Evolving polar ice and its consequences for radio UHE neutrino detection

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Introduction: Radio Detection of UHE-ν in Ice

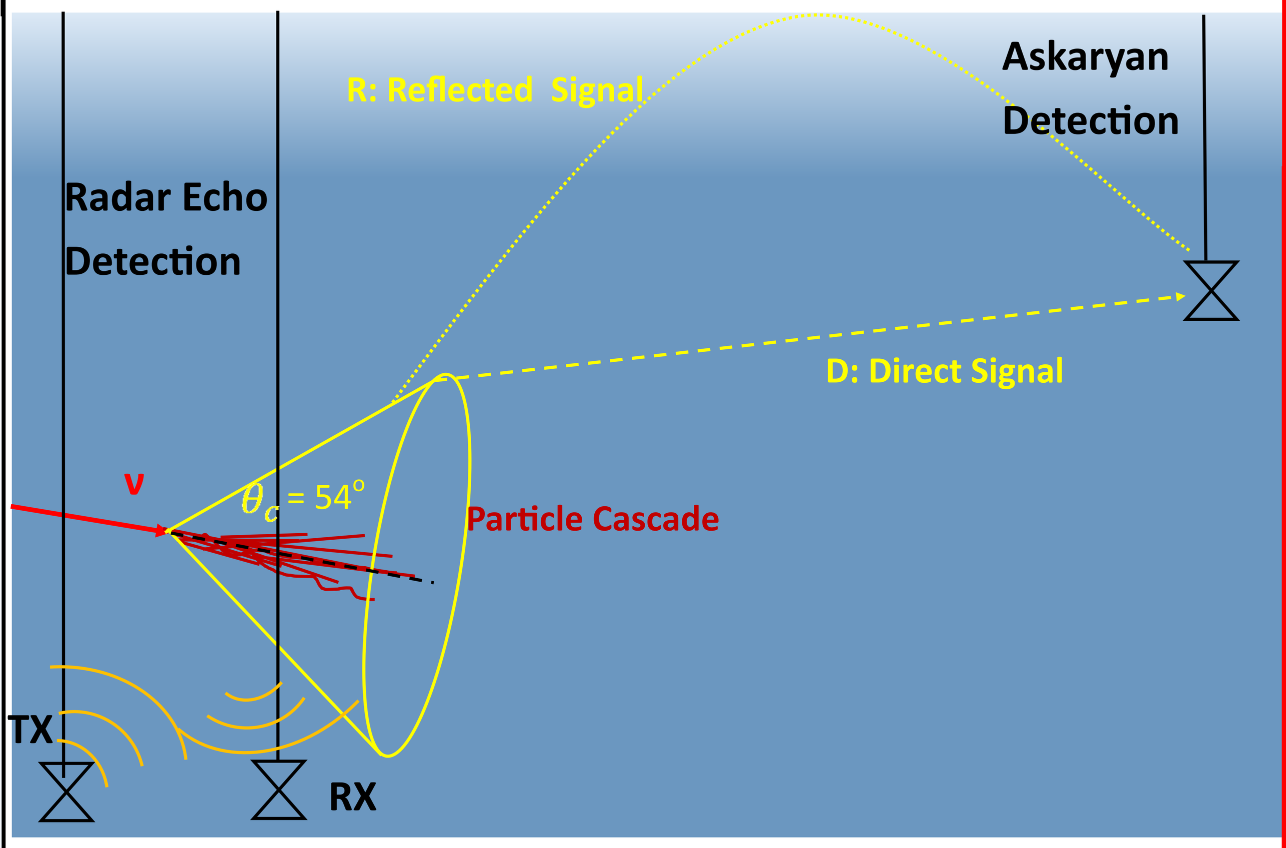


Fig. 1: Askaryan and Radar Echo methods illustrated

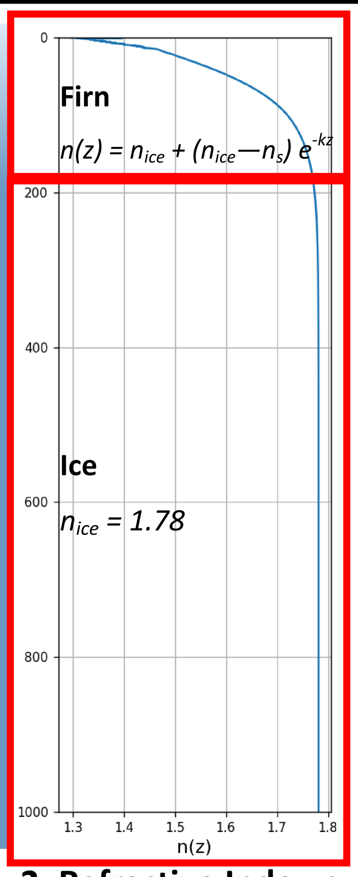


Fig. 2: Refractive Index n

Polar ice-sheets are transparent to high frequency radio-waves: 0.1 - 1 GHz (L_α = 992 ± 121 m at 0.2 GHz) [4]
→ Making them ideal detection media for ultra high energy neutrinos (UHE-ν) E_ν > 10 PeV, via:

Askaryan effect: Coherent radio emission from charge excess in the relativistic particle cascade [1],
In-Ice Askaryan experiments deploy antennas in the upper 100 m—200 m of polar ice sheets (Fig. 1)→ within or just below the firn layer *(Fig 2)* Examples: RICE, ARA, ARIANNA, RNO-G, IceCube-Gen2 Radio (proposed)

Radar-Echo effect: Ionization trail persists for a brief time after UHE-ν cascade, acts as a reflective object for in-ice radar (Fig 1.). Effect verified in the lab [13] and is currently being tested in the field using UHE cosmic rays: Radar Echo Telescope for Cosmic Rays (RET-CR) → deployed within upper 15 m of firn [2]

Verification of Radar-Echo method will facilitate future development of RET-Neutrino [14]

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

Seasonal Variation in Firn Density

Firn: the transition layer between surface snow and deep glacial ice [12]. Its density increases with depth:
$\rho(z) = \rho_{ice} + (\rho_{ice} - \rho_s)\, e^{-kz}$ → Refractive Index is proportional to density: $n(z) = 1.0 + 0.845\, \rho(z)$ [6].

- Random density fluctuations due to changing surface temperature
- Formation of refrozen ice layers due to surface melting events (and rainfall in 2021!)

Summit firn is simulated with the Community Firn Model (CFM) [3] for each month from 1980 to 2020:

Inputs: Surface Temperature, Melt Events, Accumulation Rate, etc. (Fig. 3) - **Output:** Density ρ
Density Fluctuations $\Delta\rho$ for 2000—2020 (Examples for June 2017, 2019 & 2020 in Fig 4)

- Shallow firn (z < 15 m): $\Delta\rho_{RMS}$ ~ 4—12 kg/m^3 → $\Delta n_{RMS}/n$ ~ 0.01—0.035
- Deep firn (z > 15 m): $\Delta\rho_{RMS}$ < 4 kg/m^3 , $\Delta n_{RMS}/n$ < 0.01

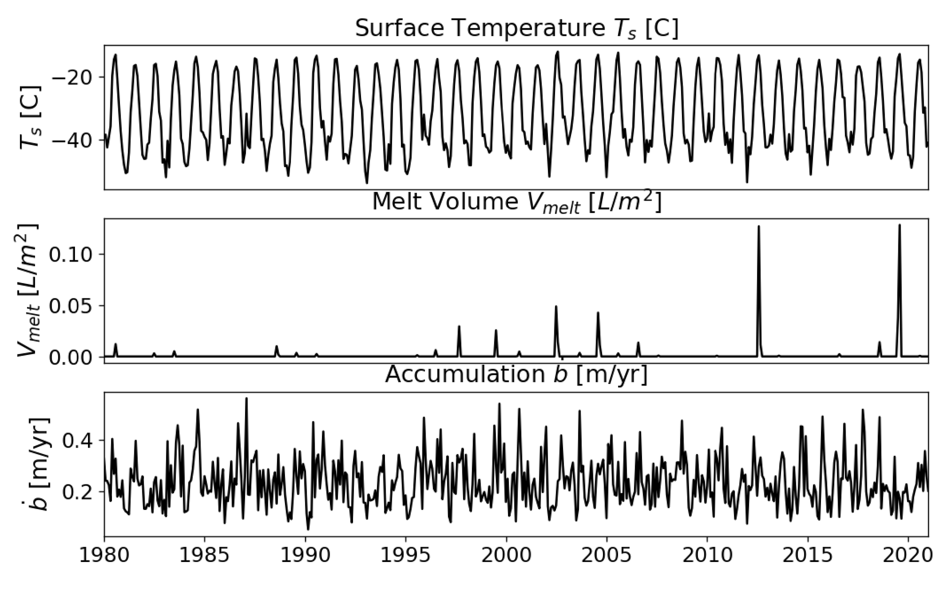


Fig. 3 CFM inputs parameters for Summit

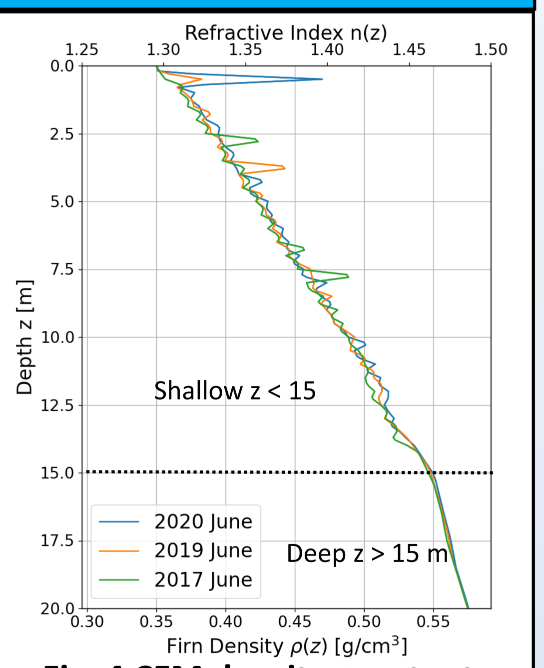


Fig. 4 CFM density ρ output

In-ice Radio Signal Modulation

***Objective:* Simulate RF Propagation from a deep source (0, z_{TX}) to receivers (x_{RX},z_{RX}) using n(z) profiles for different months and years at Summit → Quantify variation in RF signal due to changes in firn properties!**

- **RF Simulation codes**: MEEP (FDTD solution of Maxwell's equations) [7], paraProp (Parabolic Equation)[8], and
- NuRadioMC (ray tracing) [11] → **Output:** Electric field trace at RX positions: $E_{RX}(t)$ [V/m]
- **TX/Source:** (example used: z_{TX} = 500 m) vertically-polarized dipole source emits band-limited impulse (0.08-0.3 GHz)
- **Receivers** (RX) sample the signal at z_{rx} : 0 m to 200 m & x_{rx} : 400 m to 980 (se fig. 5)
- **Analysis parameters:** Peak amplitude $E_{RX,max}$[V/m], , $\Delta t_{DR} = t_R - t_D$ [ns], fluence $\phi^E = \epsilon c \int E_{RX}(t)^2 dt$ [eV/m^2]

Variation of parameter x at different times (and n-profiles), defined using residuals relative to mean x̄
→ $\Delta x/\bar{x} = |x-\bar{x}|/\bar{x}$

Fig.6 Paths of direct, reflected and refracted signals from 500 m source to RX at 100 m and 200 m (calculated with NuRadioMC)

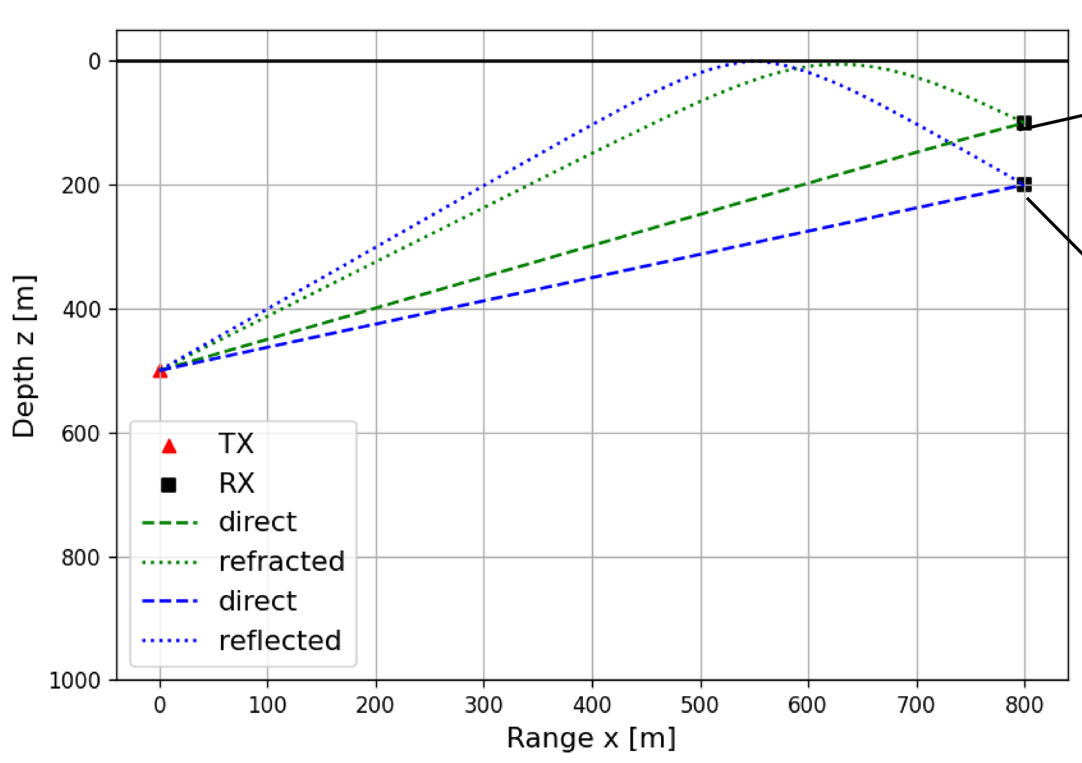
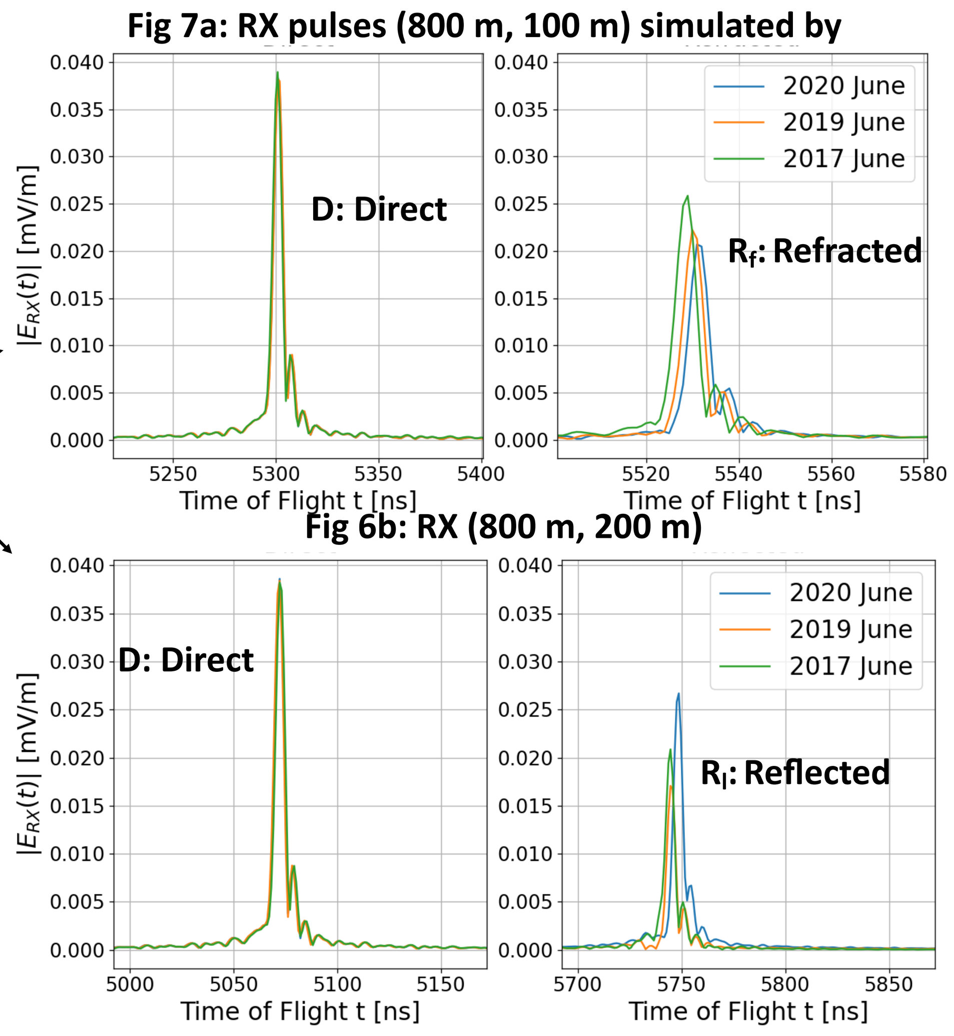


Fig 7a: RX pulses (800 m, 100 m) simulated by

Fig 6b: RX (800 m, 200 m)



Results:

Direct and Reflected/Refracted Paths (fig. 6):

- Two possible paths from TX to RX: direct & reflected or refracted (D & R_f)
- *Only the R_l-path or R_f-paths traverse through the shallow firn layer*

R-signal traces at z_{RX} = 100 m and z_{RX} = 200 m, June 2017, 2019 & 2020 (fig 6)

- R-signal $\Delta E_{max}/E_{max}$ < ~0.24 at 100 m & 200 m (paraProp)
- R-signal Δt_{DR} < ~22 ns at 100 m & 200 m (paraProp)

Fluence variation between June 2017 and June 2019, for all receivers (fig.5)

- Variation increases at shallow depths & with distance from RX (paraProp)
- Fluence at 100 m & 200 m modelled with paraProp and Meep (fig 8)

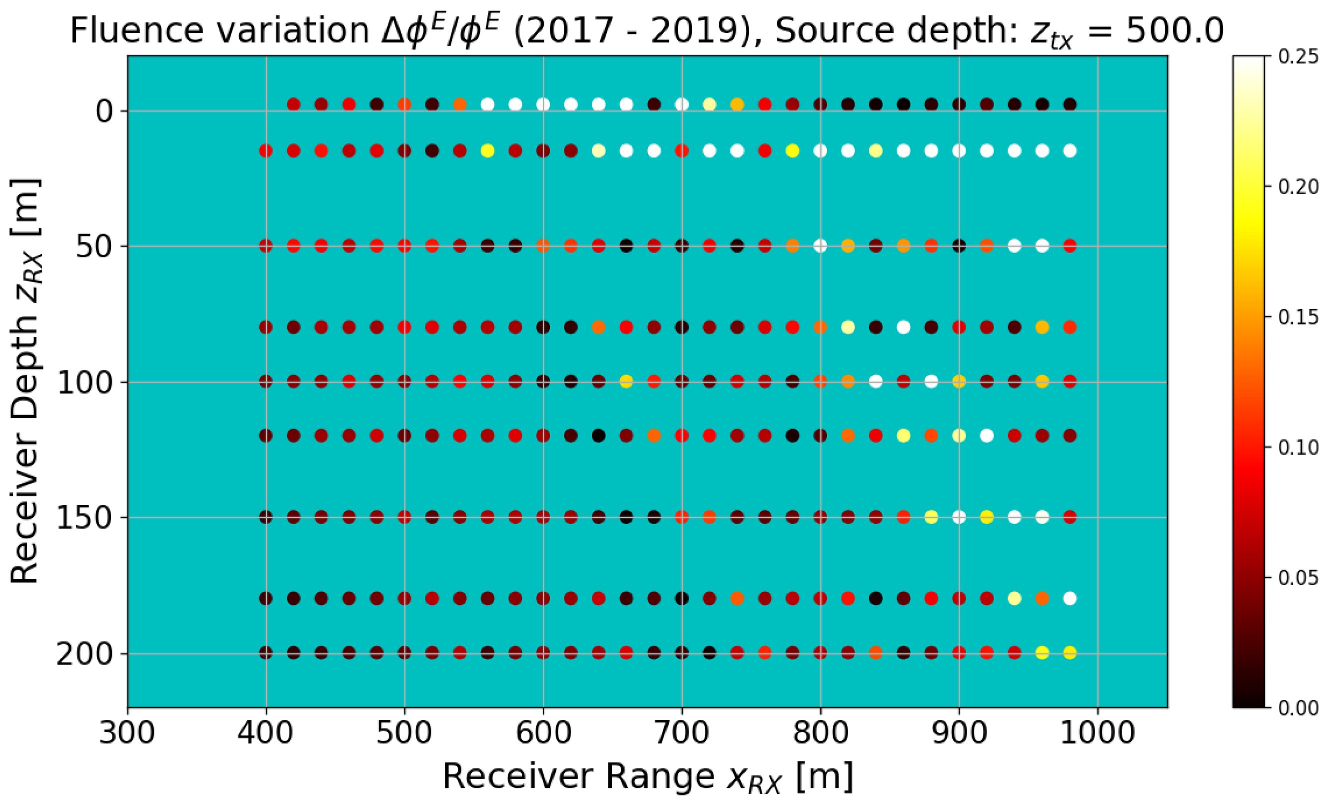


Fig.5 Fluence residuals in pulses at RX positions June 2017—June 2019 (paraProp)

Implications for Neutrino Reconstruction

Electric field fluence Φ^E is a reconstruction parameter for UHE-ν energy E_ν [5]:

$$\phi^E \propto \sqrt{E_\nu}\, e^{-L/L_\alpha}\, e^{\frac{-|\theta-\theta_C|^2}{2\sigma_\theta}}$$

For each month from 2015 to 2020 we find the variation in fluence (Fig. 8):

- paraProp: $\Delta\Phi^E_R / \Phi^E_R$ > ~0.1 (x > 600 m), ~10^{-3} < $\Delta\Phi^E_D / \Phi^E_D$ < ~10^{-2}
- Meep: $\Delta\Phi^E_R / \Phi^E_R$ > ~0.1 (x > 700 m), ~10^{-2} < $\Delta\Phi^E_D / \Phi^E_D$ < ~10^{-1} (x > 800 m)

Preliminary finding: Under likely signal geometries, shallow firn fluctuations produce systematic uncertainty in the fluence of R-signals, and possibly for neutrino energy reconstruction as well

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

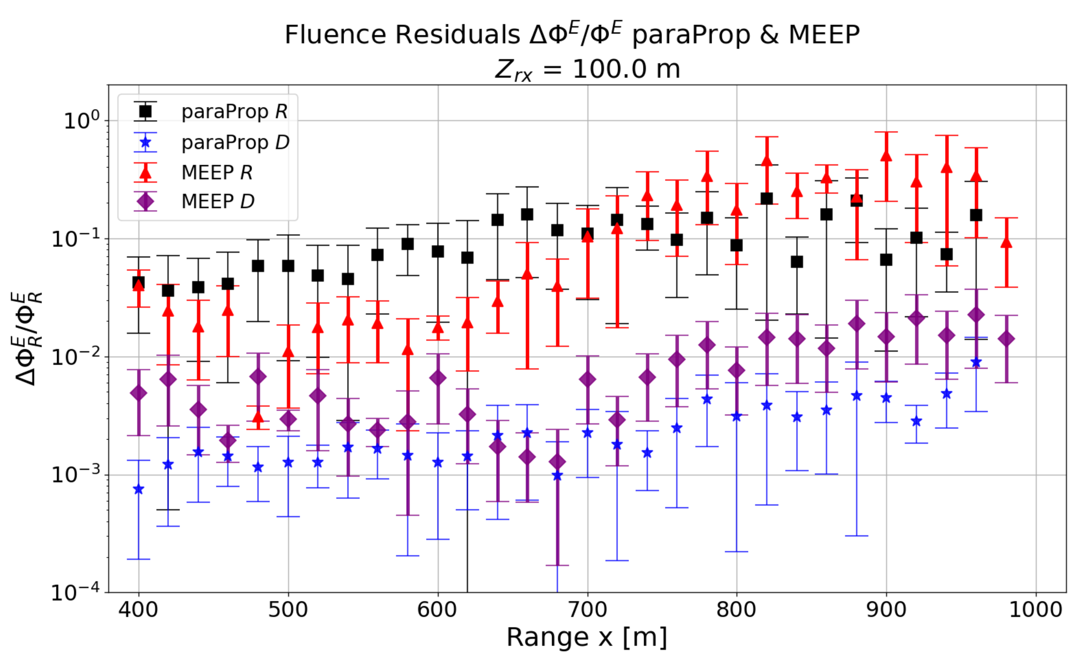


Fig.8 Φ^E residuals for CFM calculated profiles according to MEEP and paraProp: n(z) profiles between 2015 & 2020

References

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