

# Seasonal Variation of Polar Ice—Implications for UHE Neutrino Detectors

Alexander Kyriacou\* on behalf of the Radar Echo Telescope (RET) Collaboration

Department of Physics and Astronomy, University of Kansas, Lawrence KS, USA

\*Contact: akylriacou@ku.edu

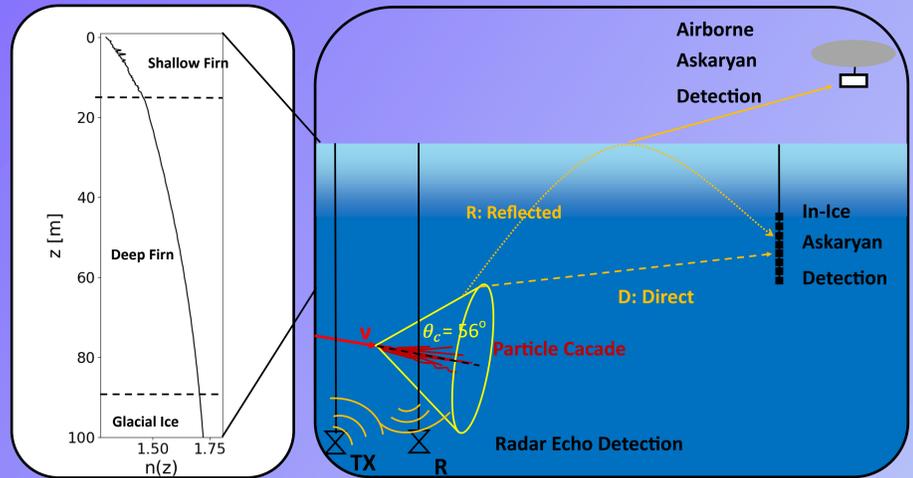
Polar ice sheets act as detection media for Ultra-High-Energy Neutrinos via:

- **Askaryan-based detection:** Excess negative charge build up in cascade leads to coherent radio emission at the Cherenkov angle [1] - can be detected by in-ice antenna arrays: RICE, ARIANNA ARA, RNO-G, IceCube-Gen2 Radio (proposed), or balloon-deployed detection: ANITA & PUEO
- **Radar Echo method:** In-ice radar broadcast is scattered by the ionization trail left in the wake of the cascade. The Radar-Echo Telescope for Cosmic Rays is a pathfinder experiment to verify this detection method in nature using cosmic rays as a test beam [2]

The firn layer is a dynamic medium with significant temporal fluctuations in density and temperature above 15 m i.e. 'shallow firn'.

We present a simulation study to quantify the modulation of RF signals due to evolving ice

→ The ice-sheet at Summit Station, Greenland (3250 m a.s.l.) is used in this analysis



## Modelling Firn Evolution

Density profiles: derived from glaciological modelling software: Community Firn Model (CFM) [3]

Input data: temperature, accumulation rates—based on MERRA-2 climate data from Summit, Greenland[4]

Output:  $\rho(z)$  for each month from 1980 to 2020

(Fig 1).

$z < 15$  m: *Shallow firn:*

Small-scale fluctuations:  $\Delta\rho_{RMS} \sim 5-6 \text{ kg/m}^3$

Large-scale fluctuations:  $\Delta\rho > 25 \text{ kg/m}^3$

$z > 15$  m: *Deep firn*  $\Delta\rho_{RMS} \sim 1 \text{ kg/m}^3$

Empirical relation used to define  $n(z)$  profiles for

the RF simulation:  $n(z) = 1 + 0.845 \rho(z)$  [5]

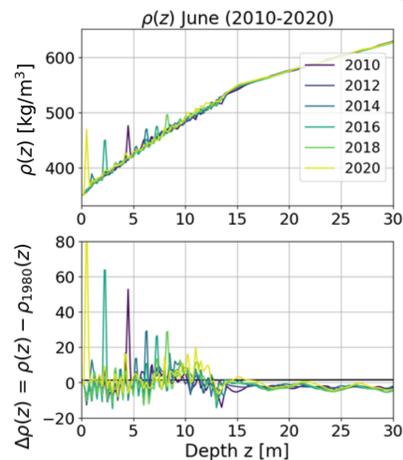


Fig. 1: Density profiles (top) at Summit, estimated with CFM. Residuals (bottom) relative to CFM starting profile (Jan 1980)

## RF Simulation

- Define a dipole RF source TX at  $x=0, z=500$  m
- Propagate a bandwidth-limited RF pulse (Fig. 2) through a 1km x 1km cylindrically symmetric domain
- Sampled at a set of receivers within the upper 200 m (Fig. 3)
- Ice model defined using CFM density profiles (left)

### Simulation Method

**paraProp:** Parabolic-wave approximation of Maxwell's equation within cylindrically symmetry volume [6]

### RF observables:

- Fluence:  $\Phi^E$  [ $\text{eV/m}^2$ ]
- Relative arrival time between D and R:  $\Delta t_{DR}$

How do these observables fluctuate in response to the firn density fluctuations?

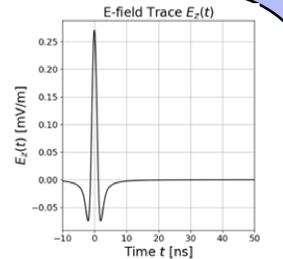


Fig. 2: RF signal at transmitter (TX)

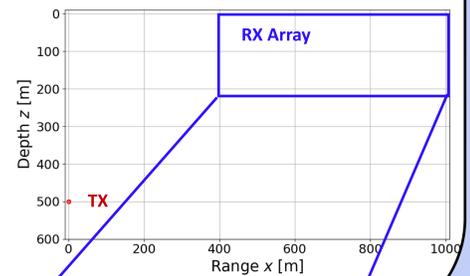


Fig. 3: Simulation geometry

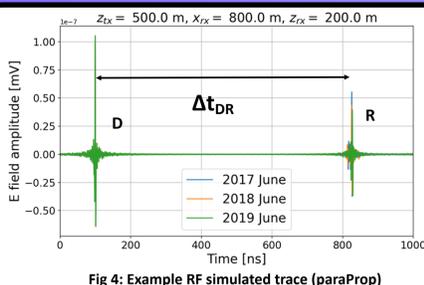


Fig 4: Example RF simulated trace (paraProp)

### Fluence: $\Phi^E$

- For deep receivers:  $z > 15$  m—only the reflected and refracted 'R-signals' propagate through the shallow firn—are affected the density fluctuations
- Domain exhibits markedly different behaviour in the zone of reflection, zone of refraction and the shadow zone (examples of each shown in Fig 5.)
- Strongest fluence fluctuations for R-signals undergoing 'shallow refraction'  $\Delta\Phi_R^E/\Phi_R^E \sim 10\%$  (Fig. 6 and Fig. 8)
- Weaker variation in the reflected signal & deep-refracted signals (Fig. 5)

### Relative time of flight: $\Delta t_{DR}$

- Fluctuates over time due to the shallow firn within range of 6 ns (2010—2014) seen in Fig 7.

## Results

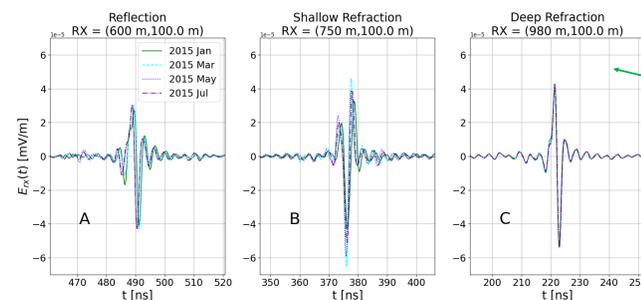


Fig 5: Secondary (R) pulses sampled at positions A, B and C

### Relative arrival time $\Delta t_{DR}$ at $z_{RX} = 100$ m

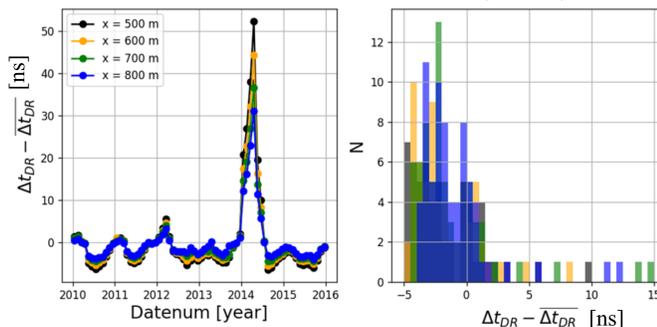


Fig 7: Variation in the relative arrival times of D and R pulses as a function of time (2010—2016) at  $z_{RX} = 100$  m, and  $x_{RX}$  at 500, 600, 700, 800 m.

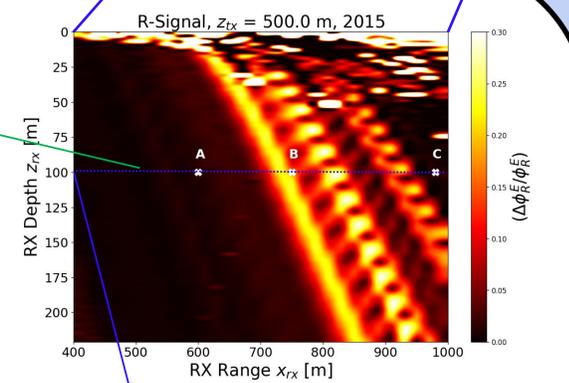


Fig 6: Heatmap showing the relative fluctuation of R-signal fluence  $\Delta\Phi_R^E/\Phi_R^E$  between all CFM models in 2015

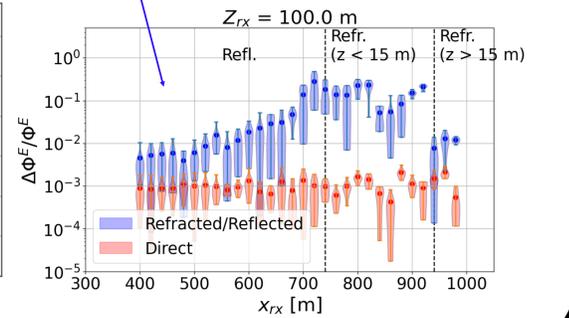


Fig 8: Relative fluctuation of fluence for the D-signals ( $\Delta\Phi_D^E/\Phi_D^E$ ) and R-signals ( $\Delta\Phi_R^E/\Phi_R^E$ ) as a function of range  $x_{RX}$  at depth  $z_{RX} = 100$  m

## Implications for Neutrino Detectors

- Similar results for TX at 250 m and 750 m
- Approximately 10% of neutrino events will occur in a zone where the secondary pulse will be a 'shallow refracted' pulse (Fig. 9)

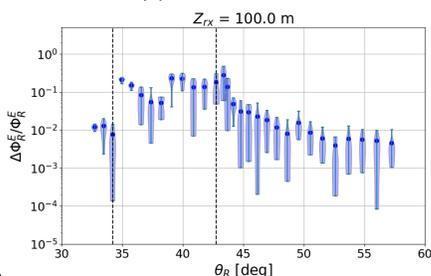


Fig 10:  $\Delta\Phi_R^E/\Phi_R^E$  as a function of arrival angle at RX

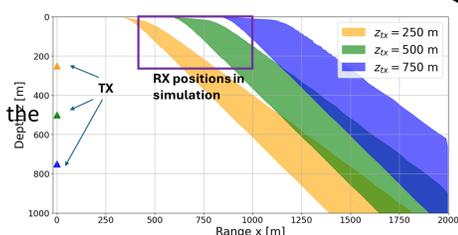


Fig 9: Shallow refraction zone relative to transmitters at 250, 500m and 750 m

- The 'shallow refraction' channel is observable for signals arriving at angles from 35—45 degrees for an RX at 100 m depth (Fig 10.)
- Fluence and relative time of flight are observables that are used for Neutrino energy and arrival direction reconstruction [7]

## Summary

Under existing (& proposed) array geometries, shallow firn fluctuations produce systematic uncertainty in the fluence and relative arrival time of D- & R-signals in shallow RX ( $z < 15$ m), and R-signals at deep RX ( $z > 15$  m)

Simulations have assumed range independence of the firn—not true in nature—signal fluctuations likely higher. The evolution of firn forms an irreducible background for neutrino energy reconstruction when the signal traverses the shallow firn

## References

1. Askaryan Zh. Ekso. Teor. Fiz 41 (1961) 616
2. Prohira et al. Phys Rev. D. 104 (2021)
3. Stevens et al, Geosci. Model Dev., 13, 4355–4377, 2020
4. Global Modeling and Assimilation Office (2015)
5. Kovacs et al. (1995), Cold Regions Science and Technology
6. Prohira, de Vries et al. (2019) Phys. Rev. Lett. 124
7. Aguilar et al. (2022) - Euro. Phys. Jour. C