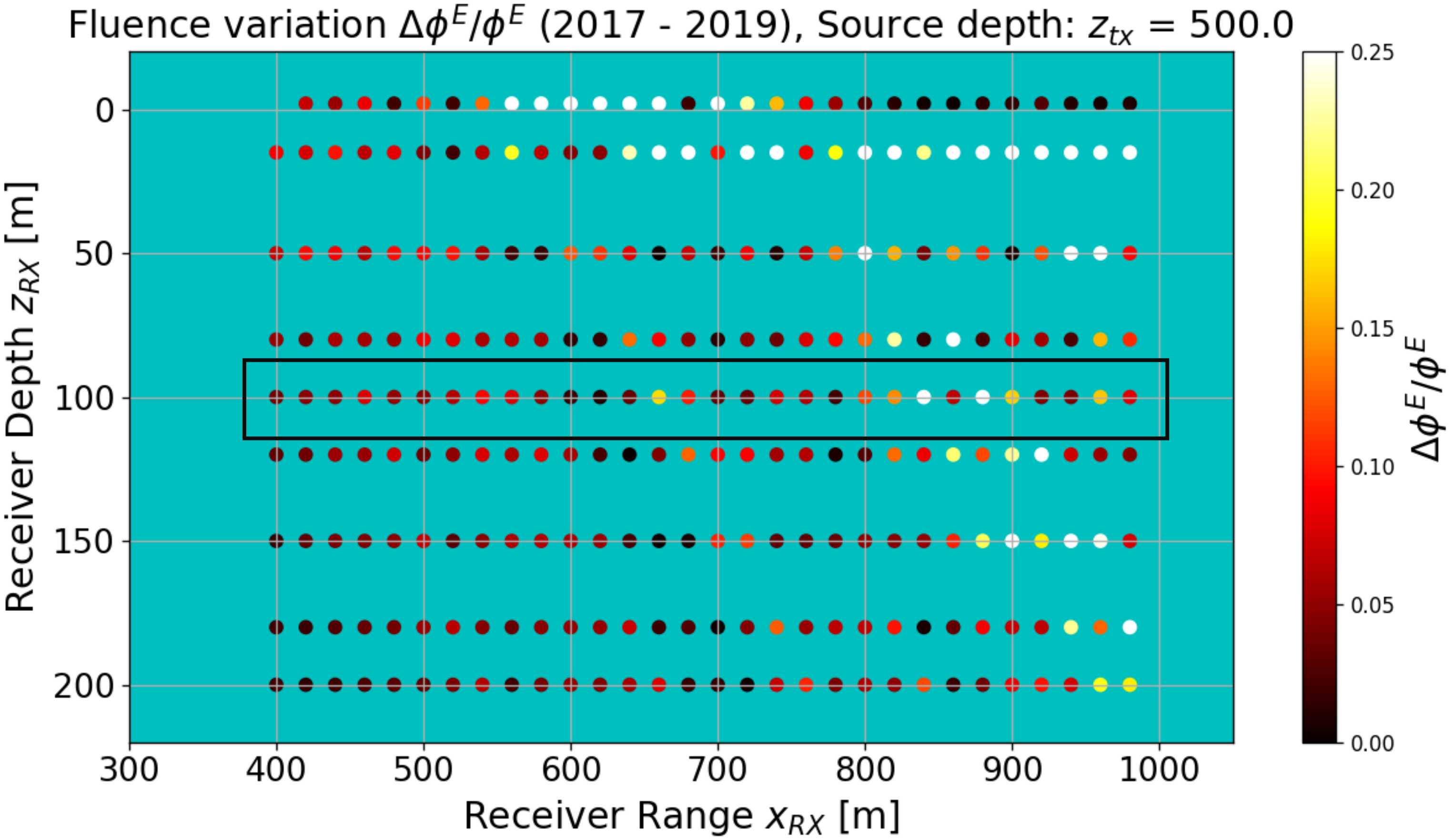
RADAR ECHO TELESCOPE



Variance in RF parameters

Electric field fluence Φ^E is proportional to the UHE-ν energy E_ν

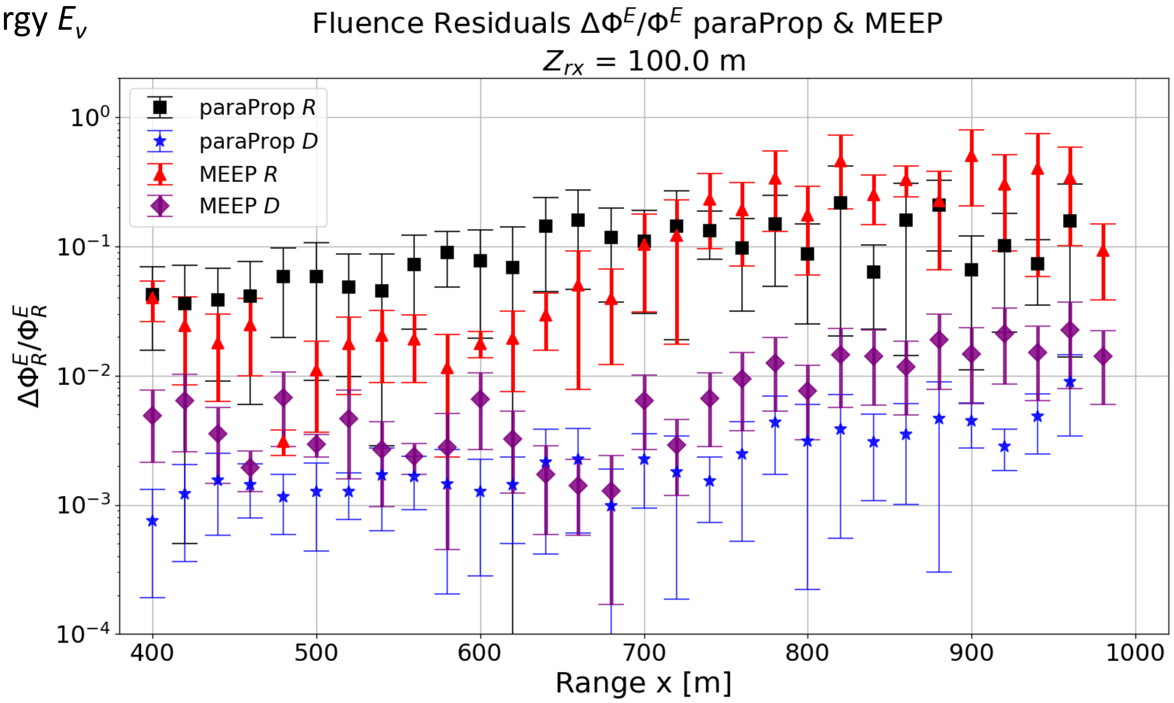
Time frame: 2015-2020, $|\theta_V - \theta_c| = 5$

paraProp:

- Reflected: $\frac{\Delta\Phi^E_R}{\Phi^E_R} > \sim 0.1$ (x > 600 m)
- Direct: $\sim 10^{-3} < \frac{\Delta\Phi^E_D}{\Phi^E_D} < \sim 10^{-2}$

Meep:

- Reflected: $\frac{\Delta\Phi^E_R}{\Phi^E_R} > \sim 0.1$ (x > 700 m)
- Direct: $\sim 10^{-2} < \frac{\Delta\Phi^E_D}{\Phi^E_D} < \sim 10^{-1}$ (x > 800 m)

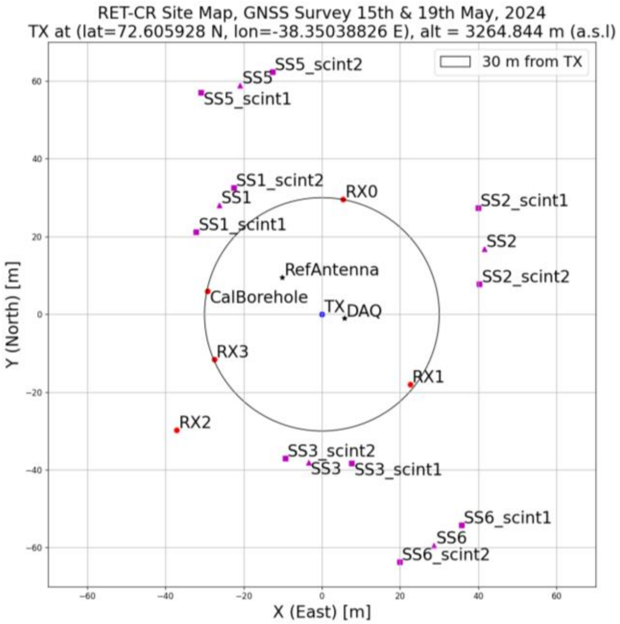


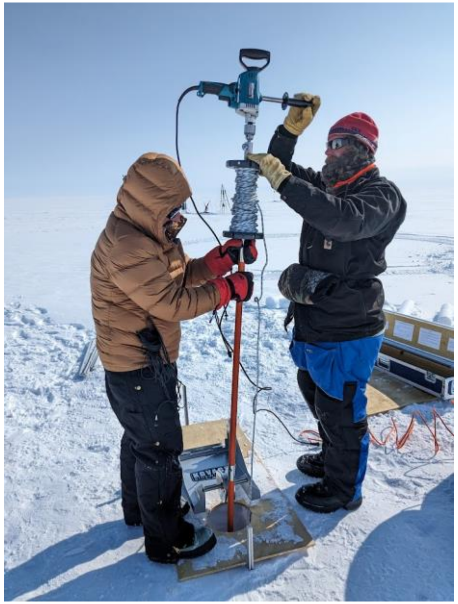
Preliminary finding: Under likely signal geometries, shallow firn fluctuations produce systematic uncertainty in the fluence of reflected and refracted signals

→ Results in systematic error for neutrino energy and arrival direction reconstruction.

Measuring firn properties at Summit

- During the May 2024 RET-CR deployment, boreholes were made using a coring drill
- Firn cores were extracted down to a depth of 13 m → used to measure the refractive index profile at the RET site in two ways:
  1. Direct gravimetric measurement of core density ρ
  2. Open-ended coaxial probe in contact with firn → measure the relative permittivity ε_r from the reflected radio energy (method described in backup slides!)





Measuring firn properties at Summit

Measurement procedure

1. Slide core through shaping-rig
2. Press firn core against coaxial probe
3. Measure dielectric properties using coaxial probe method
4. Cut core – adjustable length (usually 10 cm)
5. Measure & log the core segment weight
6. Repeat

Coaxial Probe

Results: Permittivity & Density

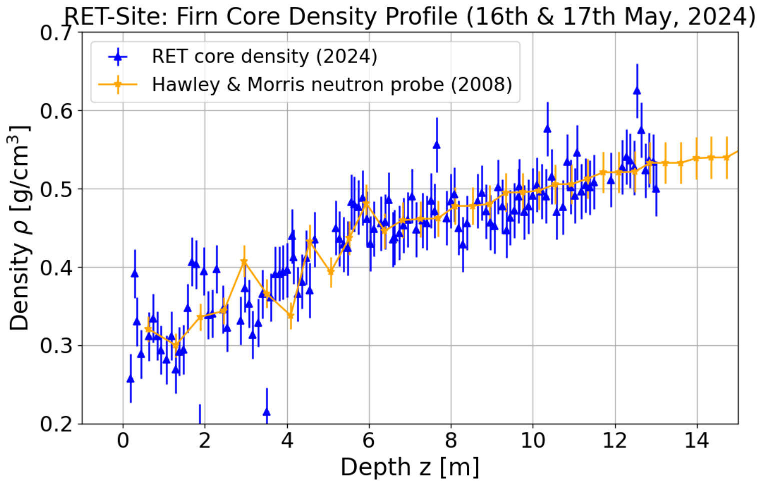
Reconstructed Density:

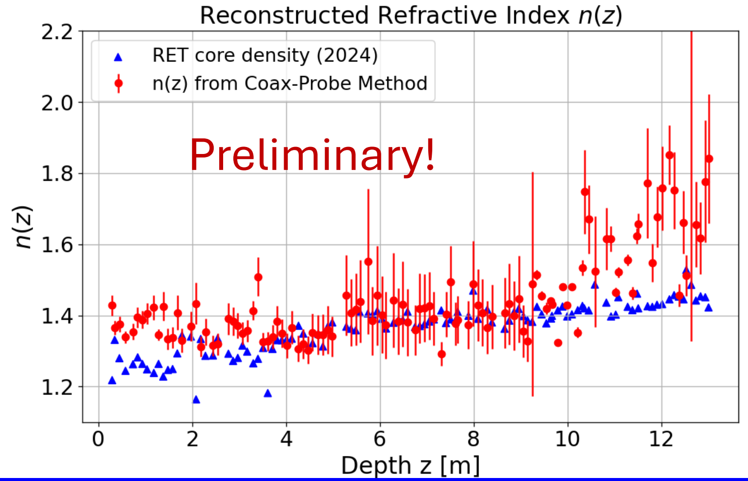
- Refractive index and density related empirically $\boldsymbol{n = 1 + 0.845\,\rho}$
- Firn density was broadly consistent with previous measurements made at Summit
  - Hawley & Morris estimated the firn density using neutron scattering measurements in 2008 to 30 m depth
- Evidence of ice layers at z = 7.65, 10.4, & 12.5 m

Reconstructed permittivity (coax probe method): $\boldsymbol{n = \sqrt{\epsilon_r}}$

Analysis ongoing!

- Averaged between 500 MHz and 800 MHz
- Large uncertainty due to frequency variation in the reconstruction (described in backup slides) → not yet explained
  - High conductivity of the firn → frequency-dependent permittivity reconstruction
  - Conductivity of test/calibration materials uncertain
- Correlation between density and permittivity with significant variations





Summary

Seasonal modulation of radio signals due to ice properties:

- ***The polar regions are warming rapidly:*** understanding firn evolution and its modulation of Askaryan and Radar-Echo signals will be important for UHE-ν searches
- Under likely signal geometries, shallow firn fluctuations produce systematic uncertainty in the fluence of R-signals, and possibly for neutrino energy reconstruction as well

In-situ measurements of ice properties

- The density profile at the Summit site is broadly consistent with previous measurements – with evidence of recent melting events
- Correlation of reconstructed permittivity with density measurements
  - Caution about results: calibration likely incomplete, frequency dependence likely unphysical

Future work:

- Simulating larger geometries – 3 km (depth) x 3km (radius)
- Analysis of TX to RX radio propagation at RET site → further insight into ice properties
- Examine seasonal radio modulation at South Pole, Antarctica

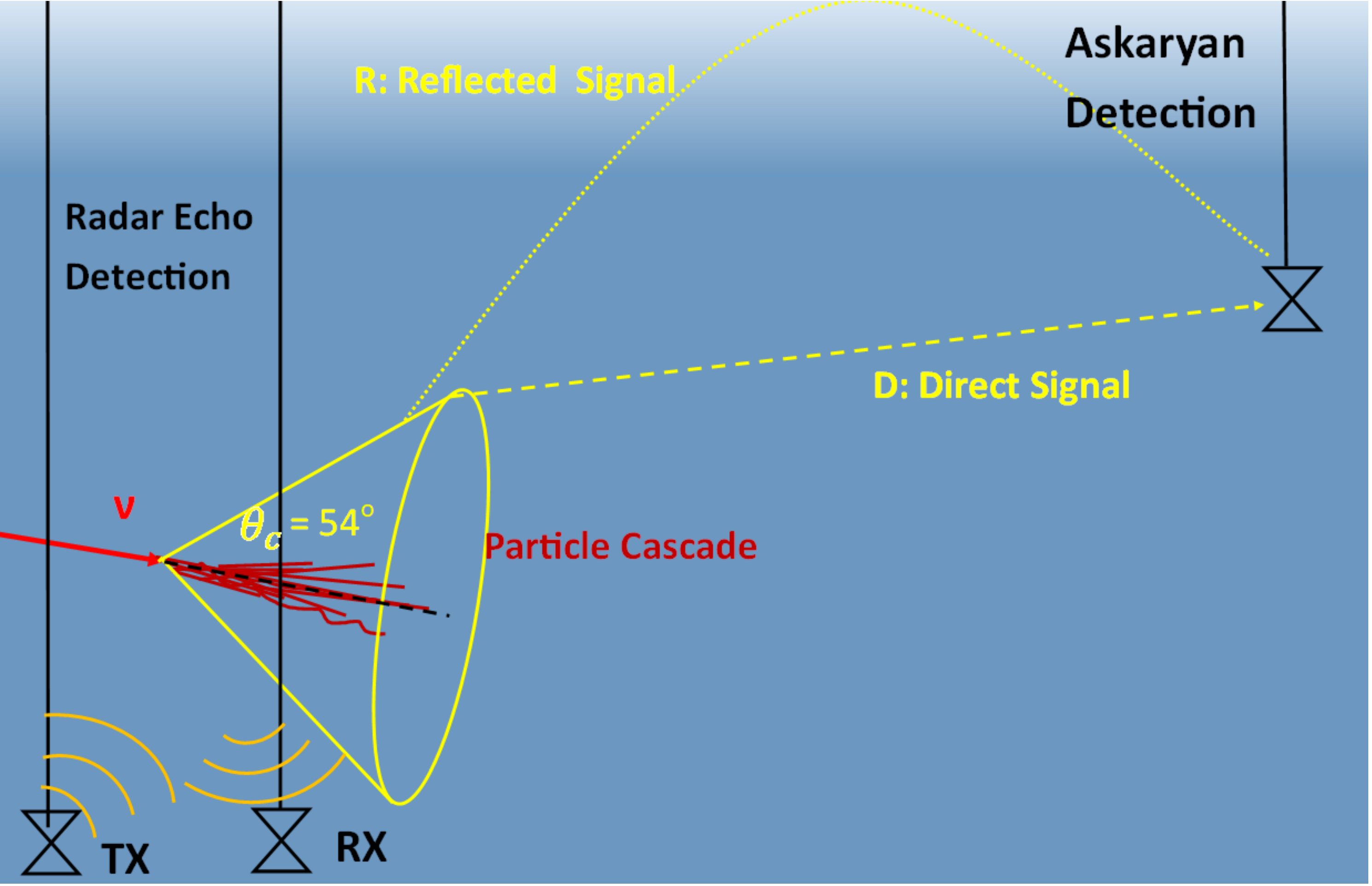
Thanks for your attention!

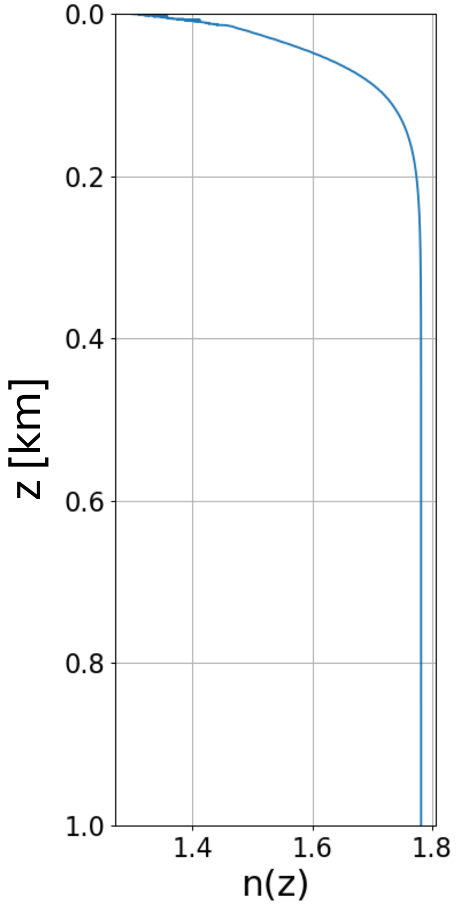
RET May 2024 Deployment Team

A. Kyriacou - akyriacou@ku.edu

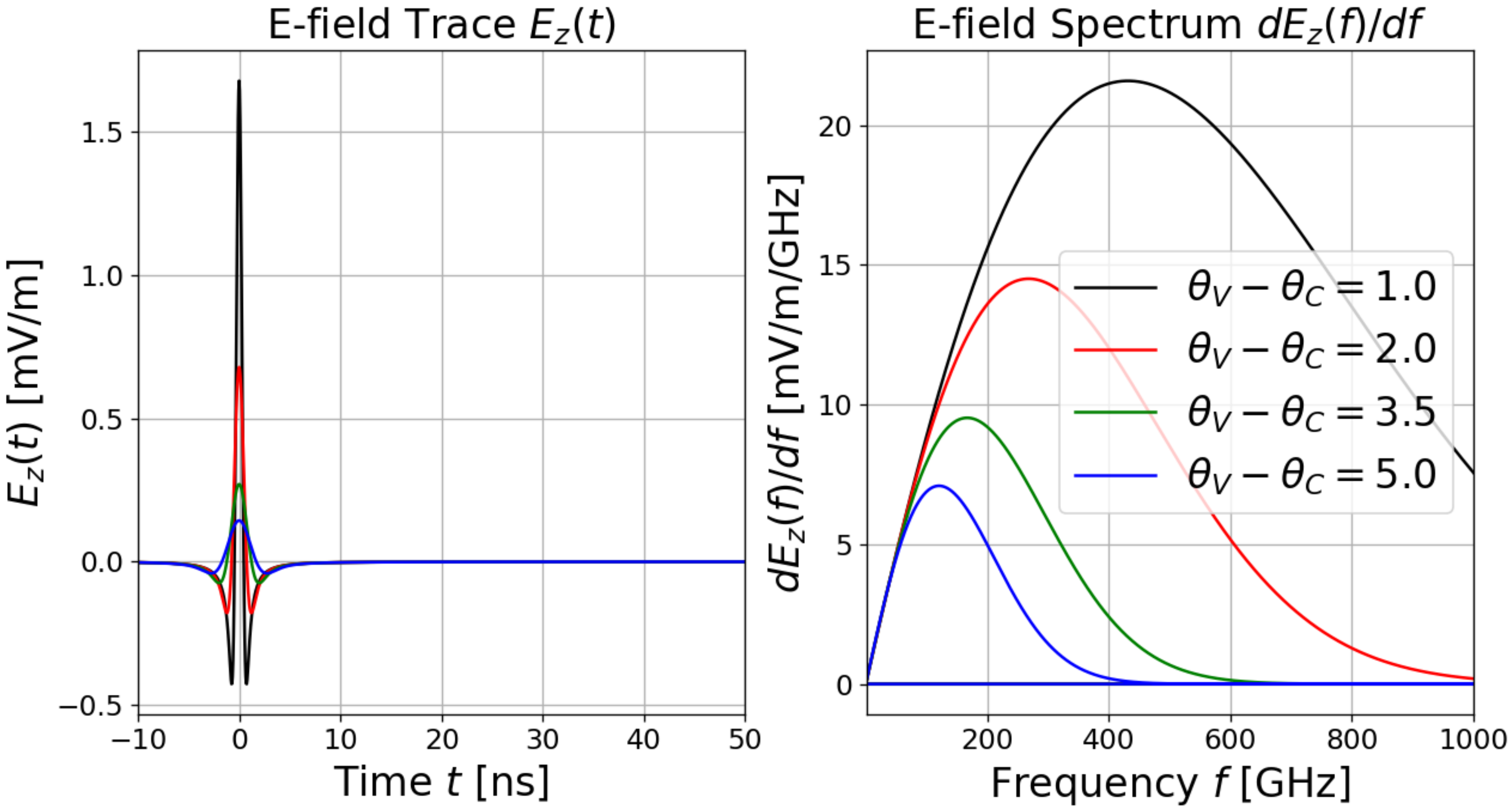
Backup Slides

UHEN Detection in Ice





Askaryan Signal



RF Simulation Methods

RADAR ECHO TELESCOPE

Challenge: Large domain size & need for high spatial resolution to accurately resolve high frequencies -> Cylindrically symmetric medium 1 km radius x 1km depth, frequency range 1 MHz < f < 1000 MHz

MEEP - Finite Difference Time Domain (FDTD) method

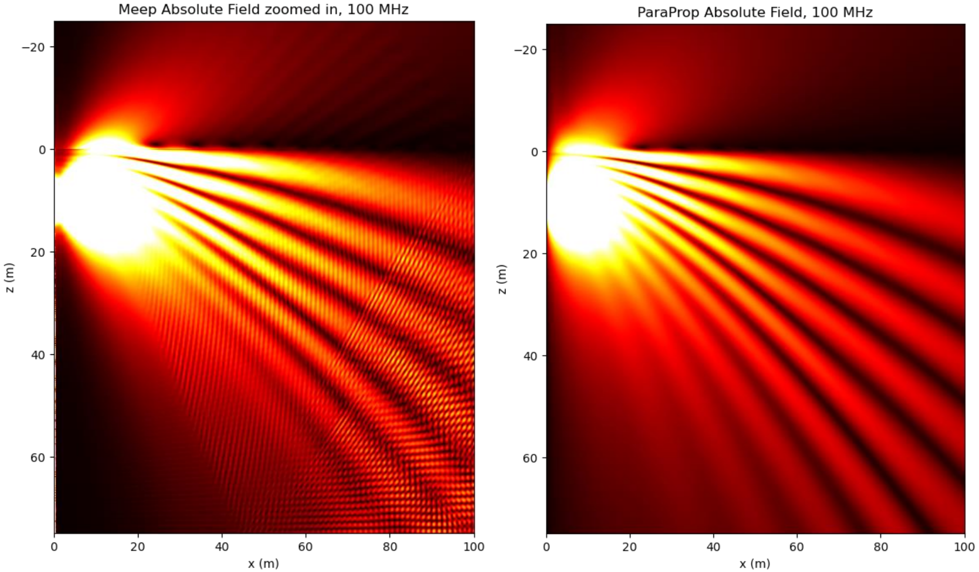
- Solves Maxwell's equations inside discrete cells
- Computationally expensive:
  - Cell size $\Delta x \leq \lambda/10$ i.e. 8 cm for f = 300 MHz in vacuum
  - Time resolution is related to cell size:

$$\Delta t \leq \frac{1}{c_{medium}\sqrt{(\Delta x^2 + \Delta y^2 + \Delta z^2)}}$$

  - Simulations for f > 500 MHz are exceedingly expensive

paraProp - Parabolic Equation:

- Parabolic wave approximation of Maxwell's equations in a cylindrically symmetric medium
- Amplitude and phase residual errors low (<0.01) relative to FDTD within the 'paraxial angle' ($\theta < 45$ deg)
- Computationally efficient -> Tractable for volumes > 1 km and f > 1 GHz



Continuous wave RF emission at f = 100 MHz from a shallow dipole antenna – simulated with MEEP and paraProp

A. Kyriacou - akyriacou@ku.edu

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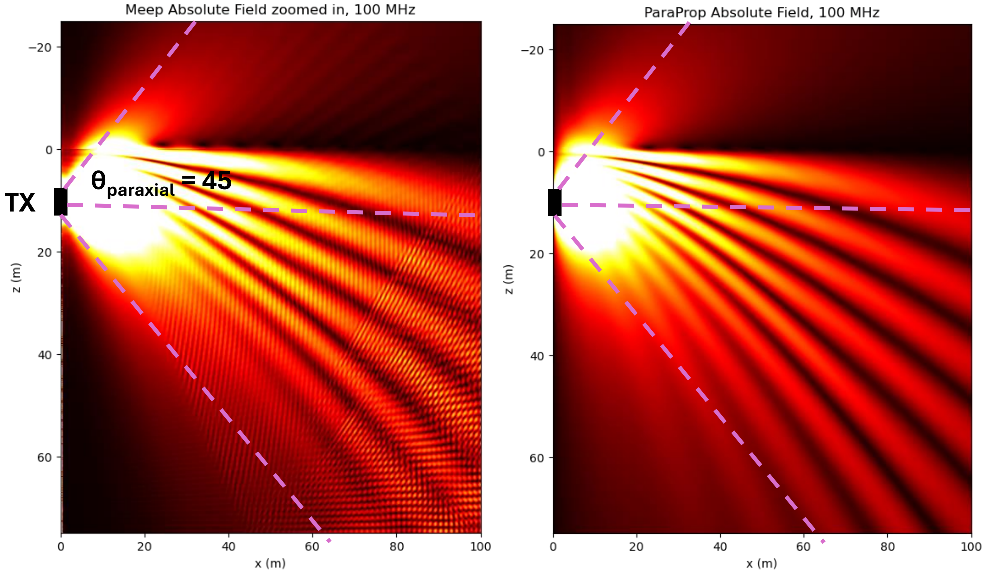

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In-Situ Ice Property Measurements

Density Measurements:

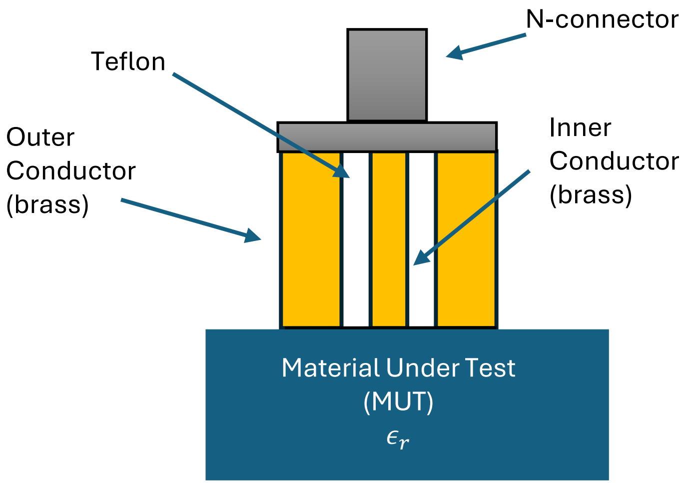
- Gravimetric: measure the mass of a firn sample with a definite volume
- Neutron Probe: measure the return scatter of neutrons from a radio-isotope

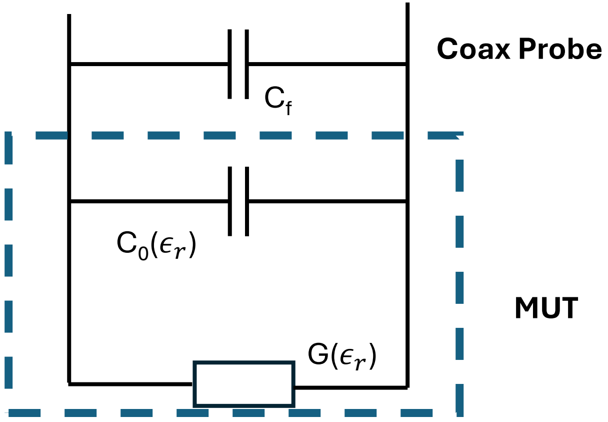
Dielectric Measurements

- Coaxial Probe Impedance Measurement
  - Open-coaxial probe in contact with a dielectric material (including firn and ice)
  - Measure the complex S_{11} (reflection) parameter (amplitude and phase)
  - Approximation of of coaxial probe impedance using equivalence circuit:

$$i\,\omega\left(C_f+\epsilon_r(\omega)\chi\right)+G\,\left(\epsilon_r(\omega)\right)^{2.5}=\frac{1}{Z_0}\frac{1-S_{11}}{1+S_{11}}$$

  - Calibration using (3+) materials with known permittivity -> allows you to measure an unknown material





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In-Situ Ice Property Measurements

Radio propagation measurements

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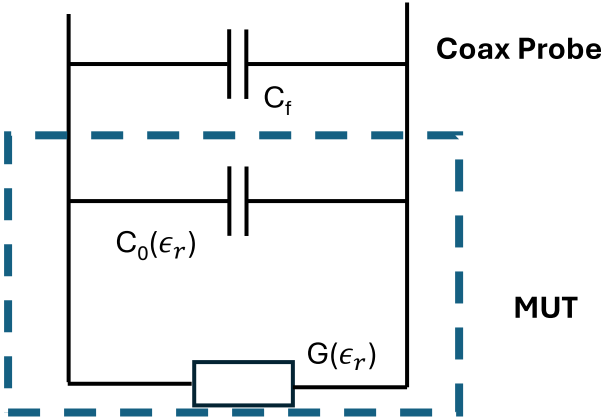


In-Situ Ice Property Measurements

RADAR ECHO TELESCOPE

Example (right): Measurements of dielectric in the laboratory (KU)

S_{11} measured using miniVNA (PC controlled VNA)

Materials used for calibration:

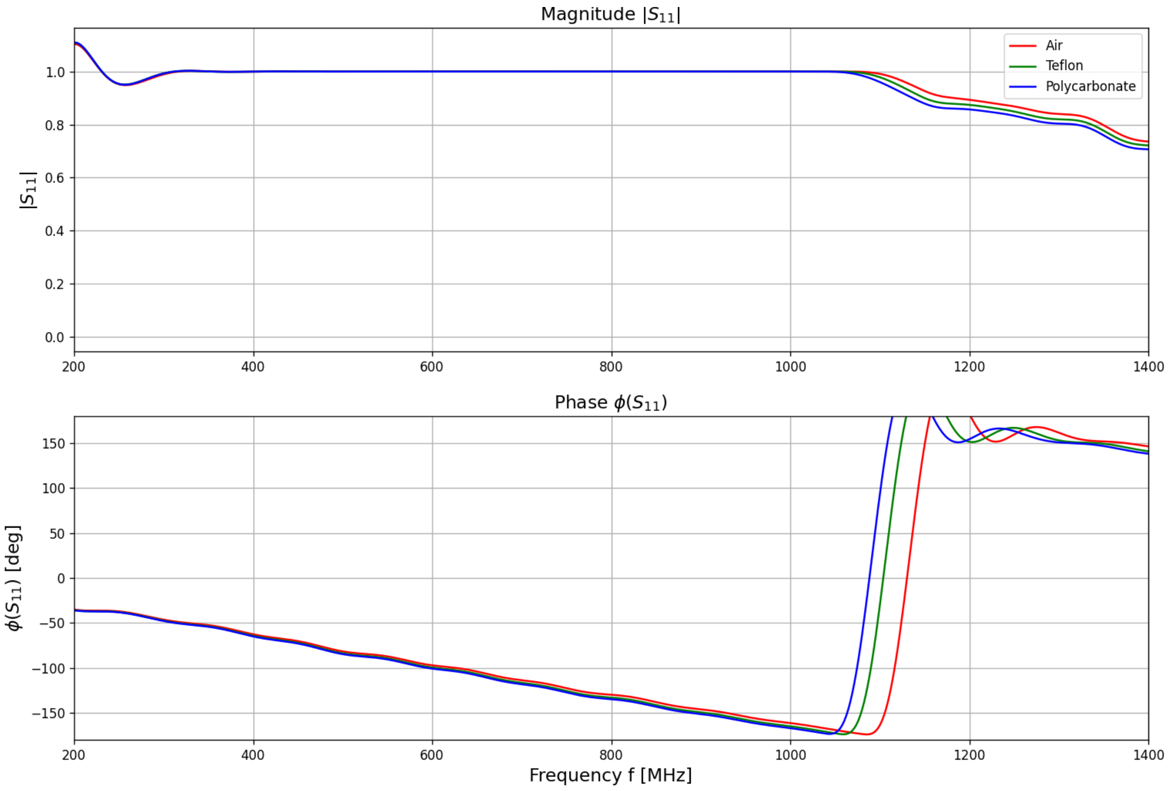
- Air
- Teflon (PTFE)
- Polycarbonate

Materials used for testing:

- HDPE
- Acyrlic
- Polyproplyene

The real part of permittivity is most sensitive to the phase of S_{11}

S_{11} Values



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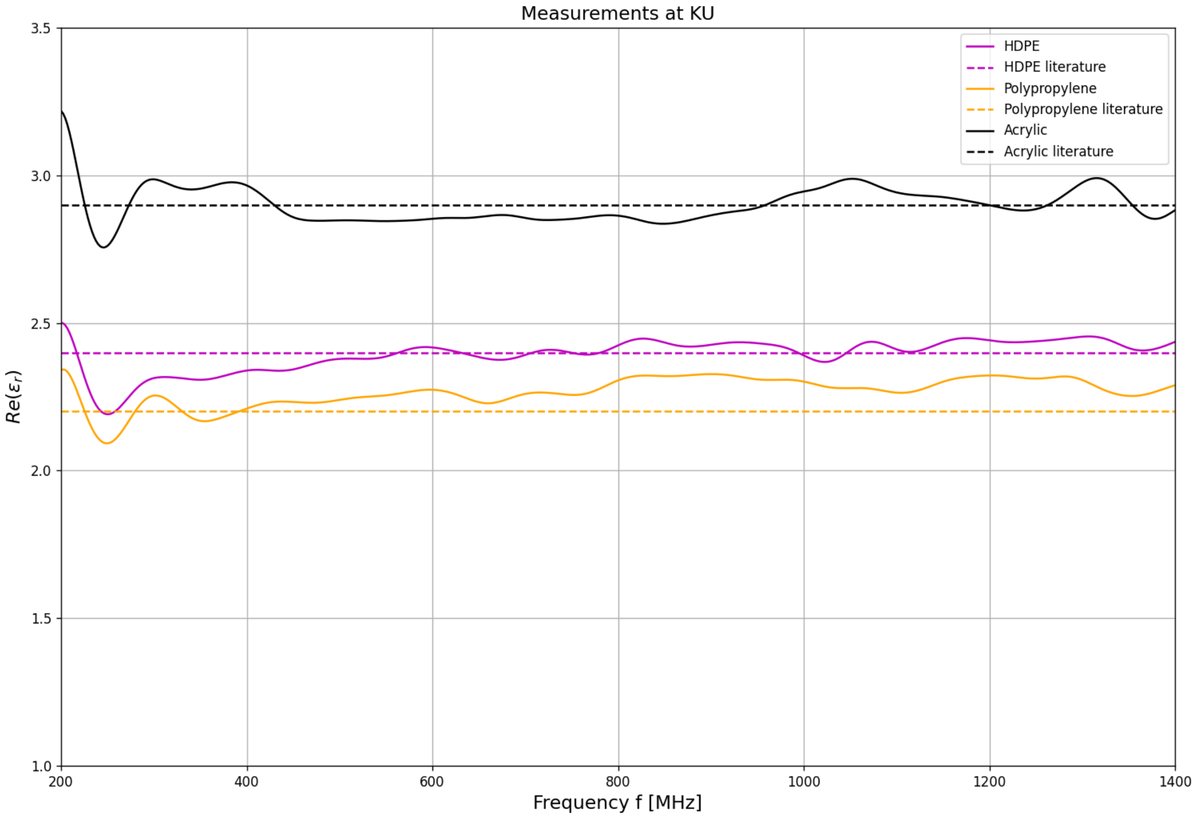
Reconstruction of ε_r

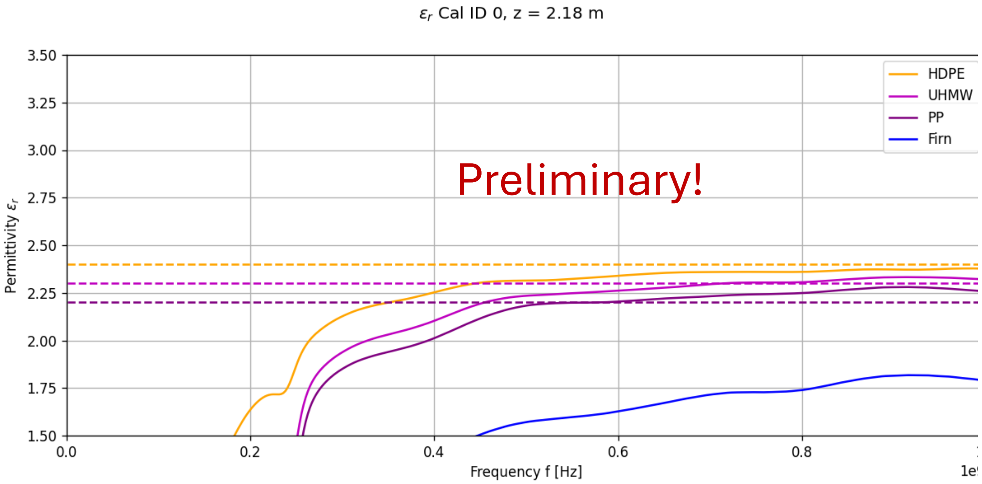


Permittivity reconstruction

Measurements in the field:

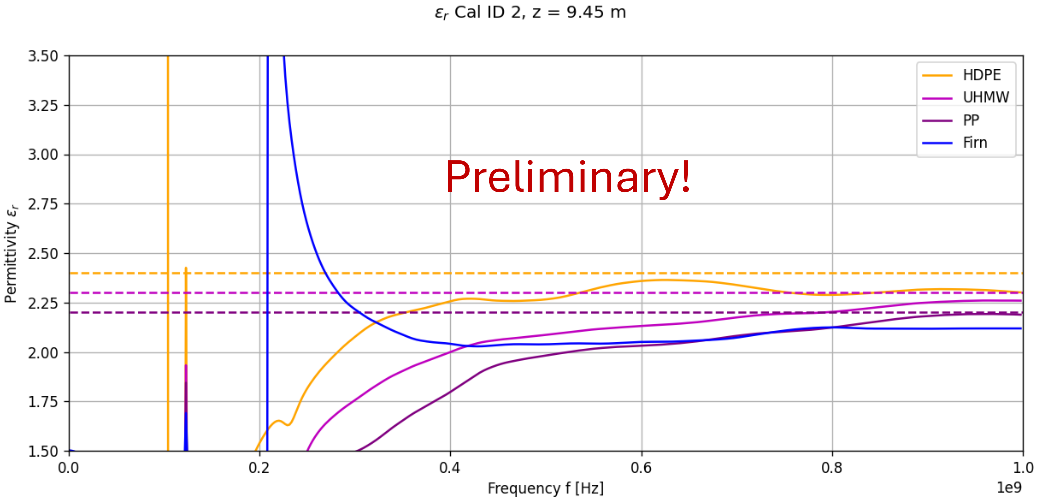
- Performed over two days → miniVNA needed to be recalibrated 3 times
- Performed with a 5 m RF cable between miniVNA and coaxial head → instrument calibration was incomplete
- High degree of frequency dependence in reconstructed permittivity → likely not physical
- Further work needed

Calibration 0, z = 2.18 m



Preliminary!

Calibration 2, z = 9.45 m



Preliminary!