Propagating Air Showers Radio Signals to In-ice Antennas

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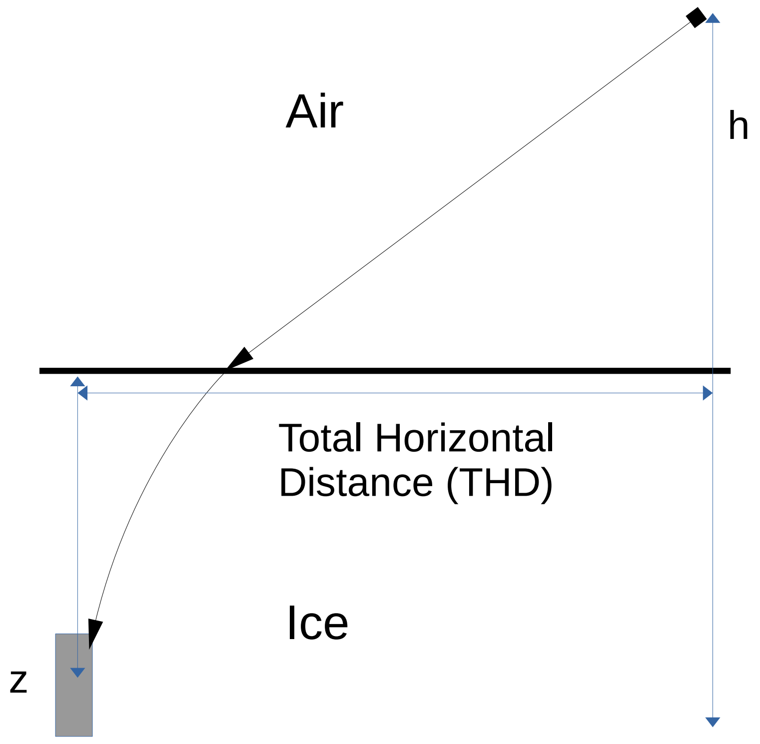
Introduction

- Radio emissions from cosmic ray showers serve as an essential background signal for in-ice radio detectors in the polar regions.
  - Can also serve as calibration sources due to their relatively large observed flux.

- Thus, we have adapted CoREAS for simulating in-air radio emissions in in-ice antennas using exponential refractive index profiles of air and ice.

- Analytic raytracing expressions are used to calculate the relevant parameters for the curved ray paths.

- Since analytic raytracing is slow, interpolation is used with pre-tabulated raytrace values to calculate raytracing parameters for all the particles in the shower.



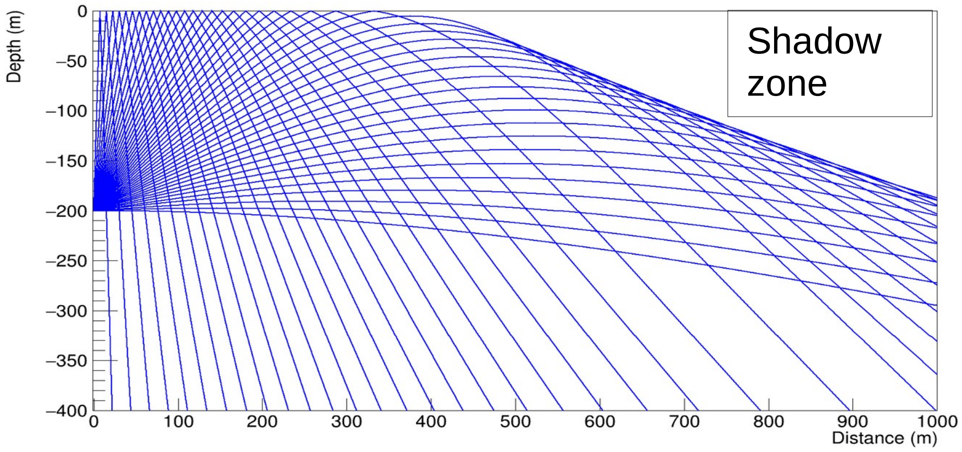
Raytracing in Polar Ice

- Rays are refracted owing to the depth-dependent density, and therefore index of refraction profile.

- For any given a transmitter and receiver geometry I have an analytic solution that traces out the rays in ice and air.

- The refractive index profile for SP ice:

$$n(z) = A + Be^{Cz}$$, here A=1.78, B=-0.43, C=-0.0132 1/m



Ray paths for a source at a depth of 200 m. The bending causes the formation of ‘shadow zones’.

Air Refractive Index Profile

- Get the GDAS atmosphere file for a given set of GPS coordinates.
  - In this case its for a location close to South Pole.

- Get the five layer refractive index model using the GDAS file.

Layer	Altitude Range (m)	A	B	C (m^{-1})
1	0 to 3217.48	1	0.000328911	0.000123309
2	3217.48 to 8363.54	1	0.000348817	0.000141571
3	8363.54 to 23141.80	1	0.000361006	0.000145679
4	23141.80 to 100000	1	0.000368118	0.000146522
5	> 100000	1	0.000368117	0.000146522

A, B and C values for the five exponential refractive index layers of the South Pole atmosphere.

$$n(z) = A + Be^{Cz}$$

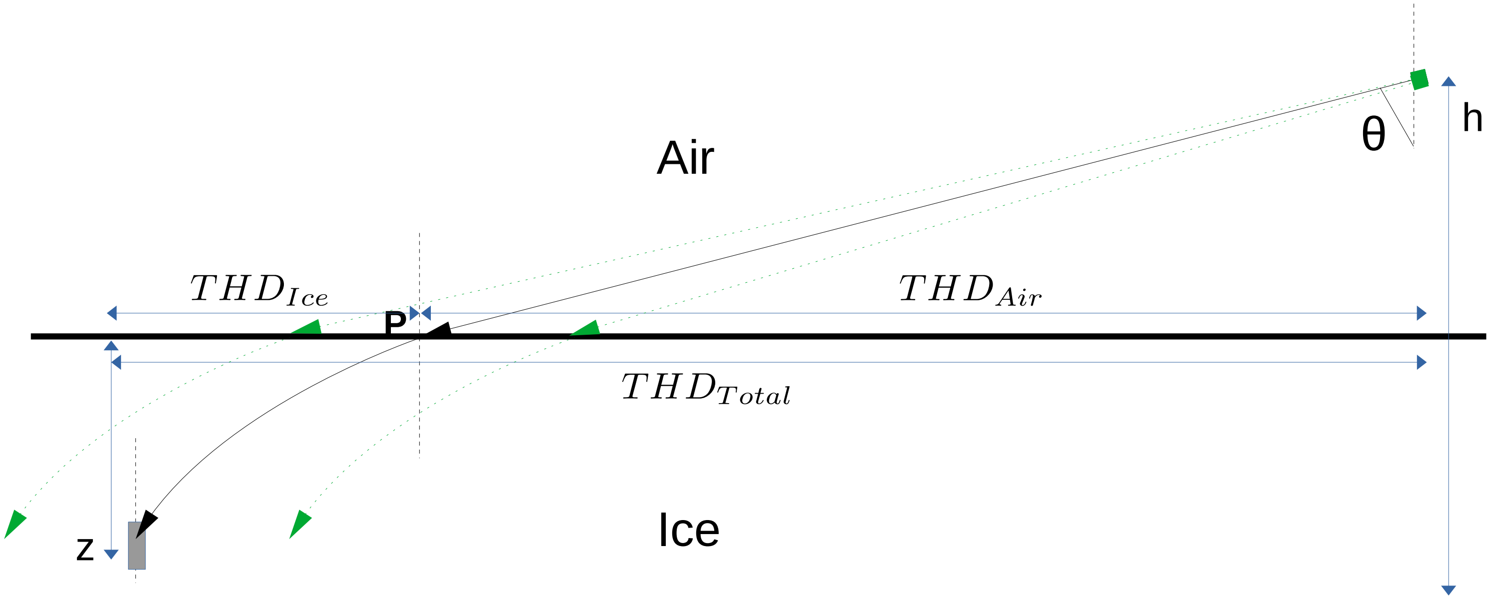
Launching Rays from Air to Ice

- Raytracing:
  - For a given transmitter receiver geometry we can always find the shortest possible path between them by minimizing the following expression:

$$f(\theta_s, h, z) = THD_{Air} + THD_{Ice} - THD_{Total} = 0,$$

Four parameters that define a Geometry

1) Transmitter altitude
2) Ice Layer Altitude
3) Antenna Depth
4) Total Horizontal Distance (THD)



Raytracing Time

- So a typical raytracing call involving air and ice takes around 0.05 to 0.1 ms.
  - Currently making the atmosphere takes around 22 ms.

- Calling the analytic raytracing function for all shower particles (~10^9) at all heights is still not feasible.
  - A shower will take around from a week to a month to simulate.

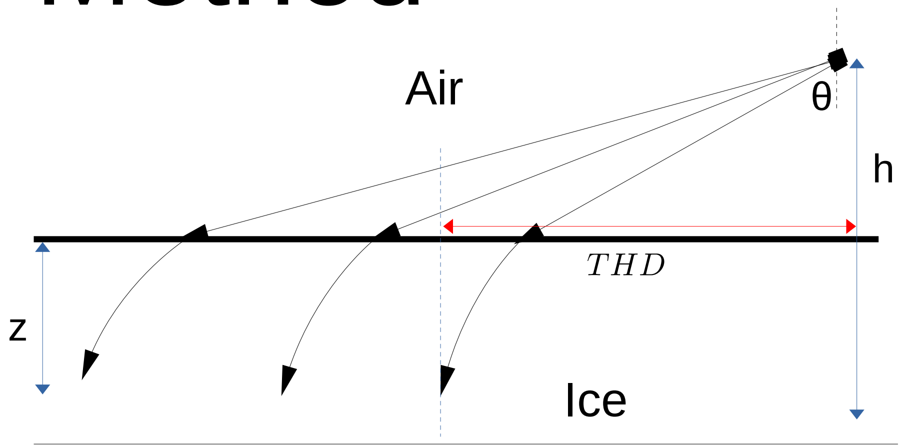
- Therefore, we have to move towards interpolation.

Interpolation Method

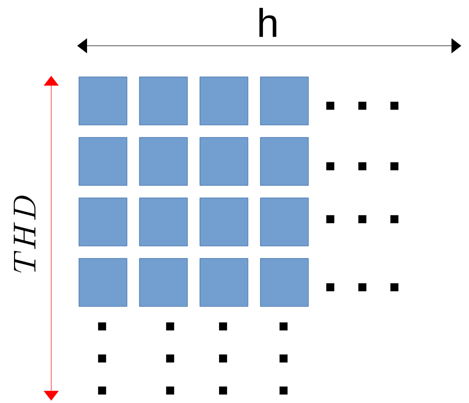
- For a given antenna depth I make 2-D grid of:
  - THD (Total Horizontal Distance)
  - The altitude of the in-air transmitter

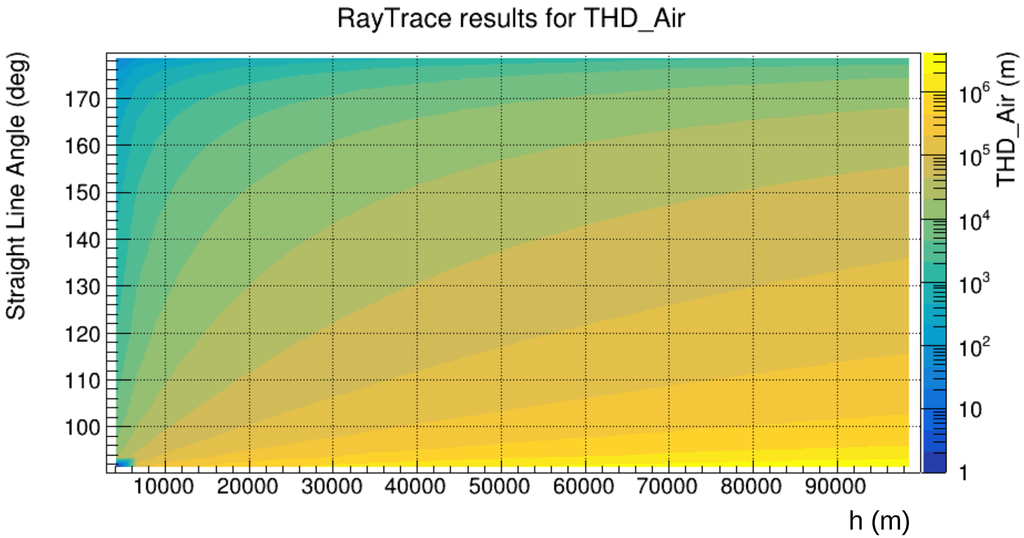
- For each grid position I do analytic raytracing and store:
  - The initial launch angle of the ray
  - The total optical path length of the ray in air and in ice
  - The horizontal distance traveled by the ray in air and ice.
  - The angle of incidence on the ice surface and the Fresnel coefficients associated with it.

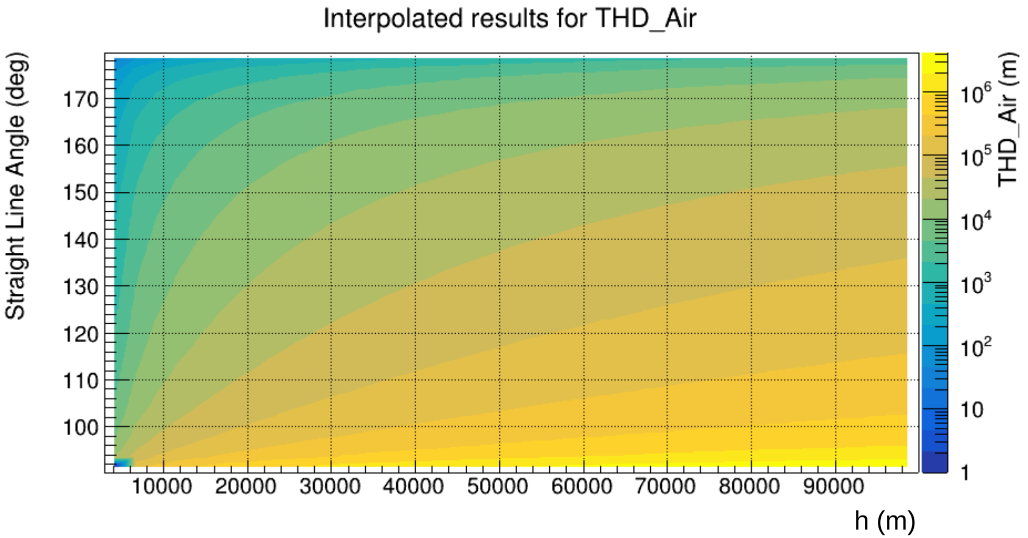
- Linear interpolation is used to calculate a given raytrace parameter.
  - It takes around 250 ns to do interpolation for each parameter.

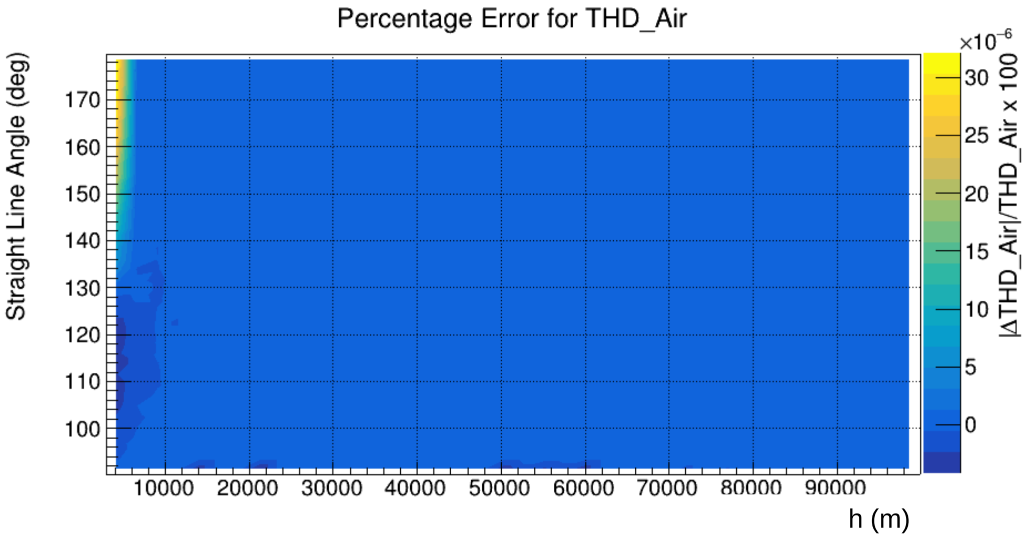


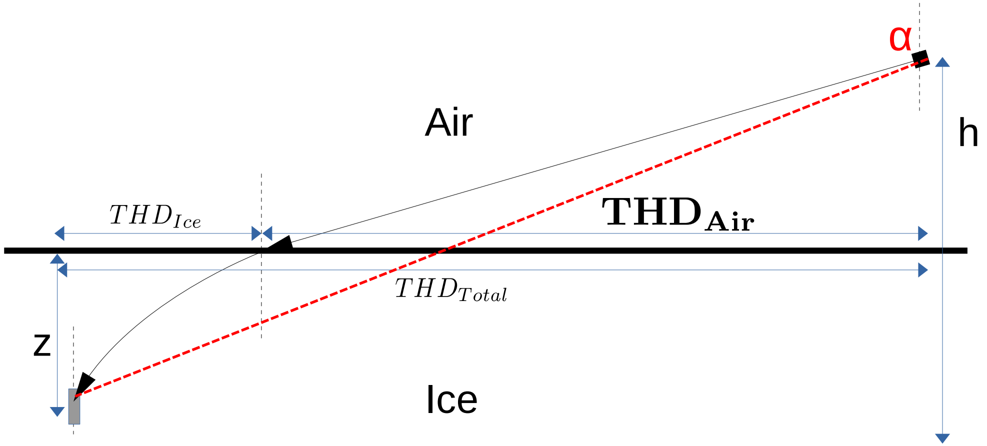
2-D Interpolation Grid




RayTrace results for THD_Air
Straight Line Angle (deg)
h (m)
THD_Air (m)


Interpolated results for THD_Air
Straight Line Angle (deg)
h (m)
THD_Air (m)


Percentage Error for THD_Air
Straight Line Angle (deg)
h (m)
|ΔTHD_Air|/THD_Air x 100


α
Air
h
THD_{Ice}
$\mathbf{THD_{Air}}$
THD_{Total}
z
Ice

Adding Raytracing to CoREAS

- CoREAS uses end point formalism to calculate E-field emissions.

$$\vec{E}(\vec{x},t) = \frac{q}{c}\left[\frac{\hat{r}\times[(\hat{r}-n\vec{\beta})\times\dot{\vec{\beta}}]}{(1-n\vec{\beta}.\hat{r})^3\ R}\right]_{ret}$$

- In this formula, I use the following raytracing parameters:
  - Launch angles as the dot product angle
  - Optical path length of the ray for the value R
  - The value of n is taken to be n at the emission point.

- Have yet to integrate Fresnel coefficient calculations to account for surface reflections.

WHY DOES THE BOOSTFACTOR MATTER?

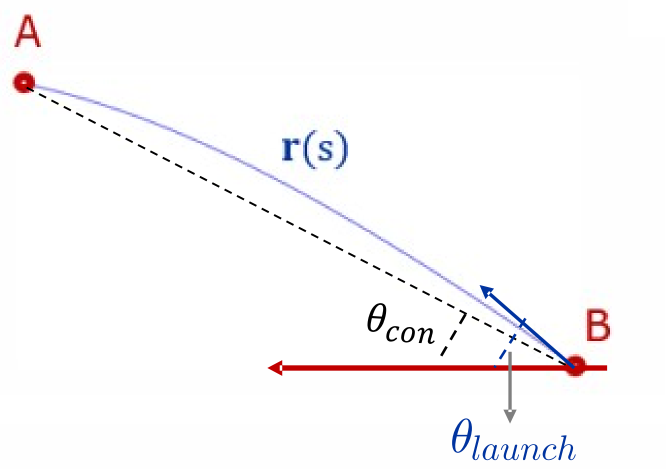
The end point formalism (arxiv.org/abs/1112.2126) :

$$\vec{E}_{\pm}(\vec{x},t) = \pm \frac{1}{\Delta t}\frac{q}{c}\left(\frac{\hat{r}\times[\hat{r}\times\vec{\beta}^{*}]}{\underbrace{(1-n\vec{\beta}^{*}\cdot\hat{r})}_{Boost\,factor^{-1}}R}\right)$$

When calculating as $1 - n\beta\cos(\theta)$:

What n?

What θ ?

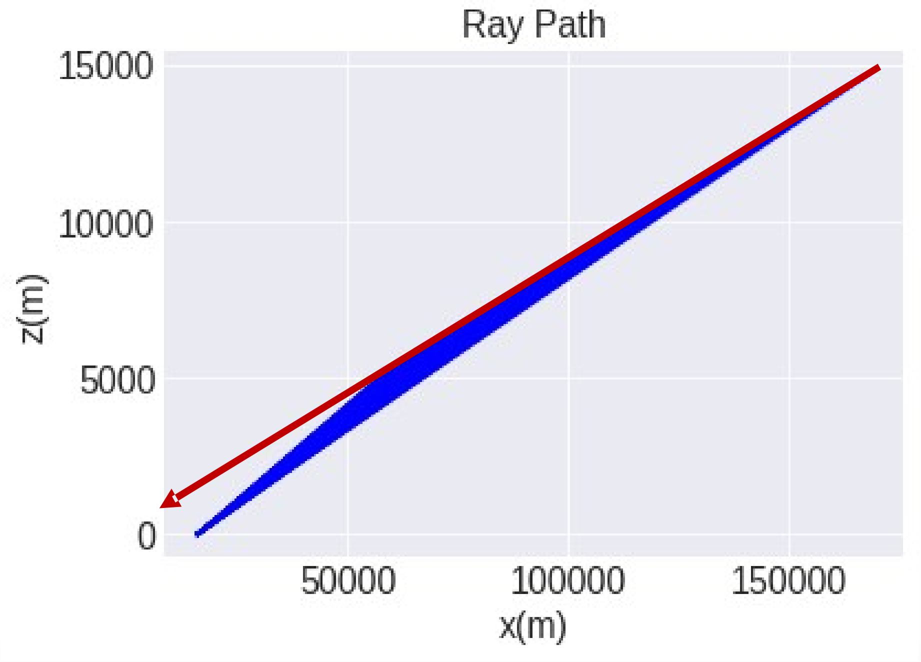


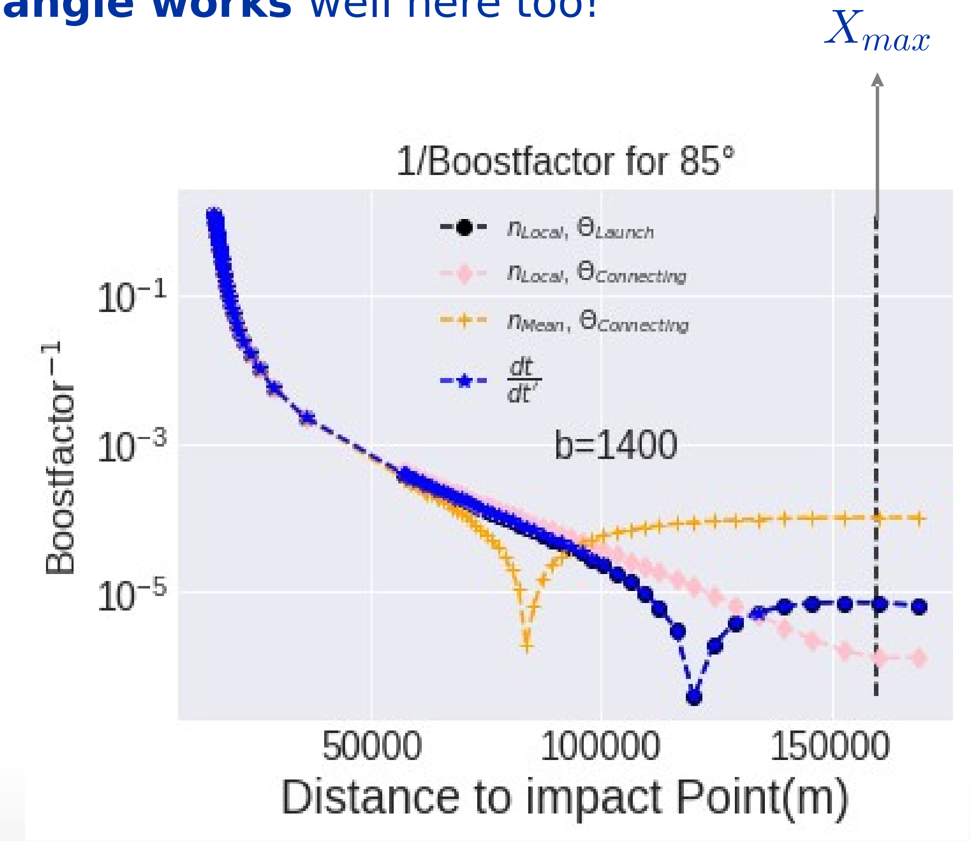
Previous studies (A. Timmermans, Ba. Thesis) show that a straight line approximation might not be valid for very inclined geometries in air

IN AIR BURSTS

WHAT ABOUT INCLINED SHOWERS?

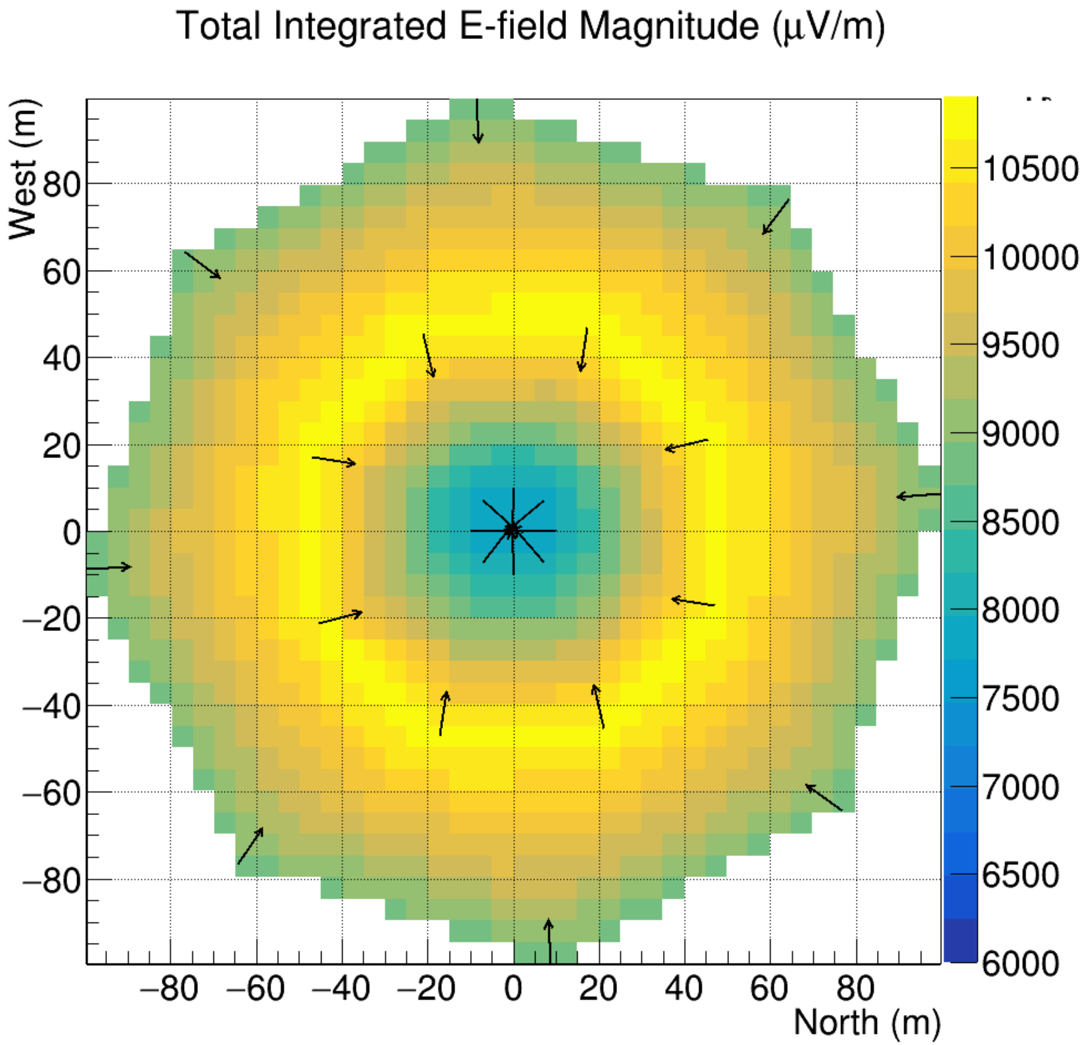
The estimator with **local n and launch angle works** well here too!
The others do not agree
Similar results found by A.Timmermans



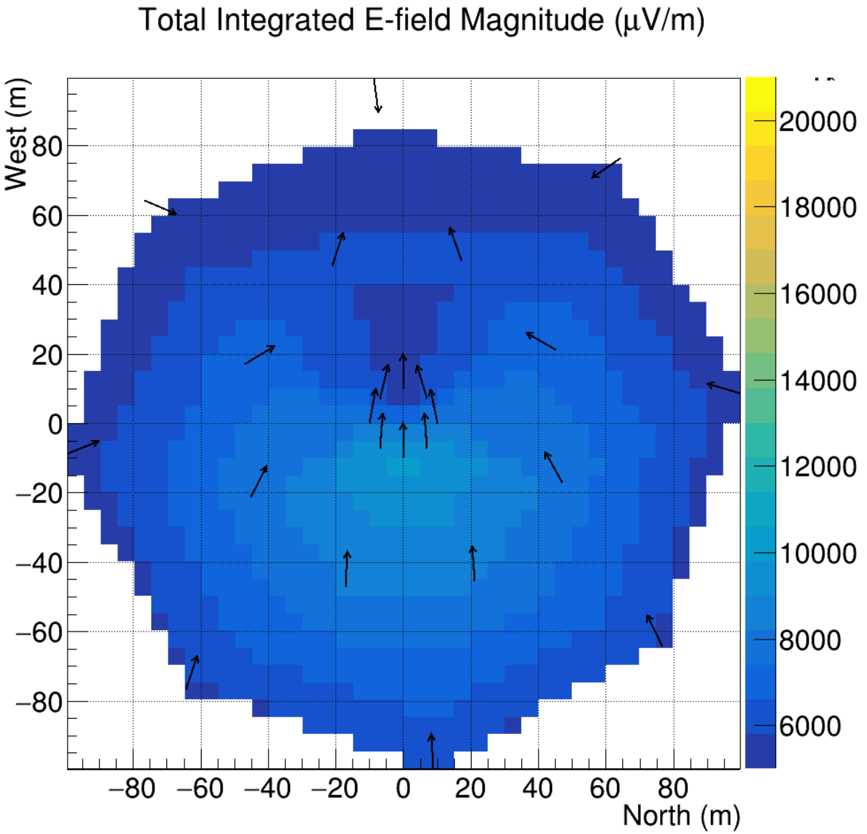


Shower Footprint in Ice without B-field

- This is for a vertical shower
- The antennas placed in a plane at 100 m depth below the ice sheet.
- The ice layer is at 3000 m altitude.
- The shower energy is 10^17 eV with a proton primary.
- As expected, the Cherenkov ring is clearly visible with no geomagnetic emission and the polarisation vectors point to the center.



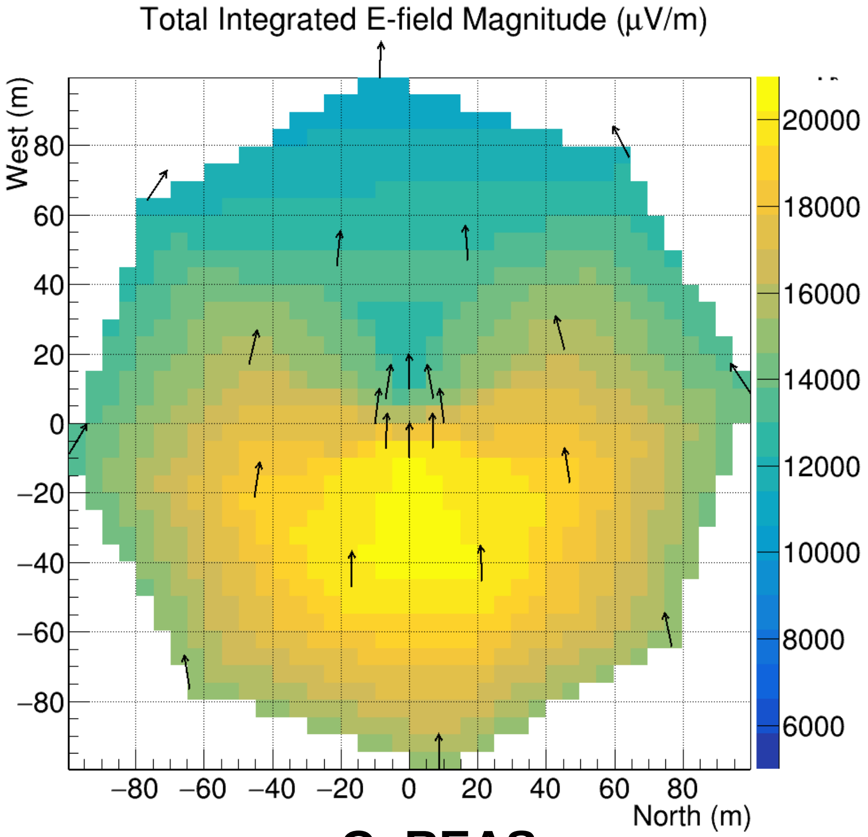
Shower Footprint- CoREAS(Air) and Ice



In-ice

100 m depth, Ice Layer at 3000 m

Vertical Shower, 10^17 eV, Proton primary



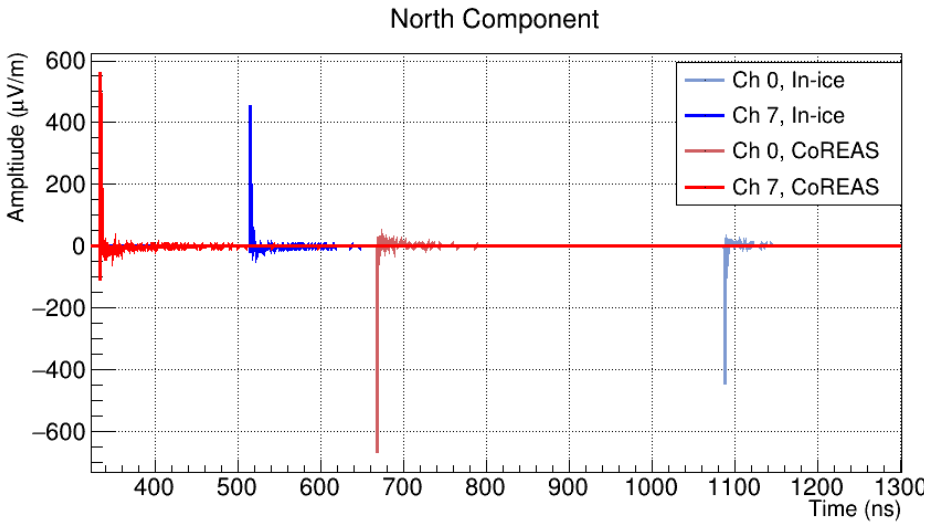
CoREAS

In air

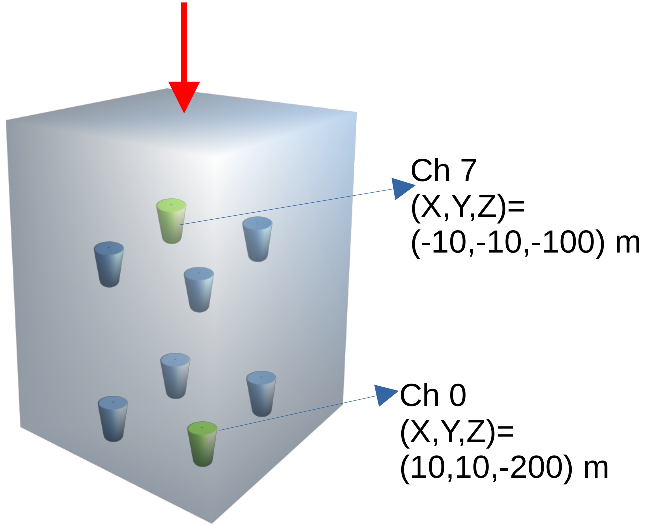
In-Ice RayTracing vs CoREAS: E-fields

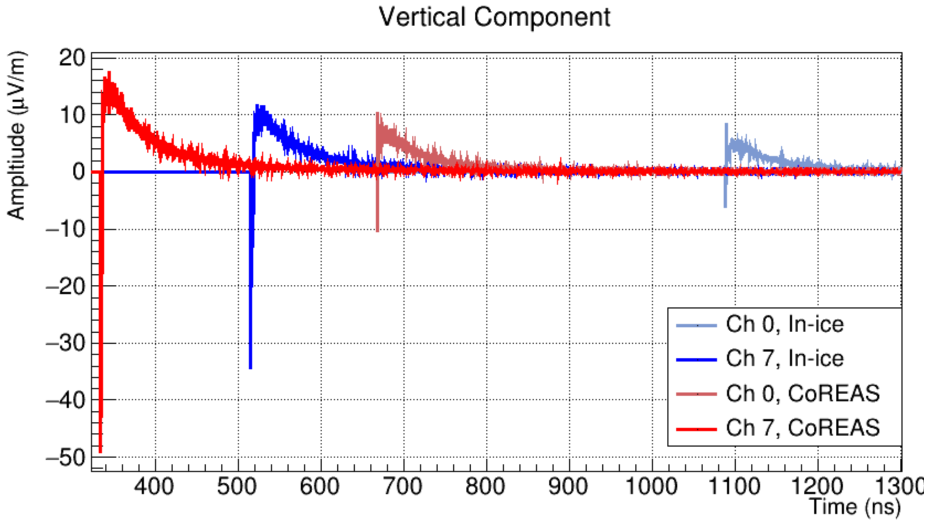
Vertical Shower,
E 1e17 eV,
Thinning ON,
Ice Sheet Altitude 3000 m

- Pulse shape is preserved in ice.
- Expected time delay in ice signals observed.
- Less power in E-fields in Ice



Geometry:



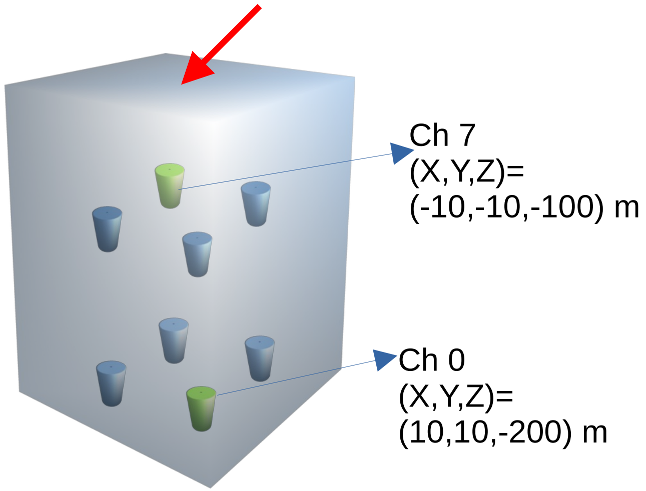


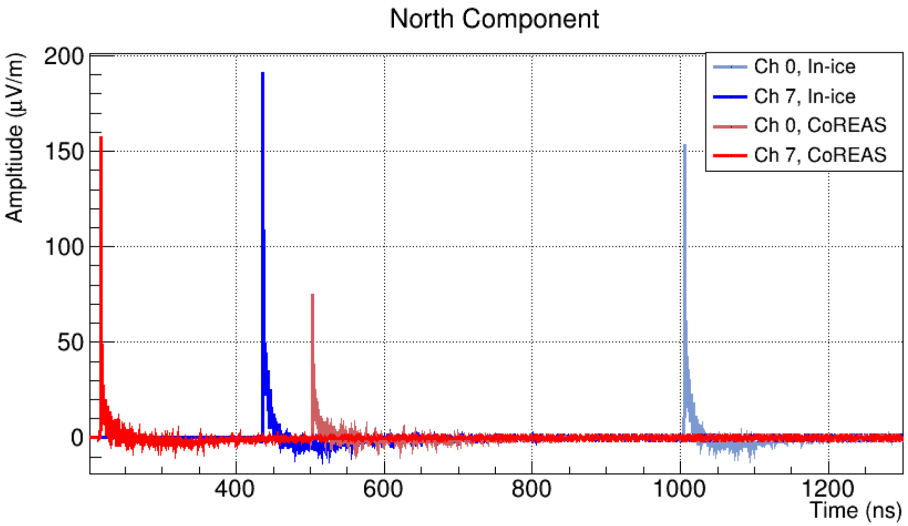
In-Ice RayTracing vs CoREAS: E-fields

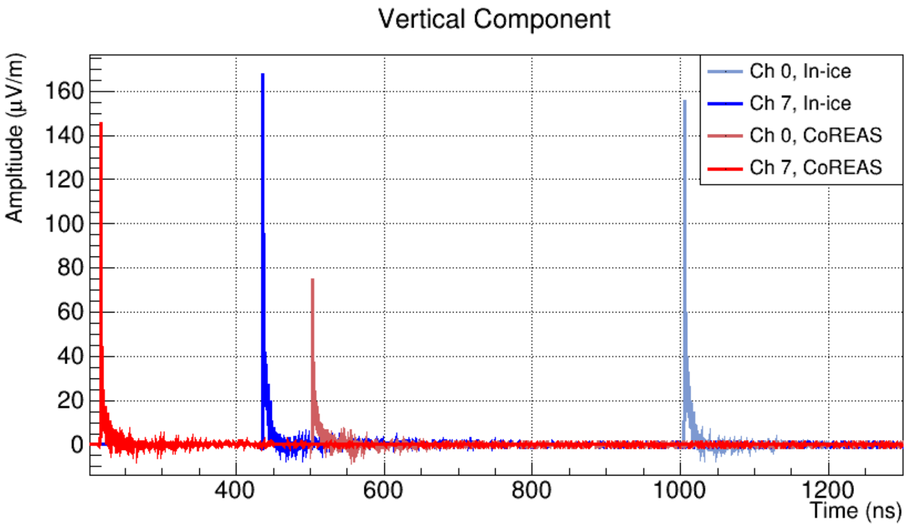
Zenith 45 deg,
E 1e17 eV,
Thinning ON,
Ice Sheet Altitude
3000 m

- Pulse shape is preserved in ice.
- Expected time delay in ice signals observed.
- More power in E-fields in Ice

Geometry:







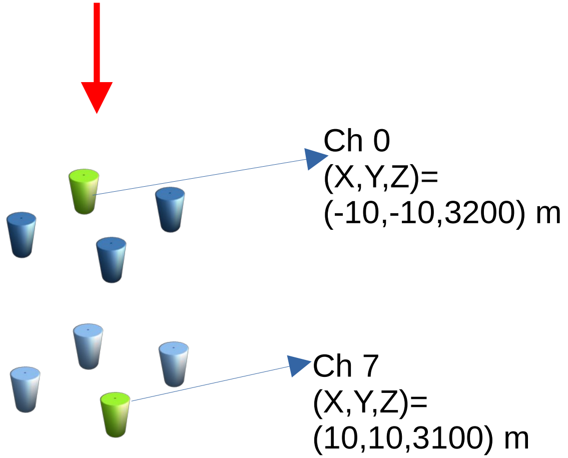
In-Air RayTracing vs CoREAS: E-fields

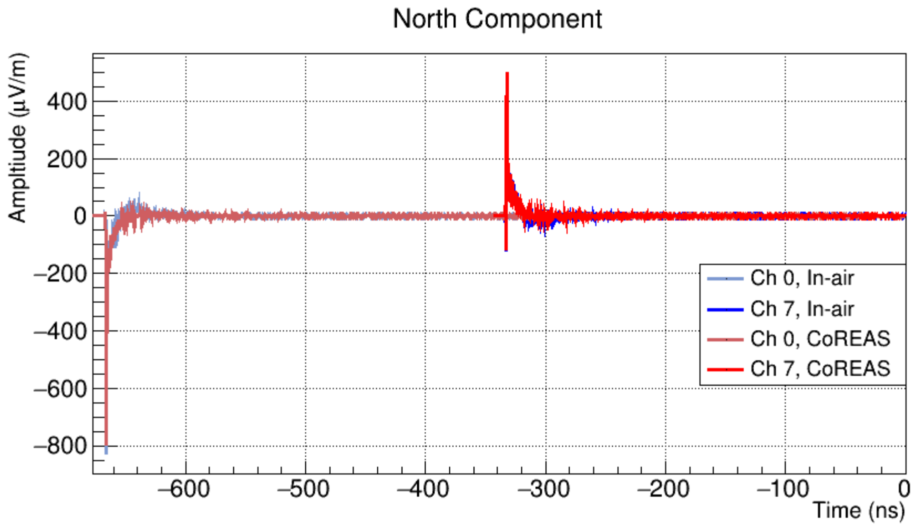
Vertical Shower,
E 1e17 eV,
Thinning ON

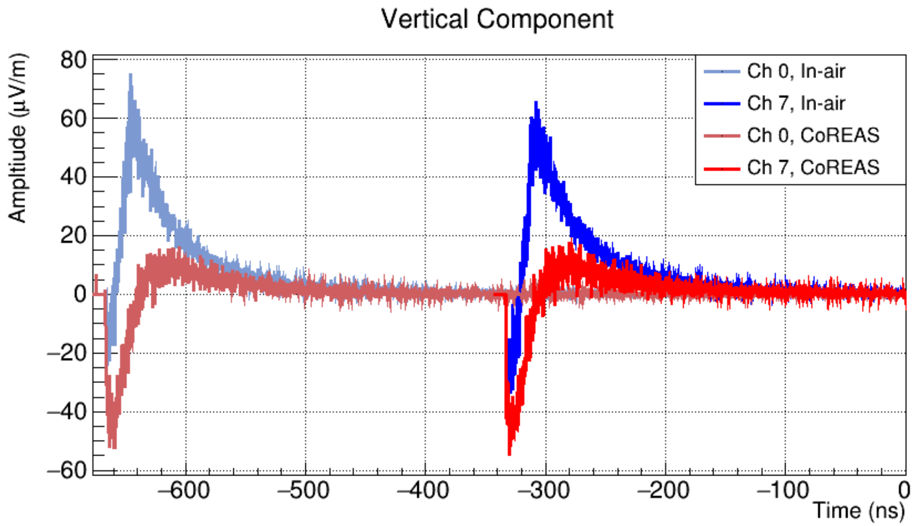
- Pulses almost identical for North and West components.

- Pulse structure significantly different for the Vertical component.

<u>Geometry:</u>







Some things to keep in mind for interpolation implementation

- How to make/load the table for each antenna when the simulation is run in parallel?
  - Load it from a file or load it directly in the memory.

- Since the tables can be big, the RAM can get filled up quickly.
  - Have to work on optimizing RAM usage.

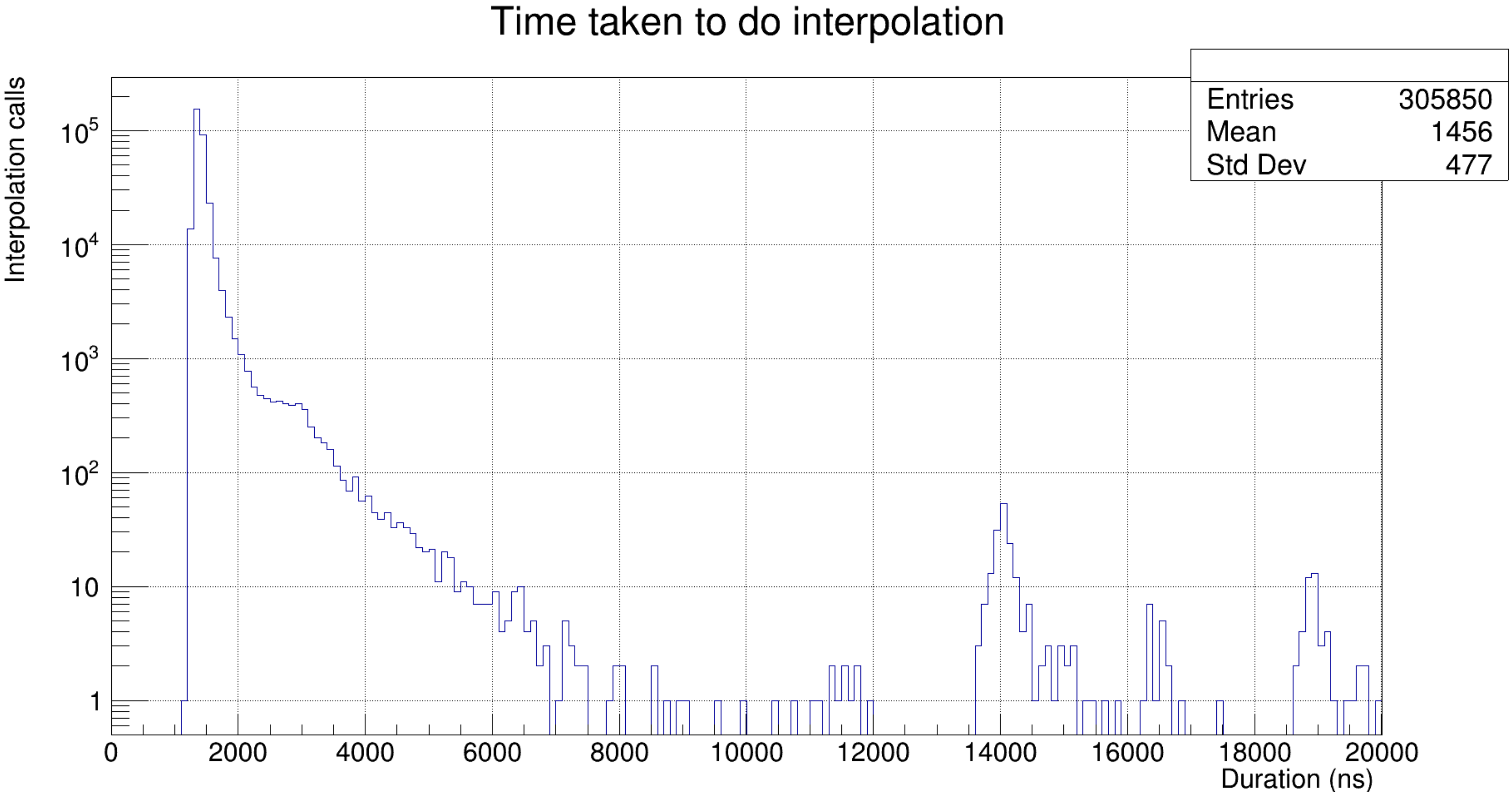
Conclusion

- The in-ice and in-air raytracing codes are working well and giving good results.

- In the process of running checks and making sense of all results.
  - Still have to include Fresnel coefficients in the calculations.
  - Take into account Earth’s curvature in raytracing.

- Simulate in-air and in-ice emissions together in one simulation for a CR shower using CoREAS.

Thank you!


Time taken to do interpolation
Entries 305850
Mean 1456
Std Dev 477
Interpolation calls
10^5
10^4
10^3
10^2
10
1
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Duration (ns)

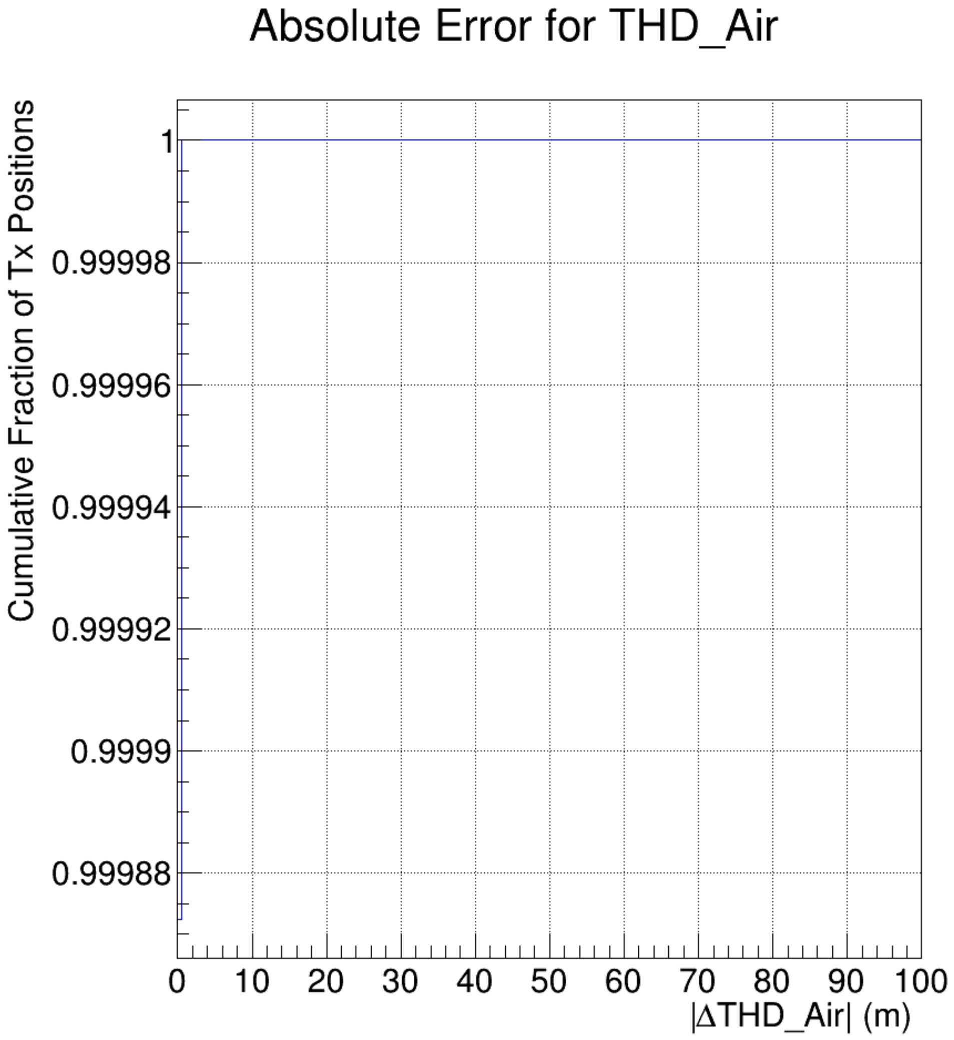
Interpolation Method

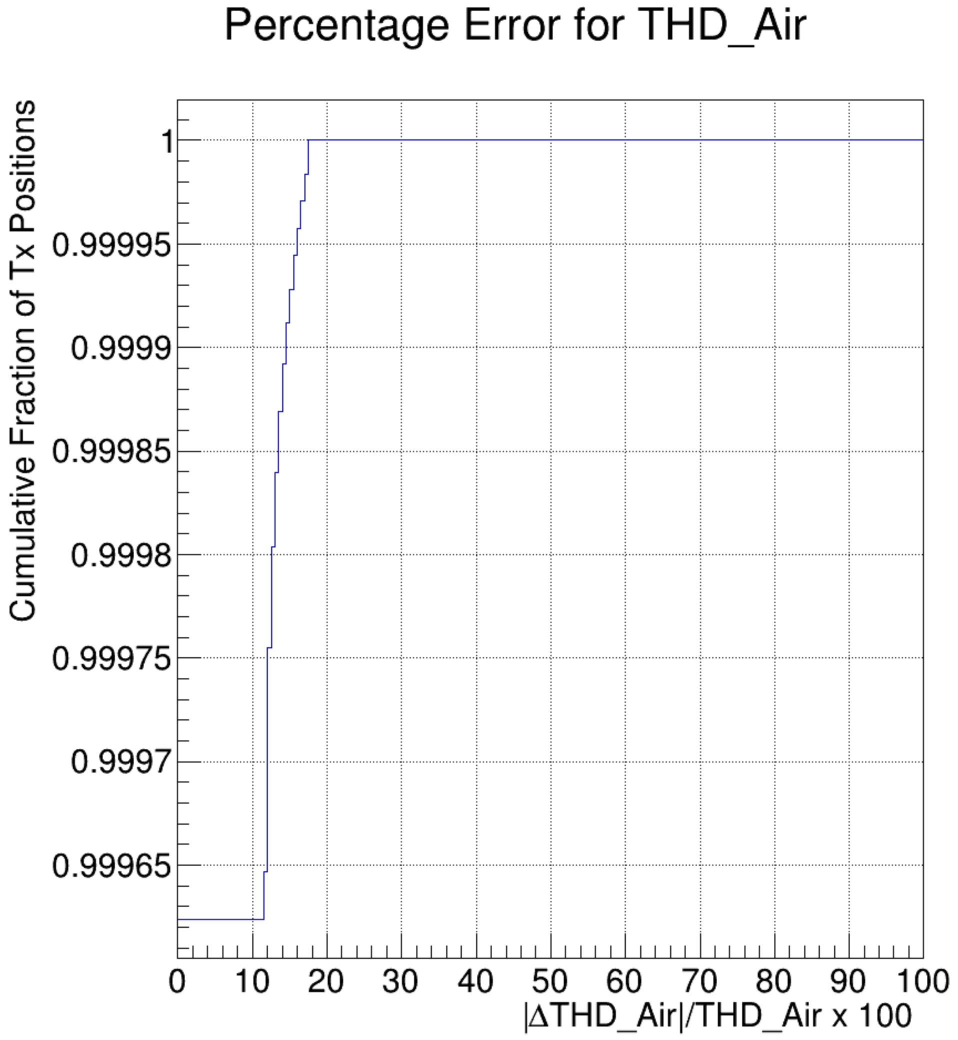
- θ (or the launch angle) has a step size of 0.1 deg and h has a step size of 10 m.
  - θ starts off at 90.1 deg and ends at 180.0 deg.
  - h starts off at 3000 m (the ice layer altitude) and ends at 100000 m.

- If the antenna depth changes we will need to make another 2-D grid for that.

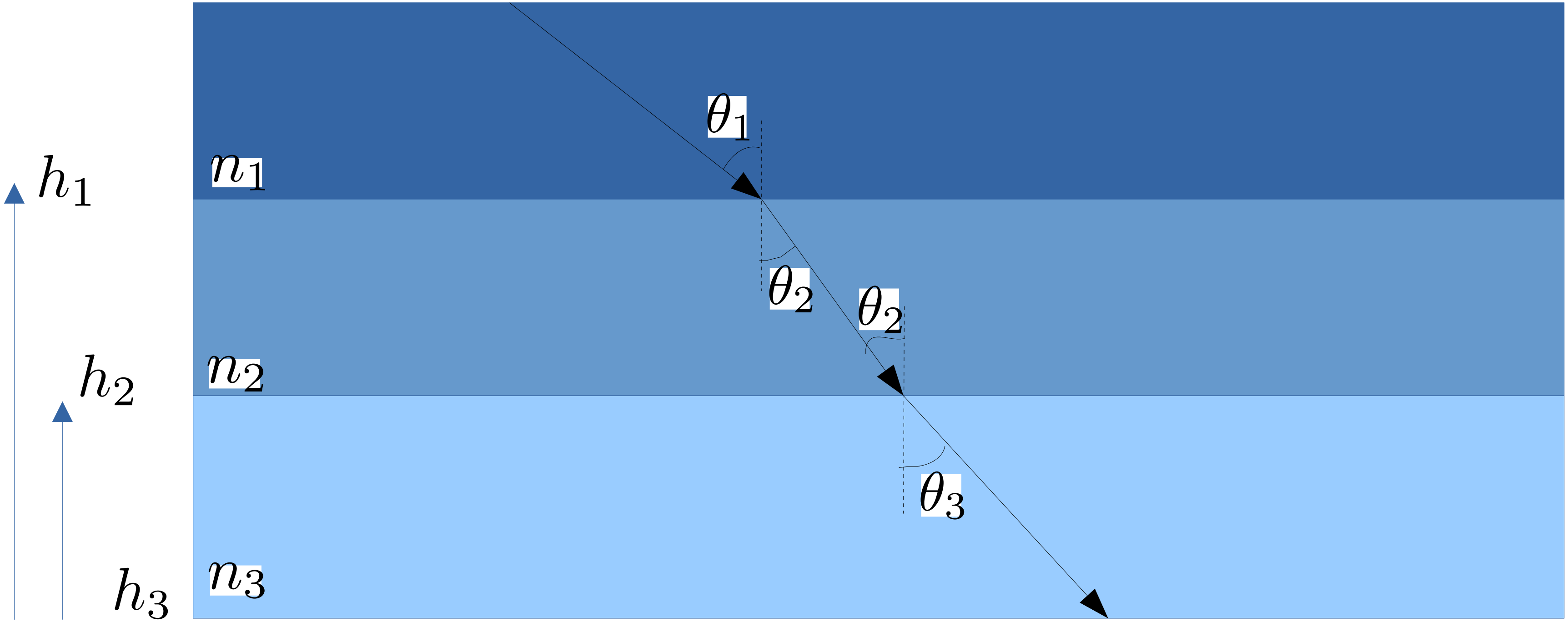
- It takes around 60±2 s to make the whole grid.

- For any given coordinate of (h,THD)
  - the closest h bins are calculated
  - The corresponding range of THDs for the h bins are found and the closest THD bins are found.
  - using the linear interpolation method the interpolation parameter value at the requested coordinate is calculated.


Absolute Error for THD_Air
Cumulative Fraction of Tx Positions
1
0.99998
0.99996
0.99994
0.99992
0.9999
0.99988
0 10 20 30 40 50 60 70 80 90 100
|ΔTHD_Air| (m)


Percentage Error for THD_Air
Cumulative Fraction of Tx Positions
1
0.99995
0.9999
0.99985
0.9998
0.99975
0.9997
0.99965
0 10 20 30 40 50 60 70 80 90 100
|ΔTHD_Air|/THD_Air x 100

Snell's law



$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$
$$n_2 \sin(\theta_2) = n_3 \sin(\theta_3)$$
$$\Rightarrow n_1 \sin(\theta_1) = n_3 \sin(\theta_3) = L$$

Each particular ray has its own value of L. Changing the initial launch angle changes the value L.

Finding the angle of incidence between the multiple layers

- For exponential n(h) profiles the same concept as the previous slide is applicable.

- Based on Snell's Law I find the incidence angles between the multiple layers in air and and the incident angle on ice:

$$\theta_3 = \arcsin\left(\frac{L(\theta_1, h_1)}{n(h_3)}\right),$$

$$\text{here } L(\theta_1, h_1) = n(h_1)\sin(\theta_1)$$

- Once we know the initial launch angle we can calculate the value of L for that ray.
  - This allows us to calculate the incident angle on all layers and also calculate the distance travelled in each layer.

Raytracing-II

The function that describes the ray paths analytically is given by:

$$\boxed{x(L,z) = \frac{L}{C}\frac{1}{\sqrt{A^2-L^2}}\left(Cz - \ln\left(A.n(z) - L^2 + \sqrt{A^2-L^2}\sqrt{(n(z))^2-L^2}\right)\right)}$$

$L = n(z_0)\sin(\theta_0)$, here L is the initial condition of the ray.

Transmitter depth

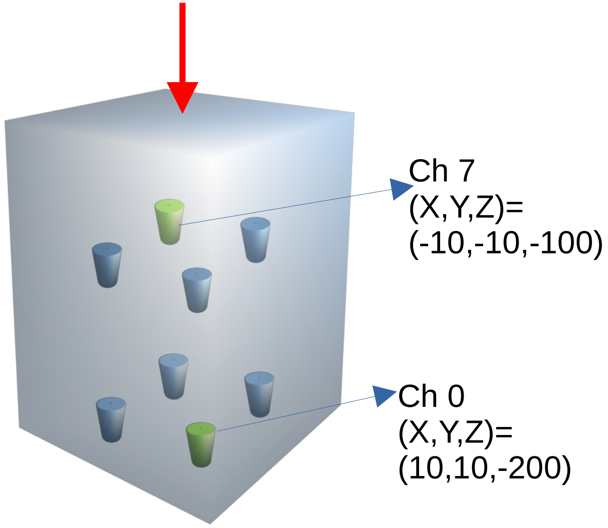
Initial launch angle

Using Fermat's Least time principle we can also calculate the time of propagation of the ray in ice:

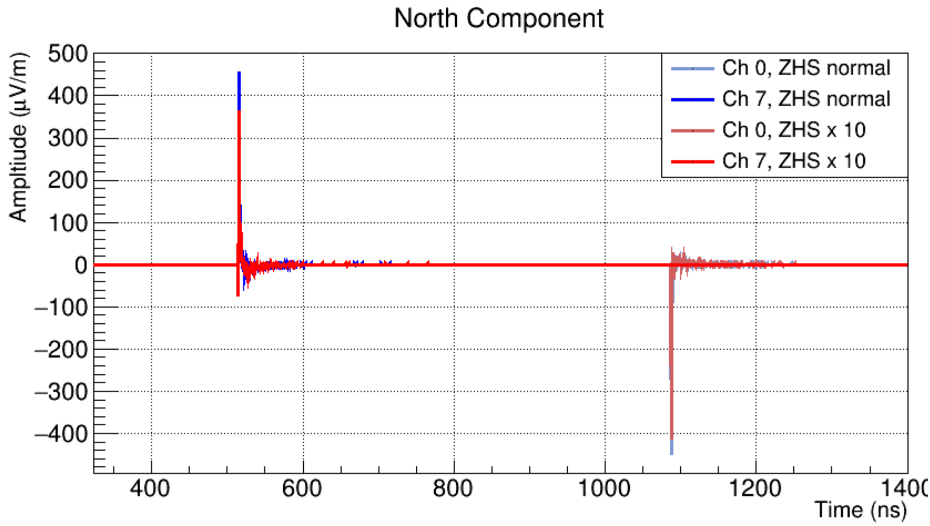
$$\Delta t = \int_{z_1}^{z_2} dz\sqrt{1+\left(\frac{dx}{dz}\right)^2}\frac{n(z)}{c}$$

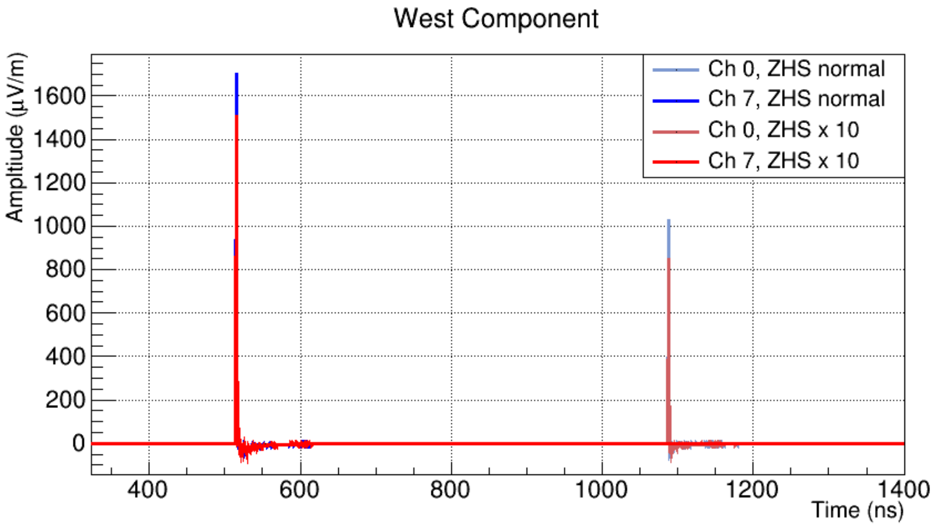
here $\frac{dx}{dz} = \tan(\theta) = \tan\left(\arcsin\left(\frac{L}{A+Be^{Cz}}\right)\right)$

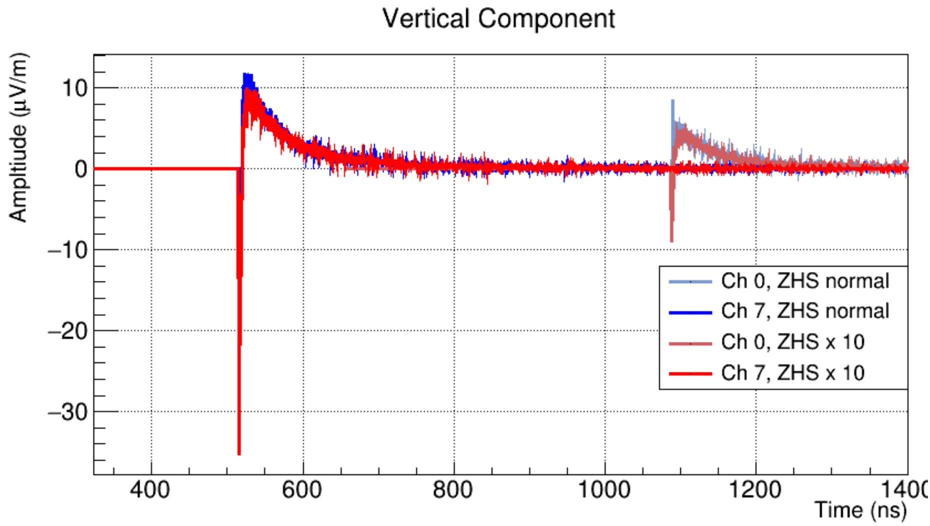
In-Ice RayTracing
ZHS vs ZHSx10: E-fields



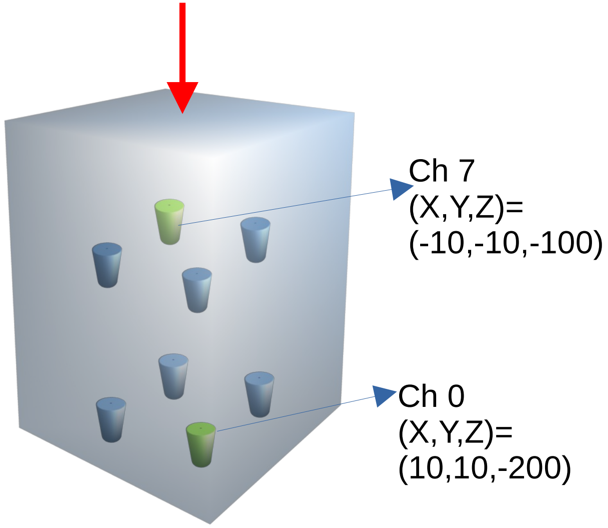
Vertical Shower,
E 1e17 eV,
Thinning ON,
Ice Sheet Altitude
3000 m



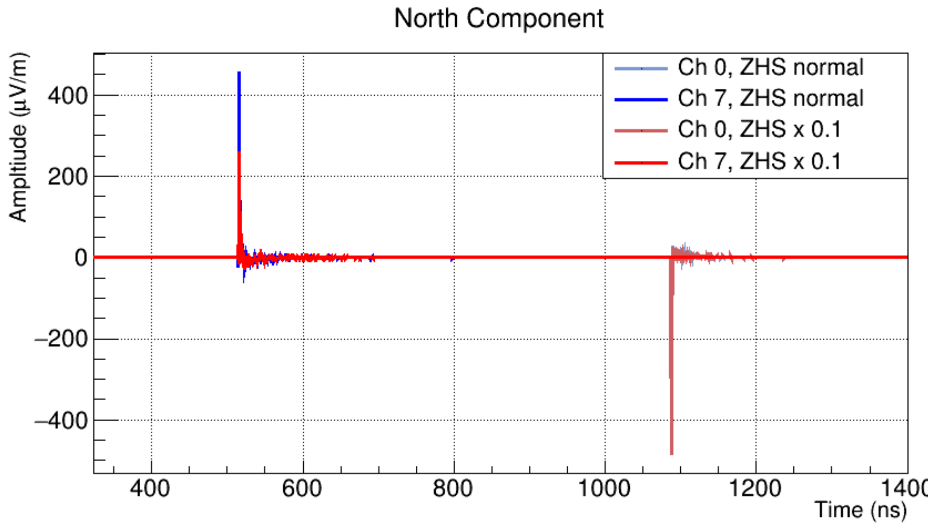


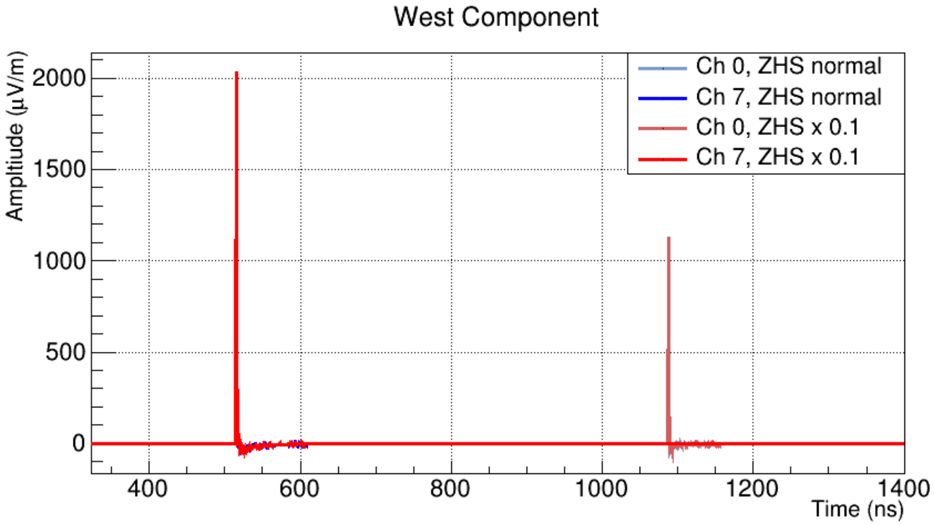


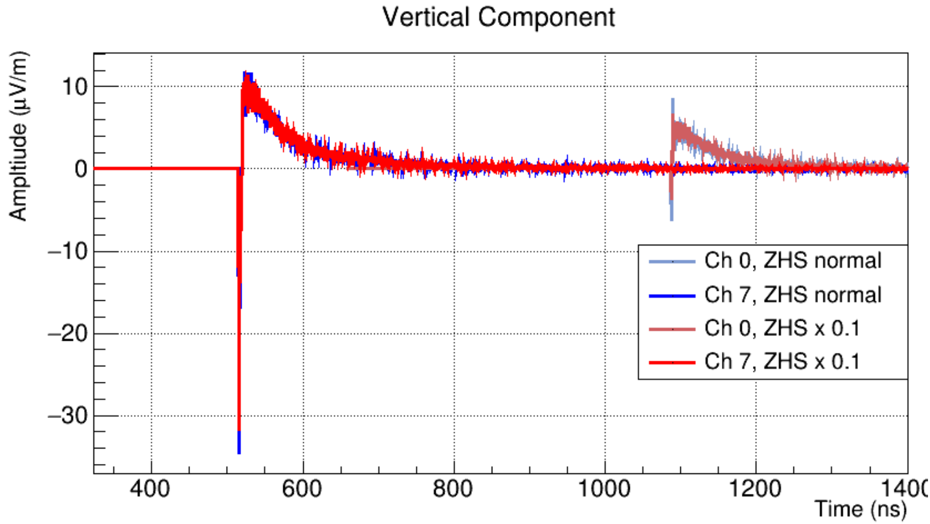
In-Ice RayTracing ZHS vs ZHSx0.1: E-fields



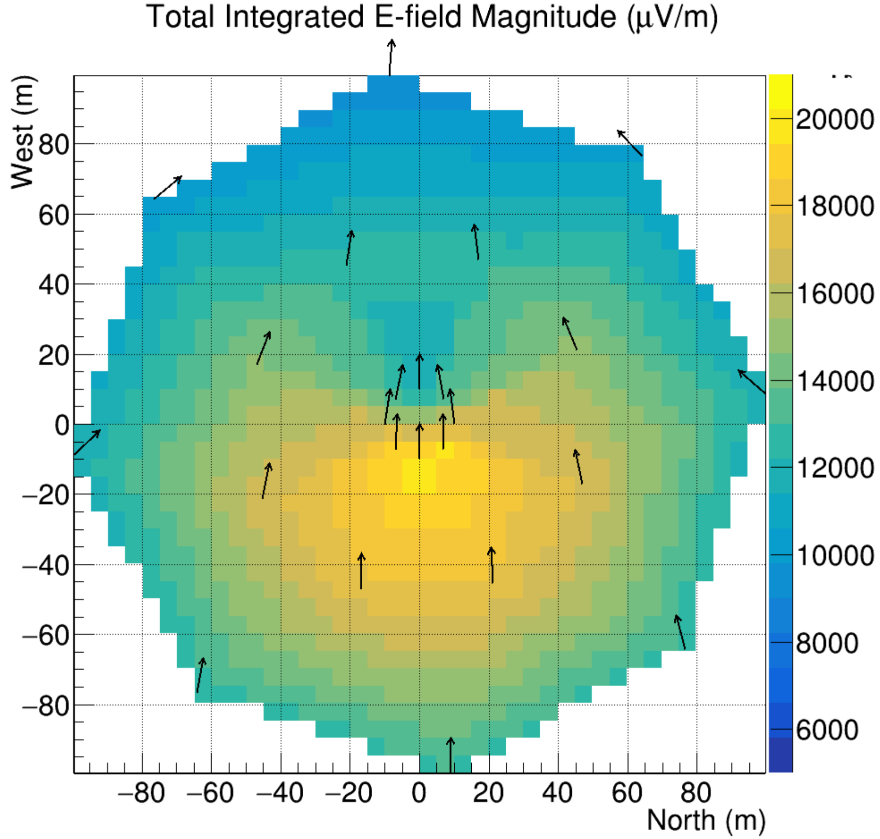
Vertical Shower,
E 1e17 eV,
Thinning ON,
Ice Sheet Altitude
3000 m







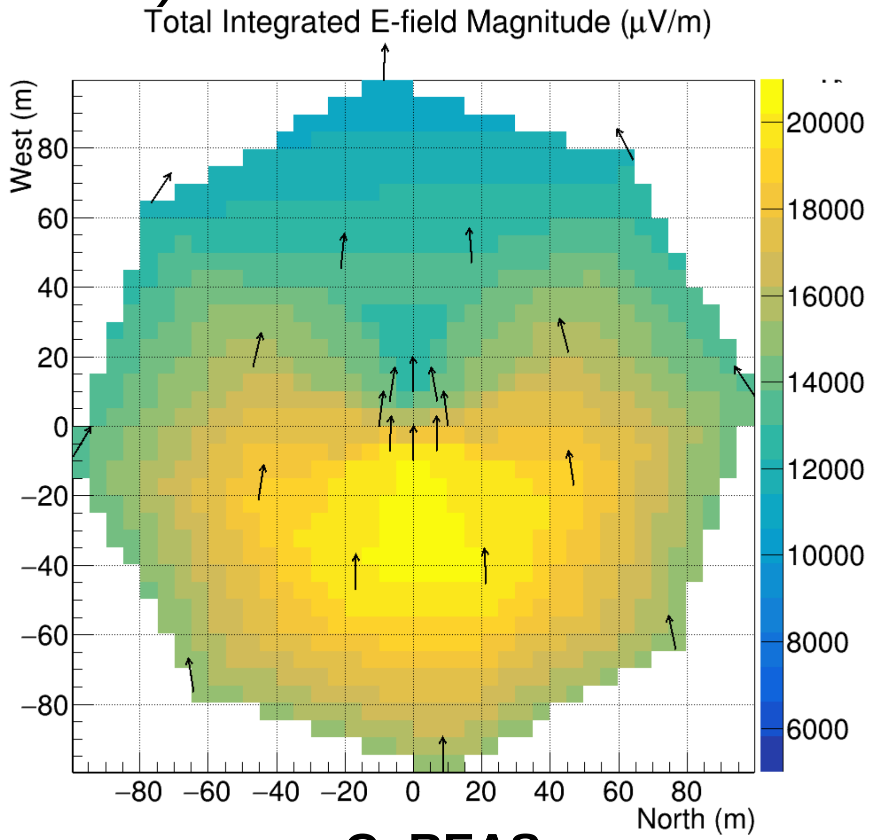
Shower Footprint- CoREAS(Air) and Ice (GeoPath)



In-ice

100 m depth, Ice Layer at 3000 m

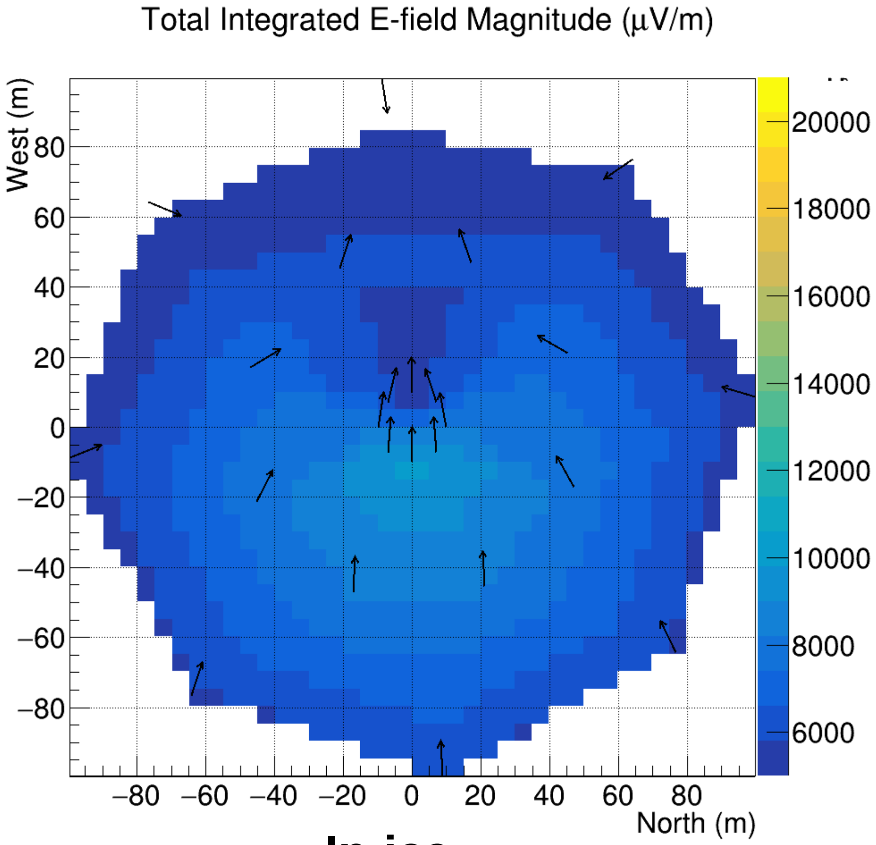
Vertical Shower, 10^17 eV, Proton primary



CoREAS

In air

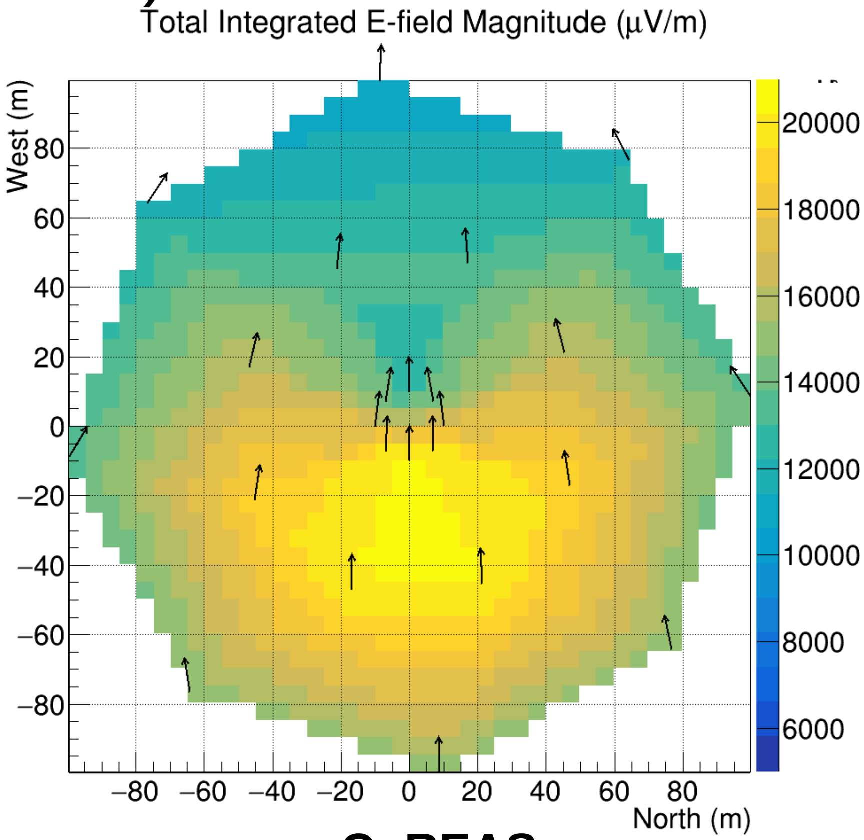
Shower Footprint- CoREAS(Air) and Ice (OptPath)



In-ice

100 m depth, Ice Layer at 3000 m

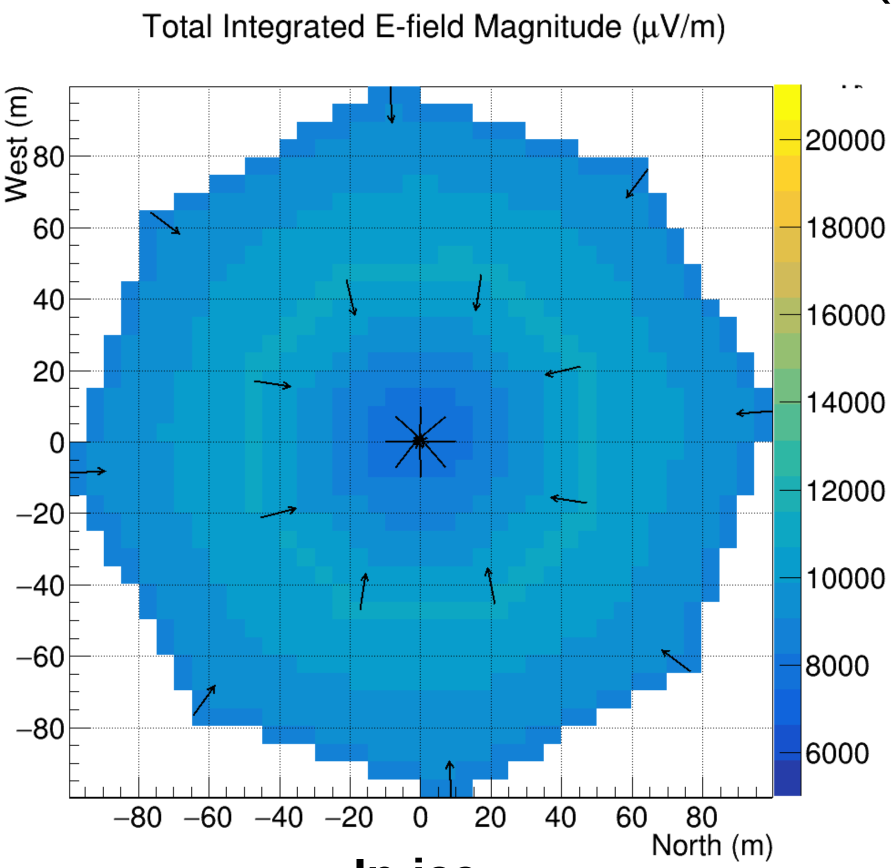
Vertical Shower, 10^17 eV, Proton primary



CoREAS

In air

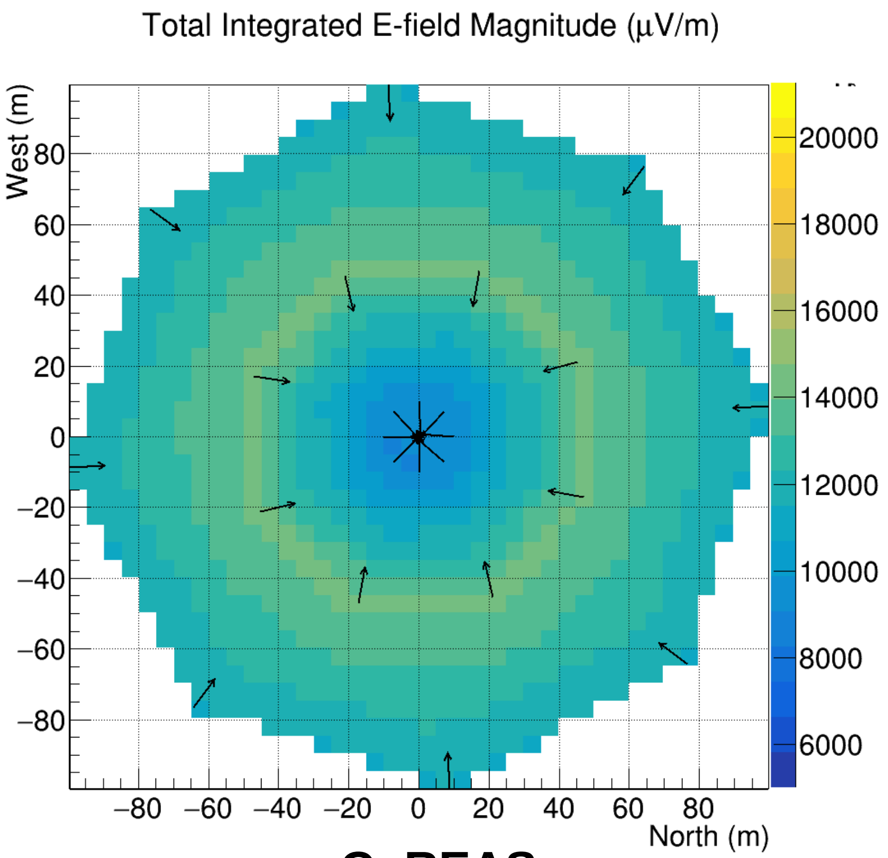
Shower Footprint- CoREAS(Air) and Ice (OptPath) BfieldOff



In-ice

100 m depth, Ice Layer at 3000 m

Vertical Shower, 10^17 eV, Proton primary



CoREAS

In air