SIMULATING COSMIC RAY CASCADE RADIO SIGNALS IN IN-ICE ASKARYAN RADIO DETECTORS

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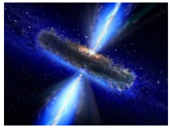
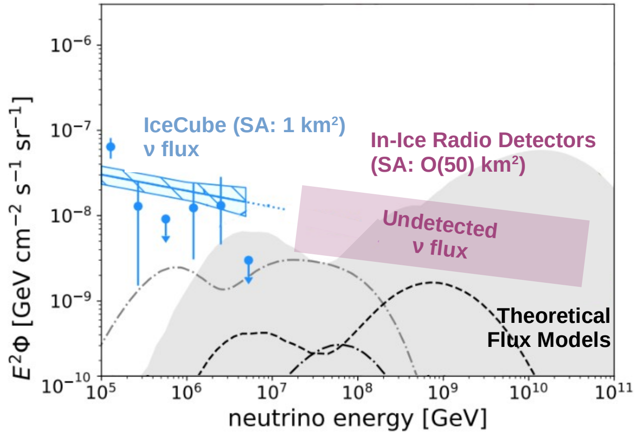
Neutrino Astronomy At Extreme Energies

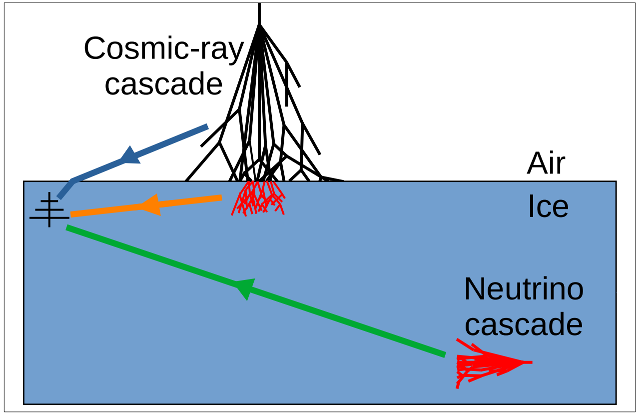
- In-ice Askaryan radio detectors are being deployed to detect & identify **the cosmic neutrino flux at the highest energy regime.**



- **Detection** of in-situ Askaryan radiation from a particle cascade will be **important proof-of-concept** for our in-ice radio detectors.

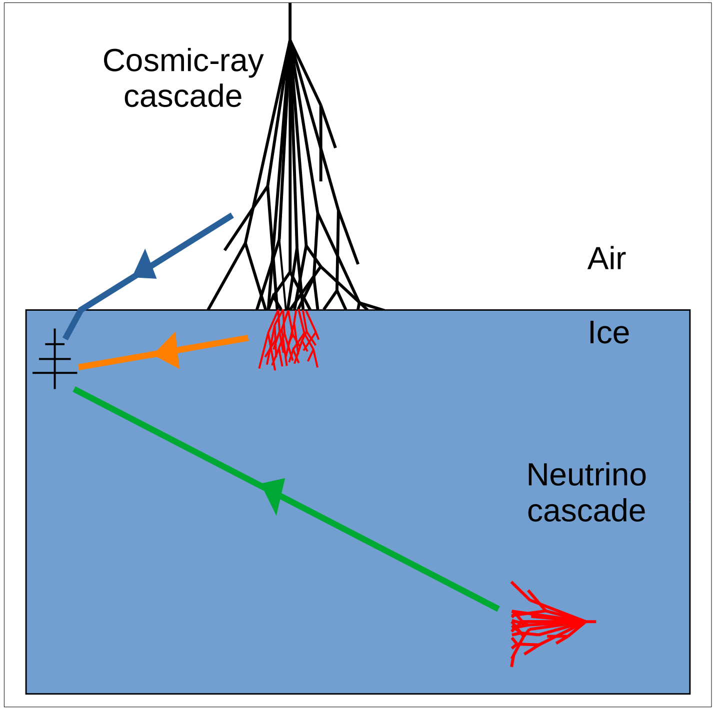
- **Radio signal from cosmic-ray** cascade → **background + calibration source** for in-ice radio detector.





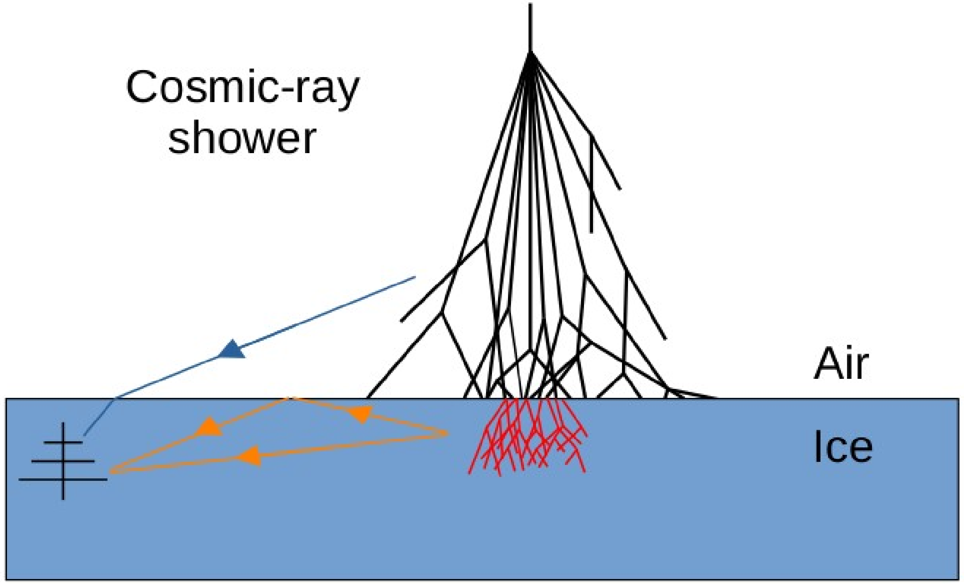
Cosmic-ray Signals In In-ice Radio Detectors

- We have **created the 1st** cosmic-ray cascade simulation that models the in-air and in-ice radio emissions.
- Will allow us to **quantify** key properties of the cosmic-ray cascade radio signal.
- Will enable us to **identify** cosmic-ray cascade radio signals in in-ice radio detector data & **distinguish** from neutrino radio signals.



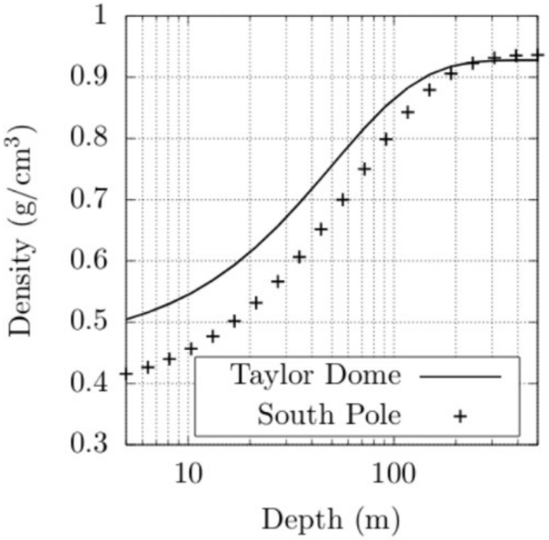
Current Status

- In-air radio emission with ray tracing ✓
- In-ice radio emission with ray tracing ✓
  - Direct (1st) and Reflected/Refracted (2nd)
- Fresnel coefficients ✓
- Focusing/defocusing factor (in-ice) ✓
- Transition radiation ("for free") ✓



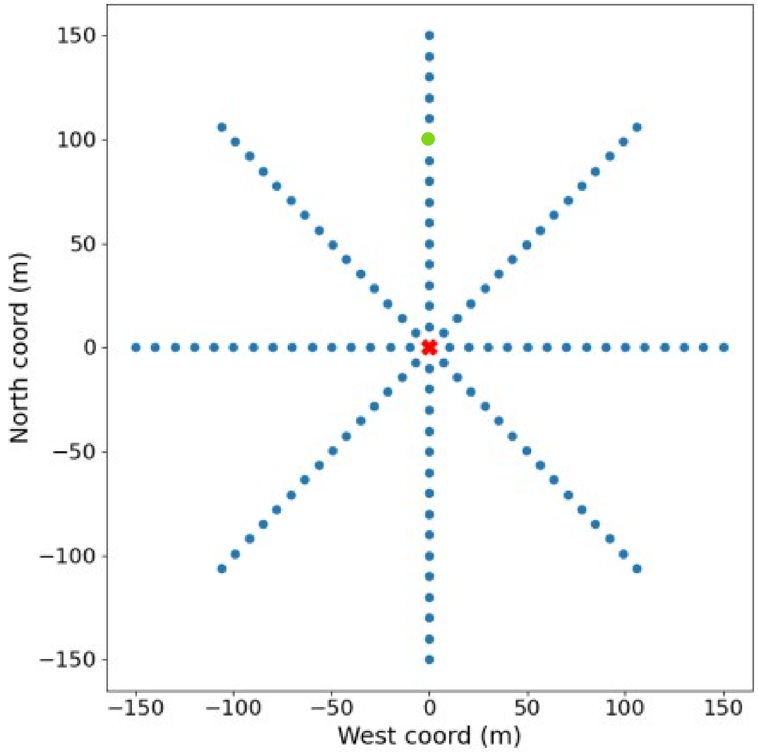
Current Configuration

- Simulation of in-air particle development using CORSIKA 7.7500 with modified CoREAS
  - Proton, Energy 1x10^{17} eV
  - QGSJETII-04 (HE), UrQMD (LE)
  - Thinning
  - Particle read-out at altitude of 2.835 km asl
- Simulation of in-ice propagation using Geant4 10.5
  - Propagation of all CORSIKA output particles within 1 m of core.
  - Using realistic ice density gradient
  - End-point formalism for radio emission

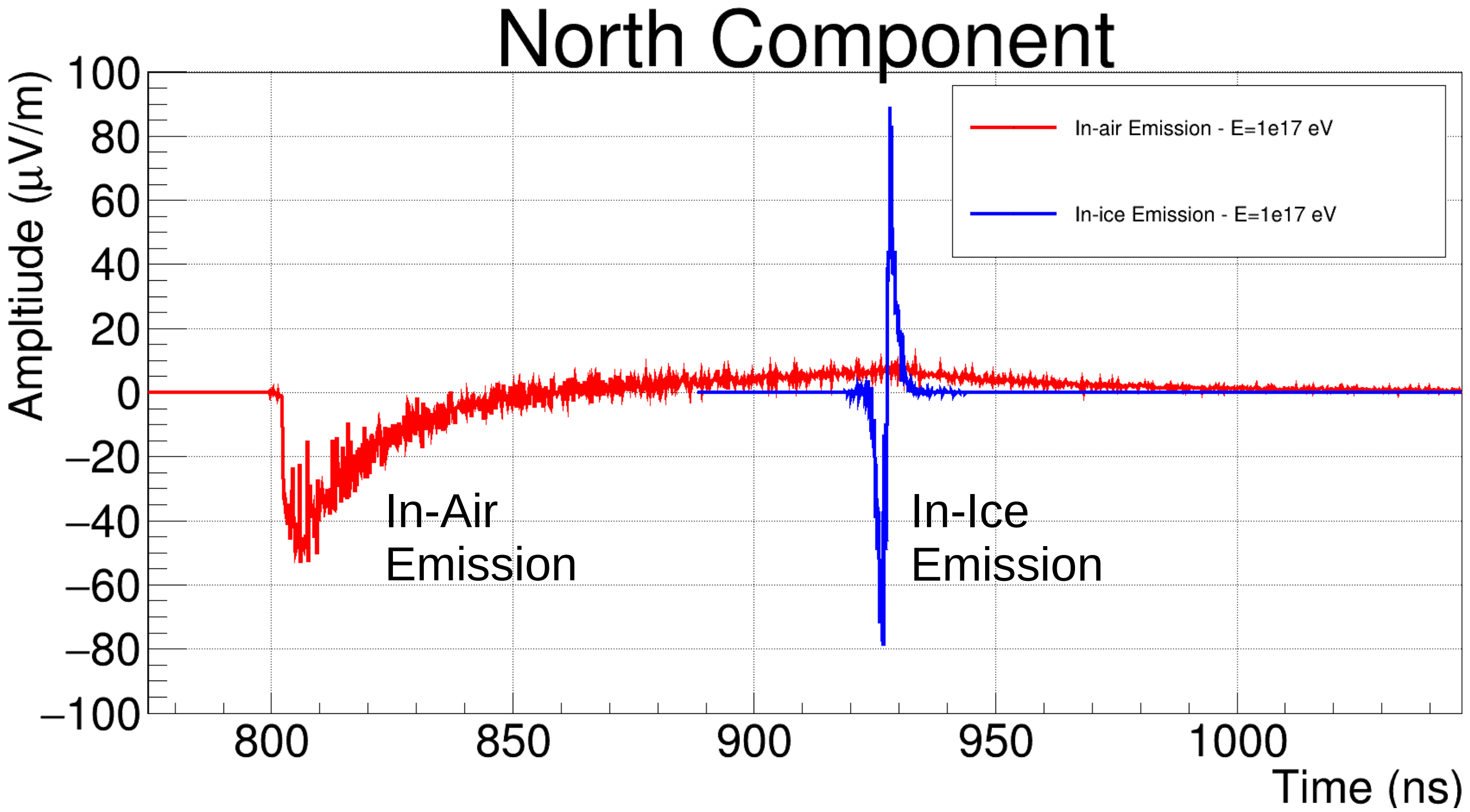


Shower Geometry

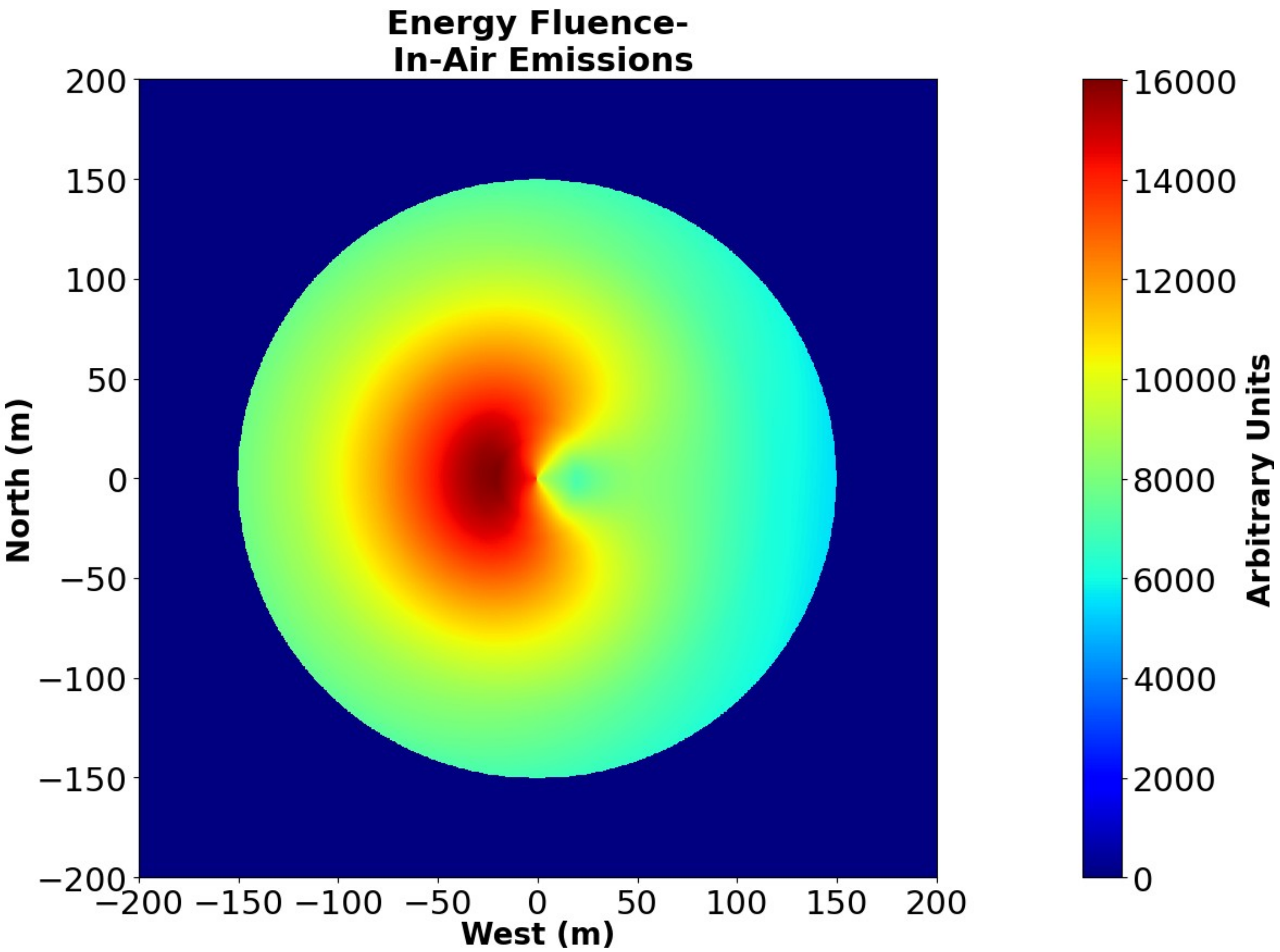
- Vertical Proton Shower at 10^{17} eV
- Ice layer at around 2.85 km a.s.l
- Antenna Star Grid at -150 m depth.
- Shower core hitting at the center of the star.



Electric Field Waveform

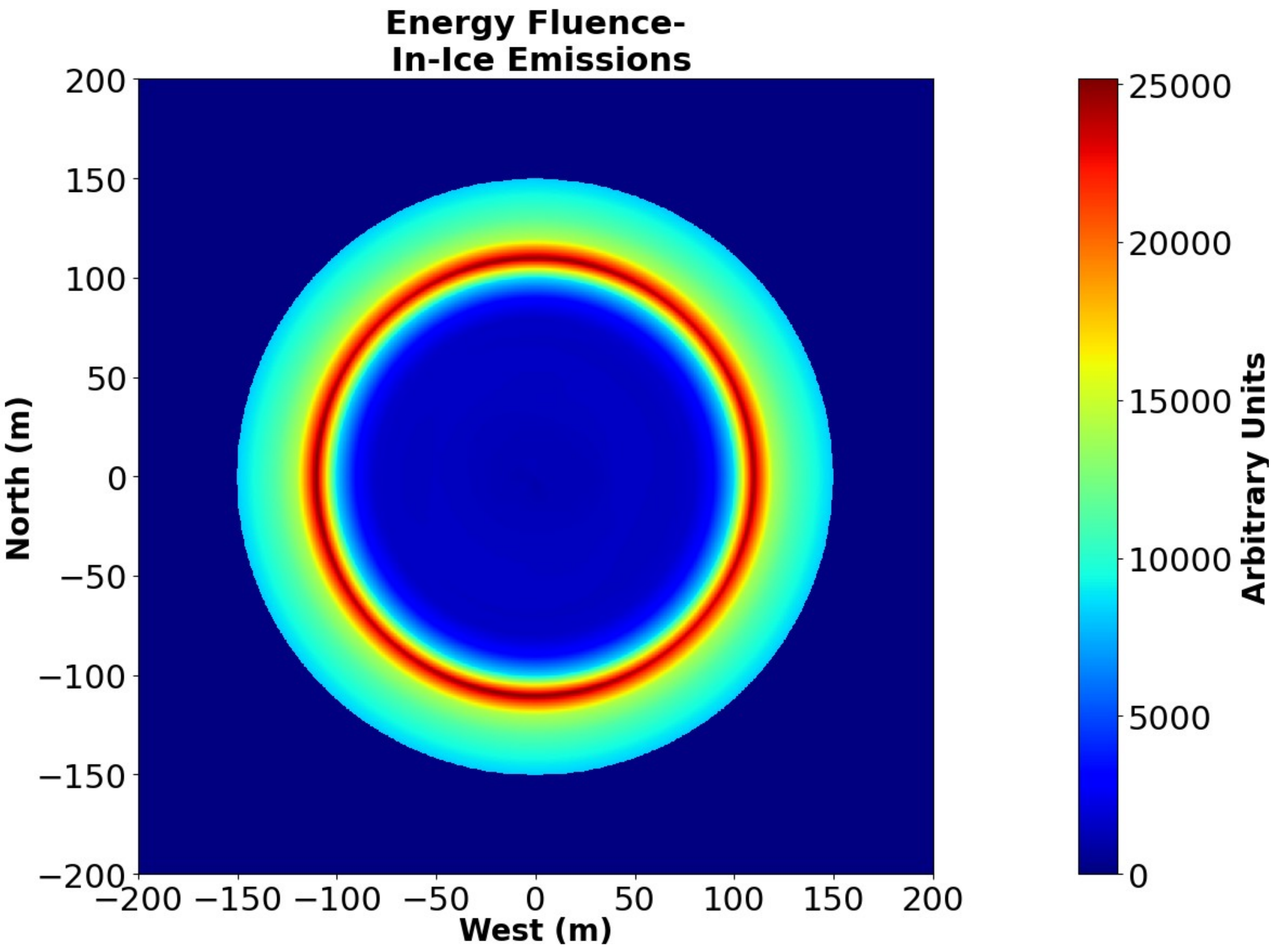


- In-air emission generates both Askayran and geomagnetic emission, interference explains the asymmetry
- Very similar to radio footprint on the surface



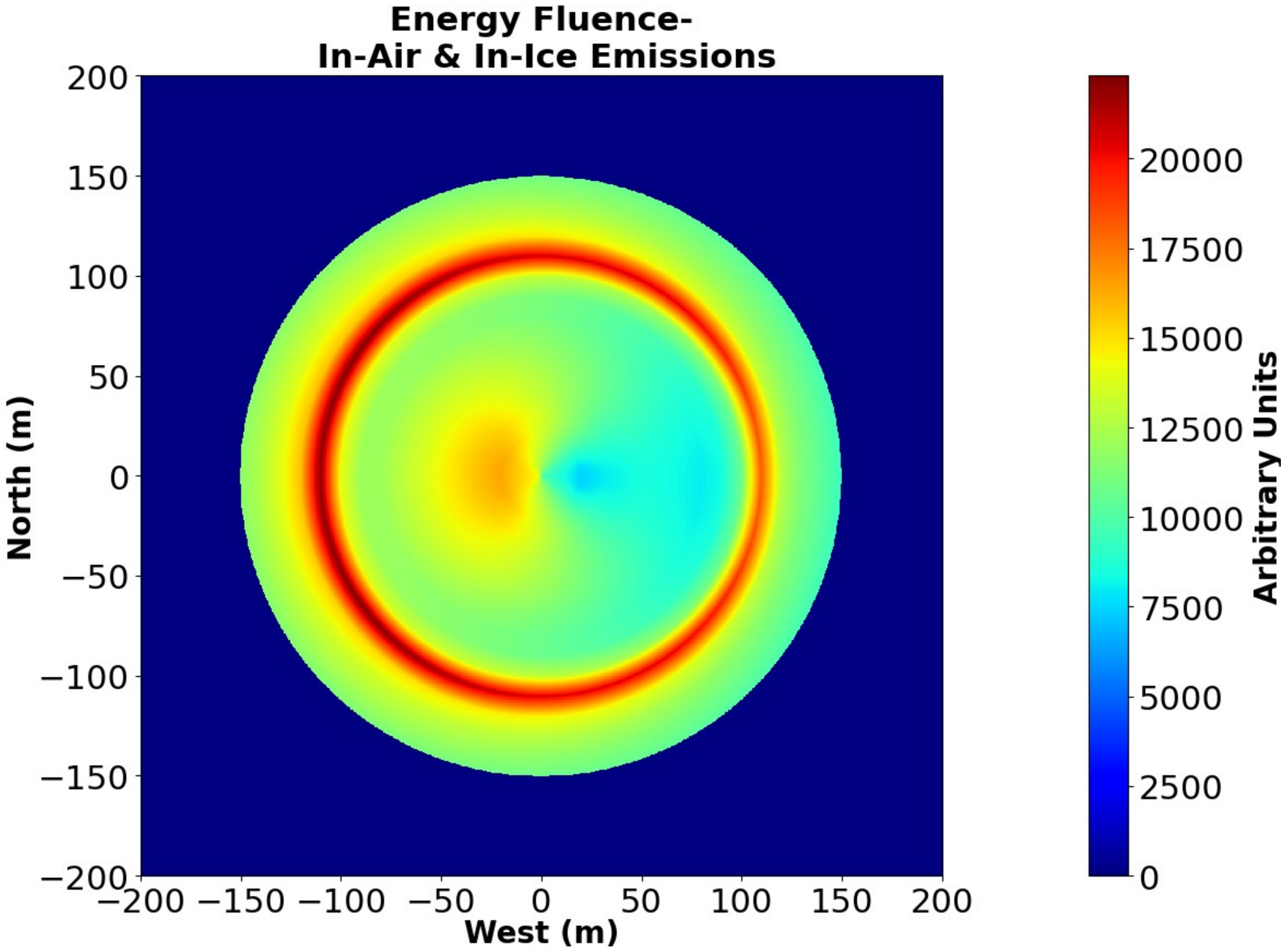
- In-ice emission only generates Askayran emission, giving a very symmetric pattern

- Cherenkov ring clearly visible, as cascade in the ice is very compact O(5 -10 m), concentrating emission in small opening angle.



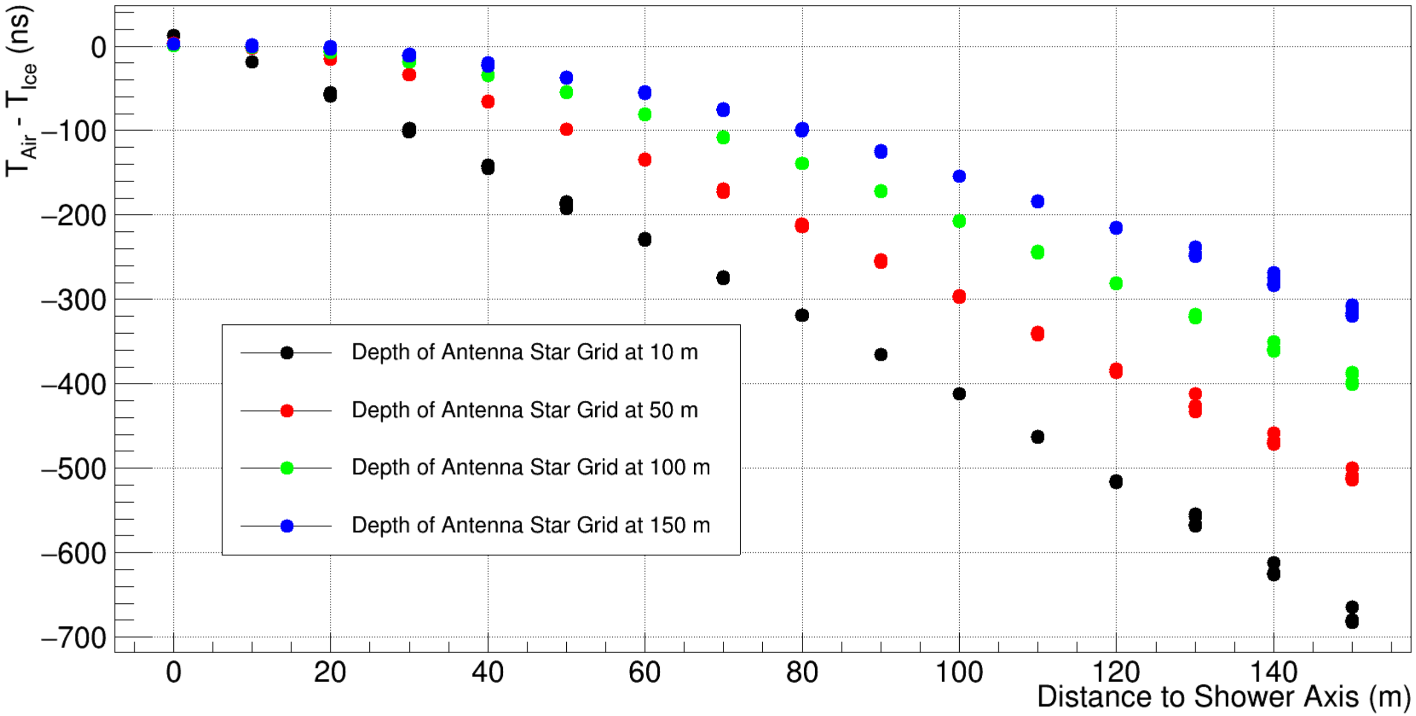
- In-air emission illuminates the center, while in-ice emission is very concentrated around its Cherenkov ring

- Slight asymmetry in ring due to interference with geomagnetic in-air emission.



Time Delay Between Air & Ice Pulses

- Time delay as a function of Antenna Star Grid and distance to shower axis.
- Is an important feature to identify cosmic ray events in data.



Conclusion

- The simulation is working well.

- Simulating more shower geometries to get a better understanding.

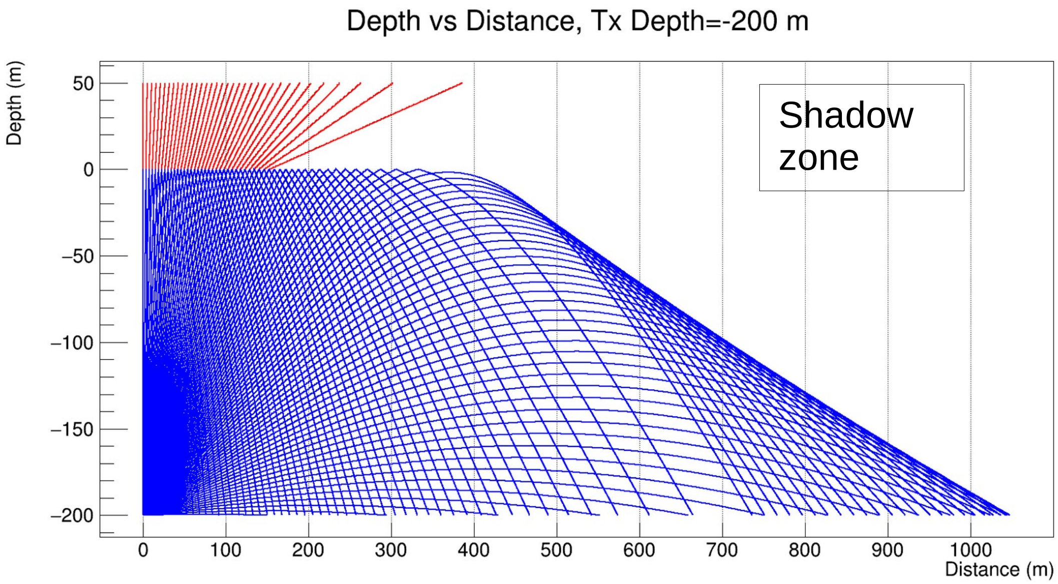
- We can start exploring ways initiating comparisons with CORSIKA 8 and also porting the framework into CORSIKA 8.

Thank you!

Raytracing

- 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 can be parametrised as:

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

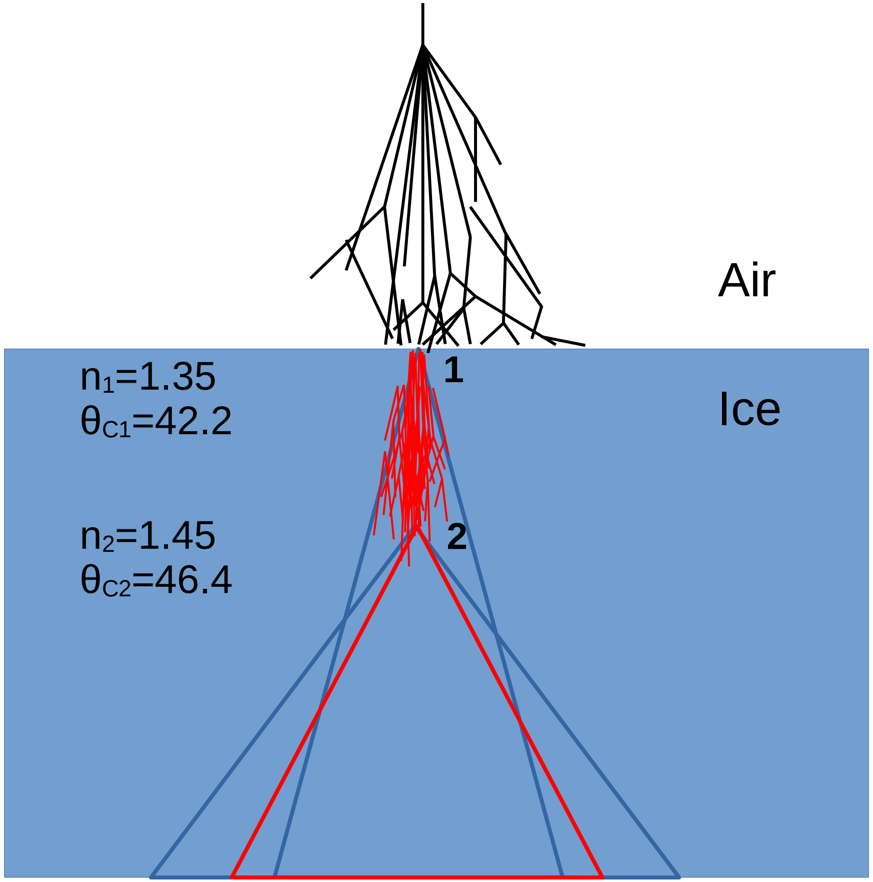


Ray paths for a source at a depth of 200 m. The bending causes the formation of 'shadow zones'.

Other details

- Raytracing implemented using interpolation
  - Helps account for non-linear refractive index profiles
- Focusing factor formula taken from NuRadioMC
  - Limited to a maximum of 2

Spread of In-Ice Cherenkov Cone



"Adding" Raytracing to CoREAS

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

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

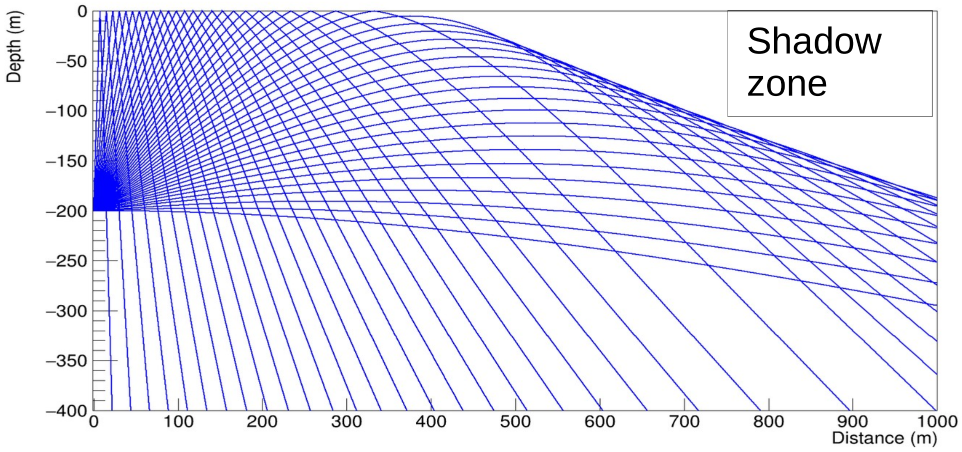
- In this formula, I use the following raytracing parameters:
  - Launch angles as the dot product angle
  - Geometrical path length of the ray for the value R
  - The value of n is taken to be n at the emission point.

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.

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

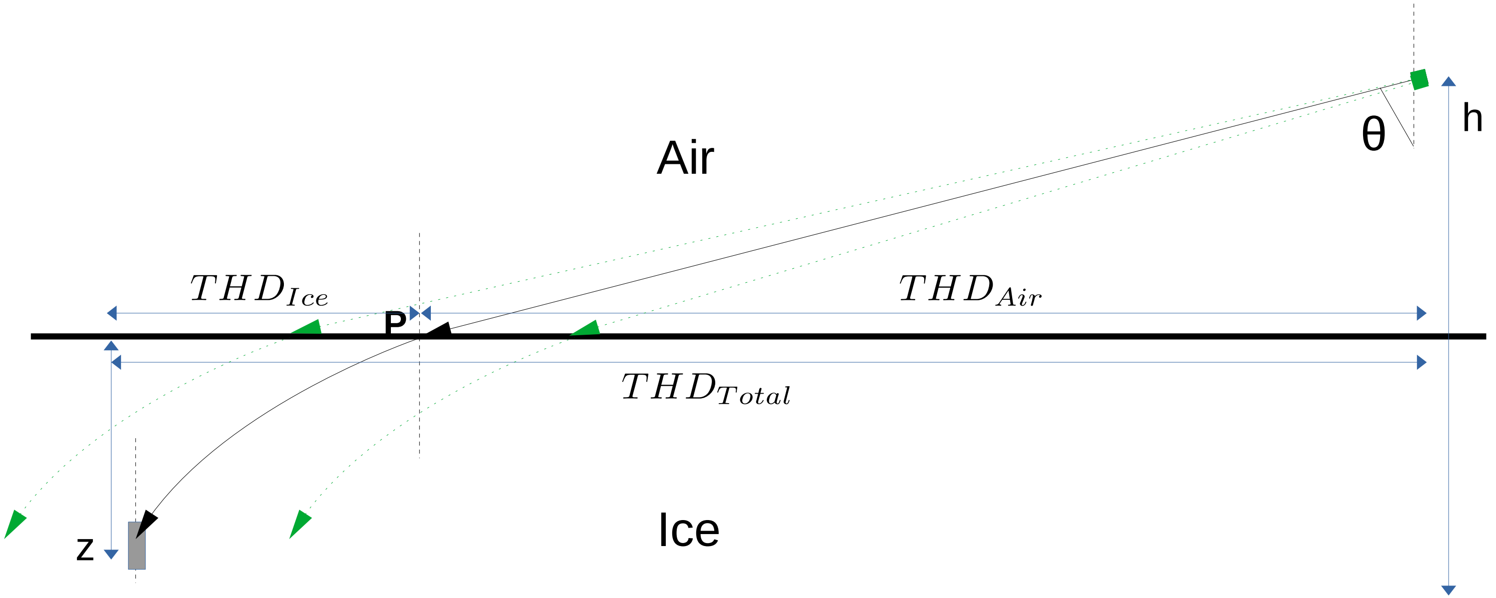
Launching Rays from Air to Ice

- 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

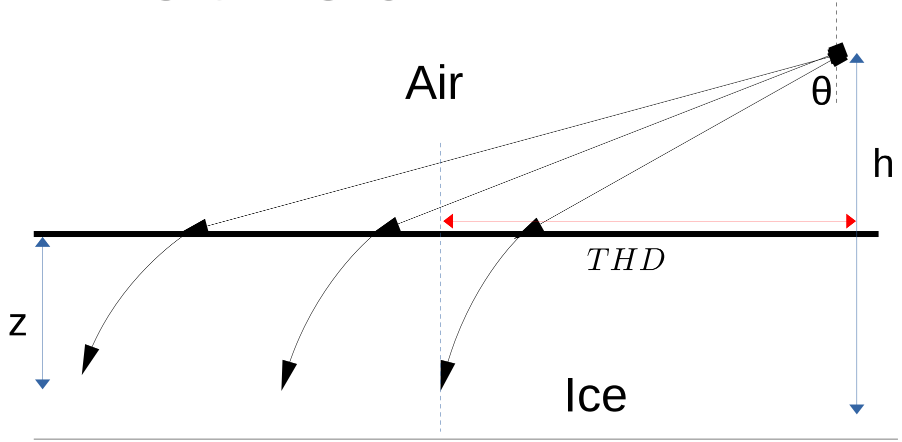
- So a typical raytracing call involving air and ice takes around 0.05 to 0.1 ms.
  - Currently making the atmosphere takes around 22 ms.

- 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.

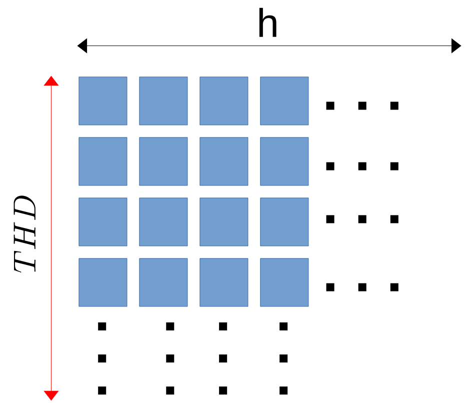
- Therefore, we have to move towards interpolation.

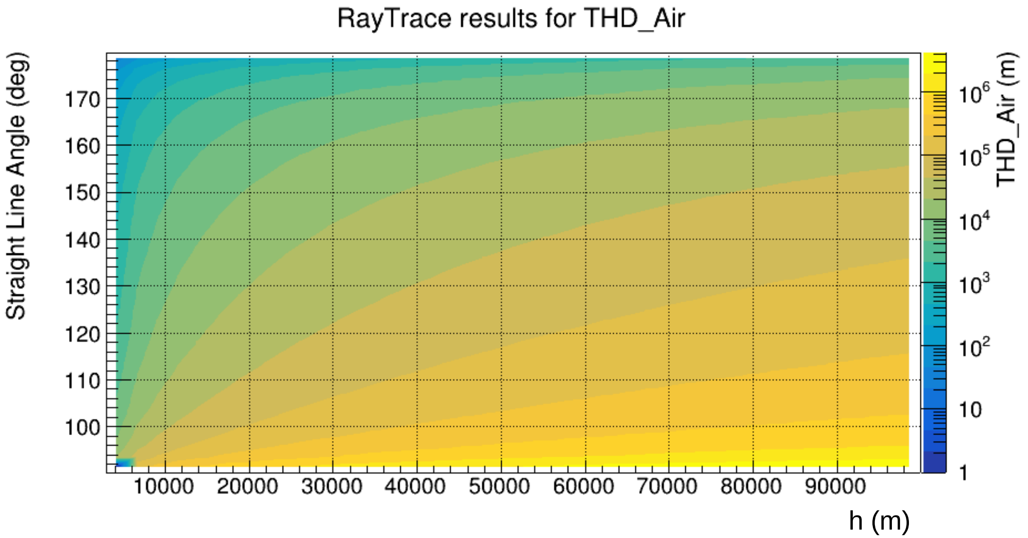
Interpolation Method

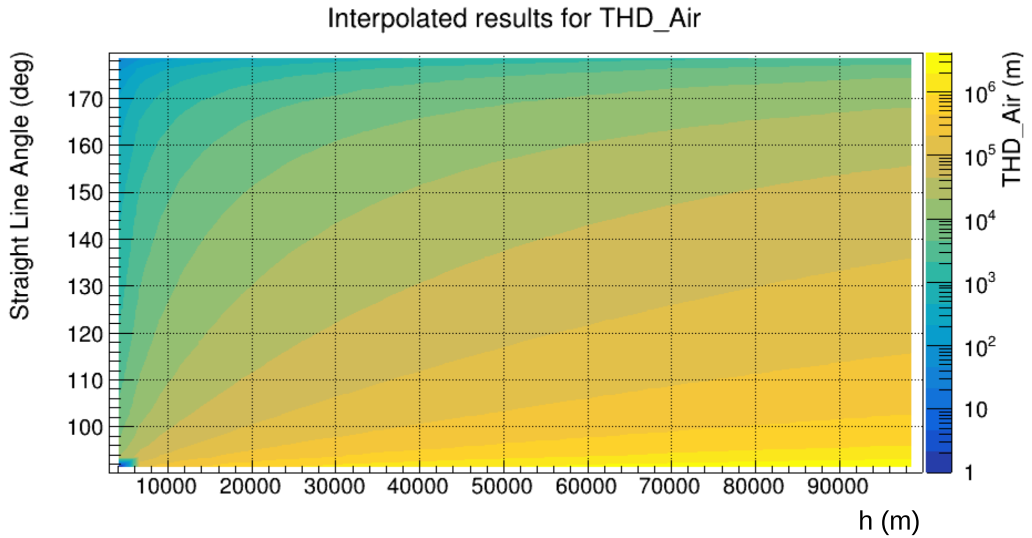
- For a given antenna depth I make 2-D grid of:
  - THD (Total Horizontal Distance)
  - The altitude of the in-air transmitter
- For each grid position I do analytic raytracing and store:
  - The initial launch angle of the ray
  - The total optical path length of the ray in air and in ice
  - The horizontal 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.

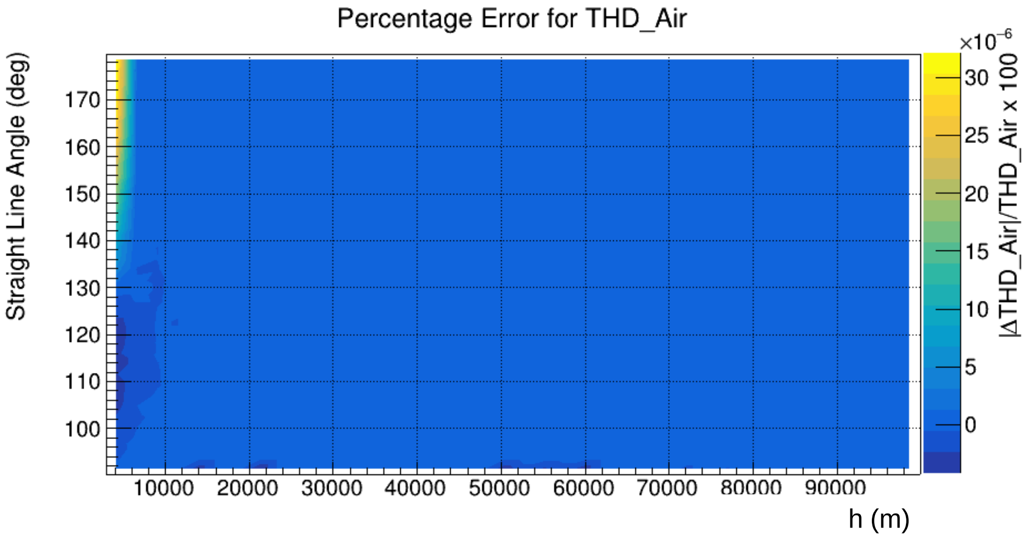


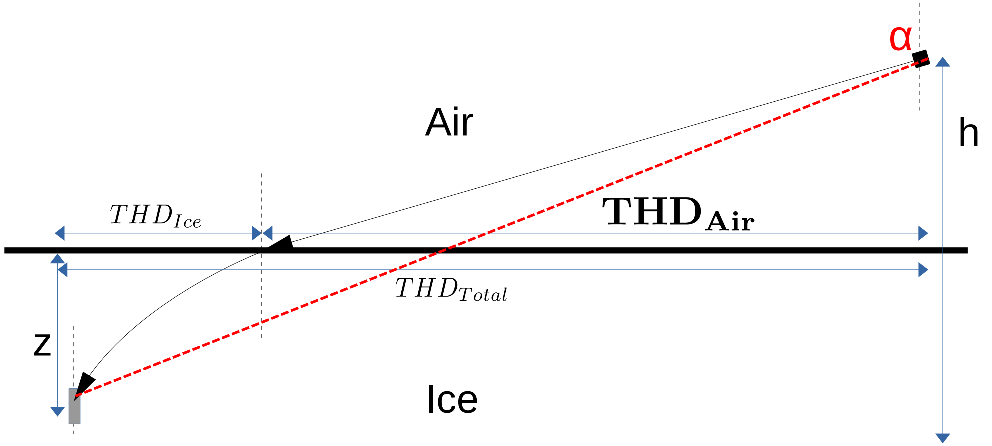
2-D Interpolation Grid

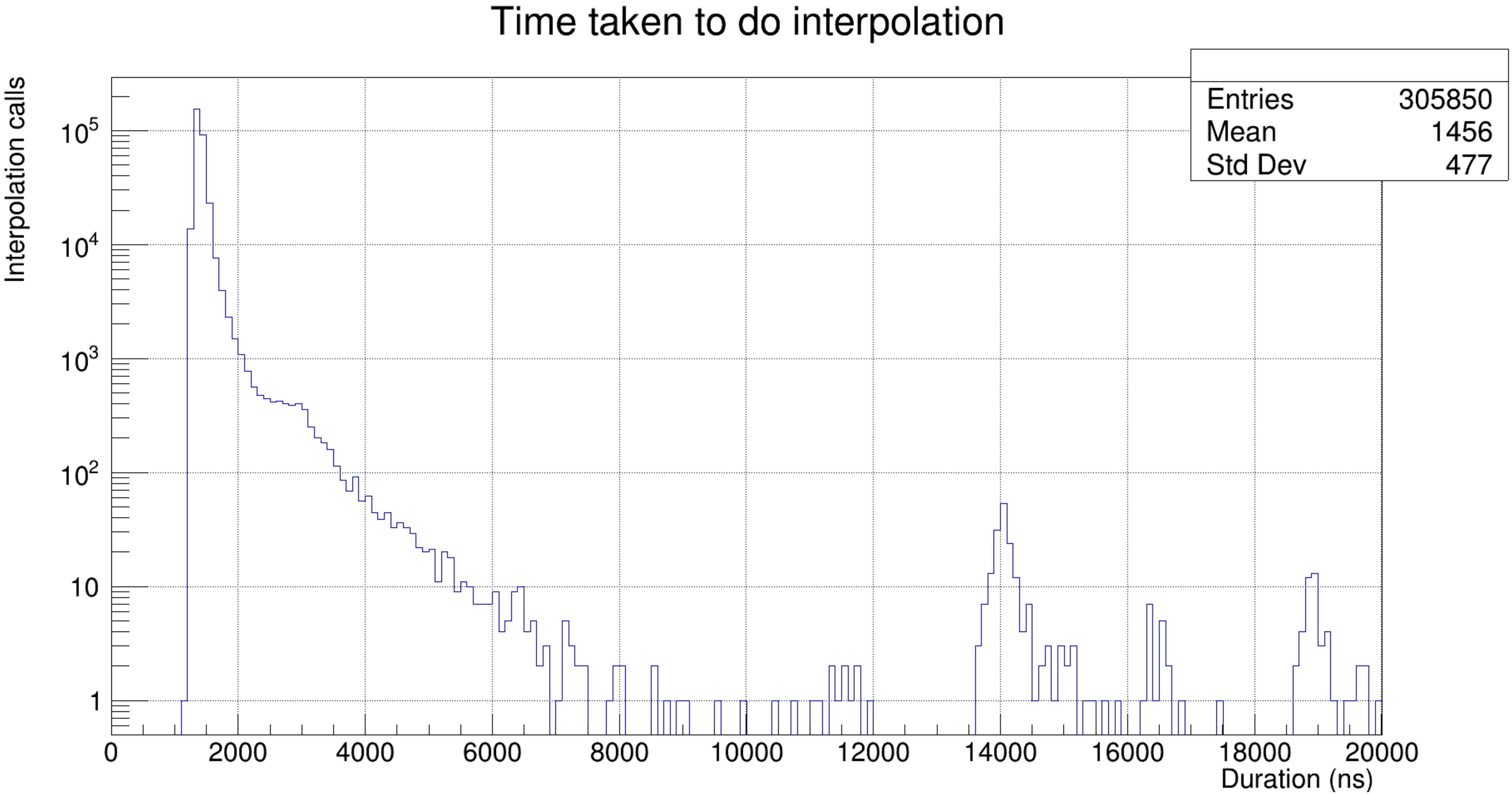



RayTrace results for THD_Air
Straight Line Angle (deg)
h (m)
THD_Air (m)


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

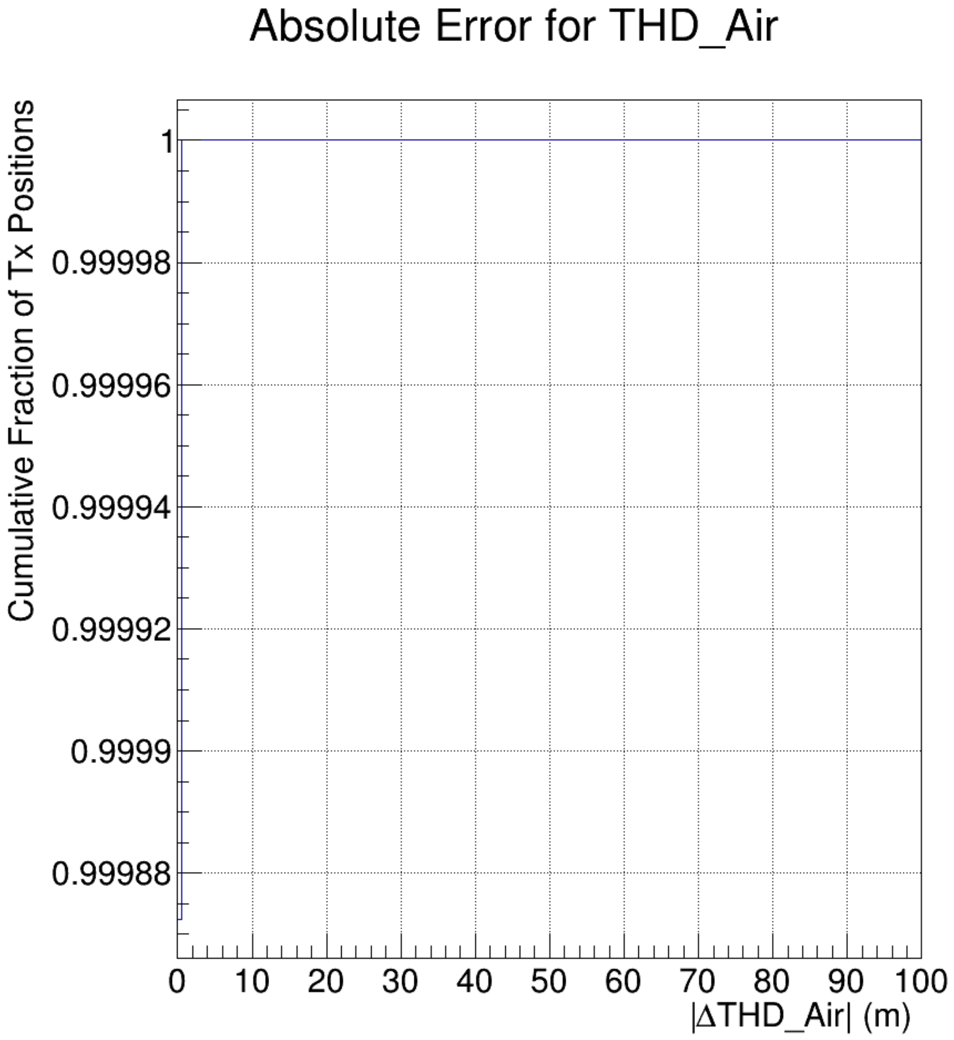

Percentage Error for THD_Air
Straight Line Angle (deg)
h (m)
|ΔTHD_Air|/THD_Air x 100

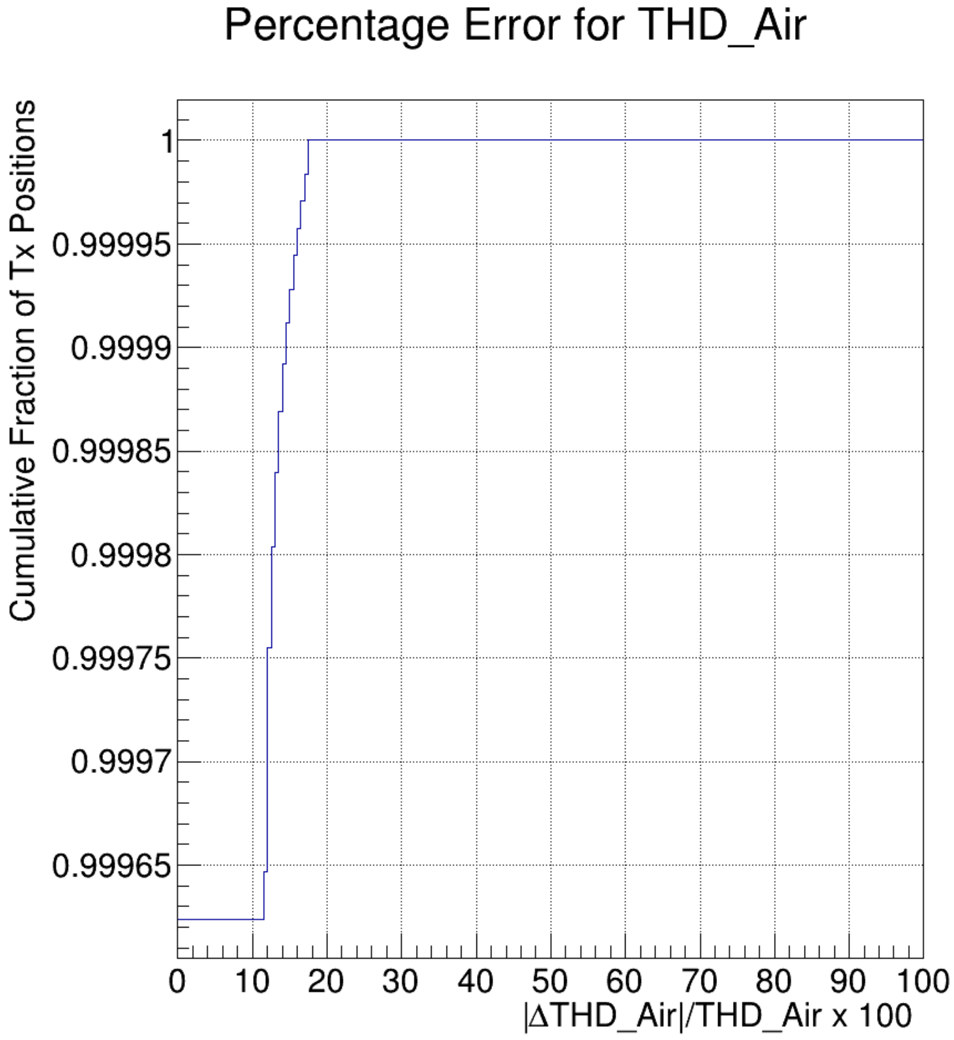

α
Air
h
THD_Ice
THD_Air
THD_Total
z
Ice


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)

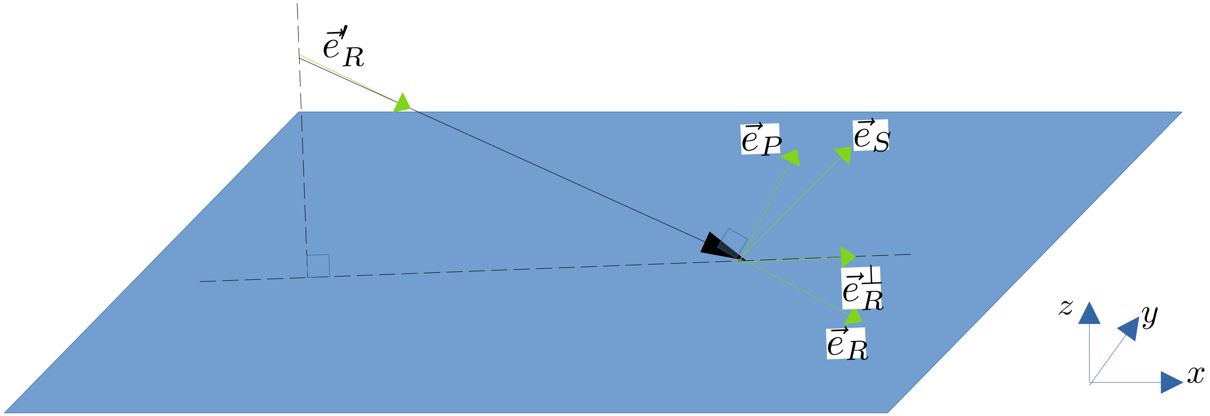
Interpolation Method

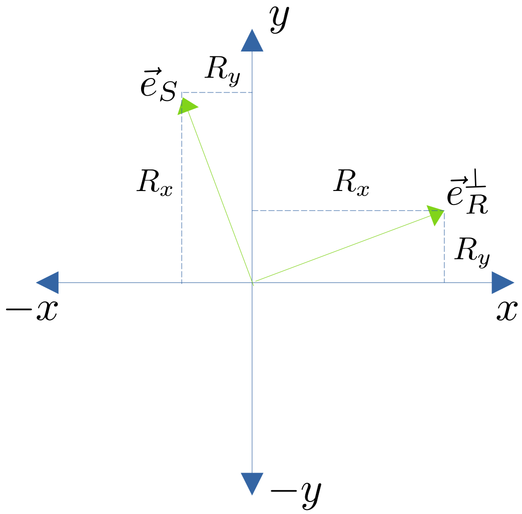
- θ (or the launch angle) has a step size of 0.1 deg and h has a step size of 10 m.
  - θ starts off at 90.1 deg and ends at 180.0 deg.
  - h starts off at 3000 m (the ice layer altitude) and ends at 100000 m.
- If the antenna depth changes we will need to make another 2-D grid for that.
- It takes around 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

Fresnel Coefficient calculation





$$\vec{e}_R = (R_x, R_y, R_z) \quad (1)$$

$$\vec{e}_P = (P_x, P_y, P_z) \quad (2)$$

$$\vec{e}_S = (S_x, S_y, 0) \quad (3)$$

$$\vec{e}_R^{\perp} = (R_x, R_y, 0).\frac{1}{\sqrt{R_x^2 + R_y^2}} \quad (4)$$

$\vec{e}_S \perp \vec{e}_R^{\perp}$ in the x-y plane

$$\vec{e}_S = (-R_y, R_x, 0).\frac{1}{\sqrt{R_x^2 + R_y^2}}$$

$\vec{e}_R =$ unit incidence vector

$\vec{e}_R' =$ unit launch vector

$\vec{e}_P \perp \vec{e}_R \perp \vec{e}_S$

$$\Rightarrow \vec{e}_P = \vec{e}_R \times \vec{e}_S = \begin{vmatrix} \hat{x} & -\hat{y} & \hat{z} \\ R_x & R_y & R_z \\ -Ry & R_x & 0 \end{vmatrix} . \frac{1}{\sqrt{R_x^2 + R_y^2}}$$

$$\Rightarrow \vec{e}_P = \frac{1}{\sqrt{R_x^2 + R_y^2}} [-R_z R_x \hat{x} - R_z R_y \hat{y} + (R_x^2 + R_y^2)\hat{z}]$$

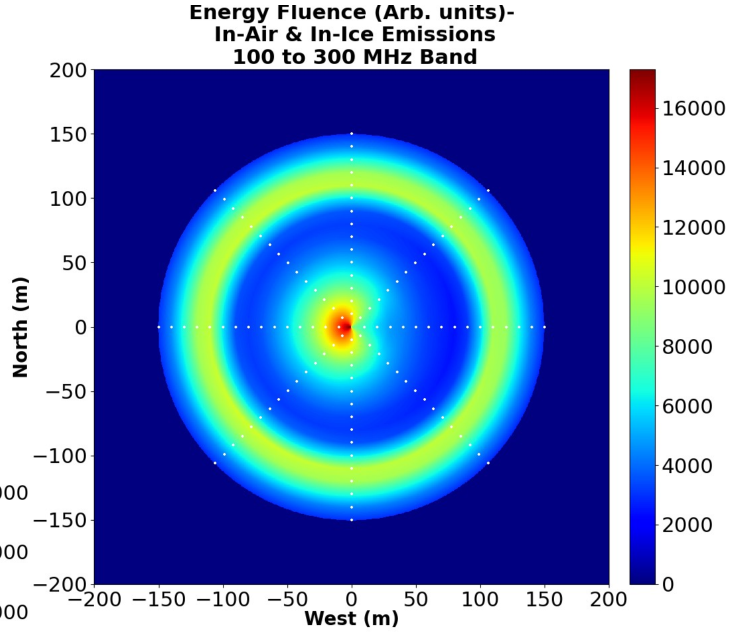
So effectively we have described the S and P vectors in terms of the vector of incidence.

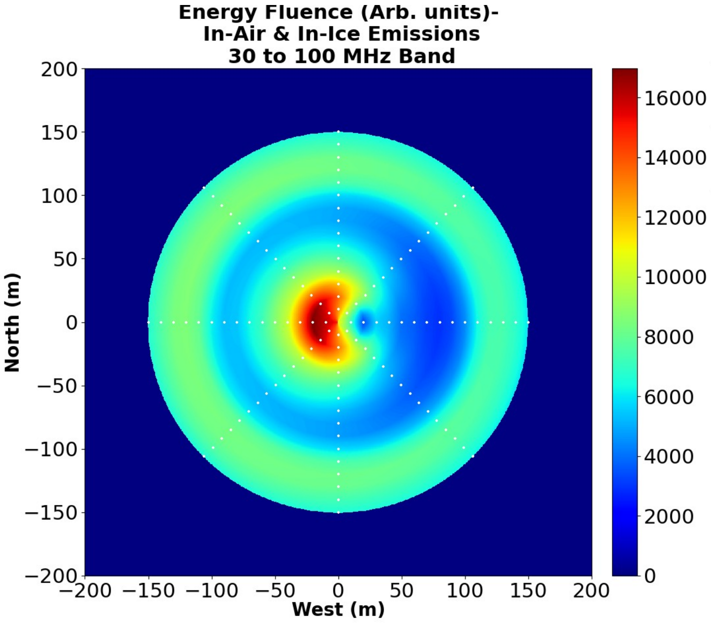
So in order to apply Fresnel Coefficients to E-fields we will do:

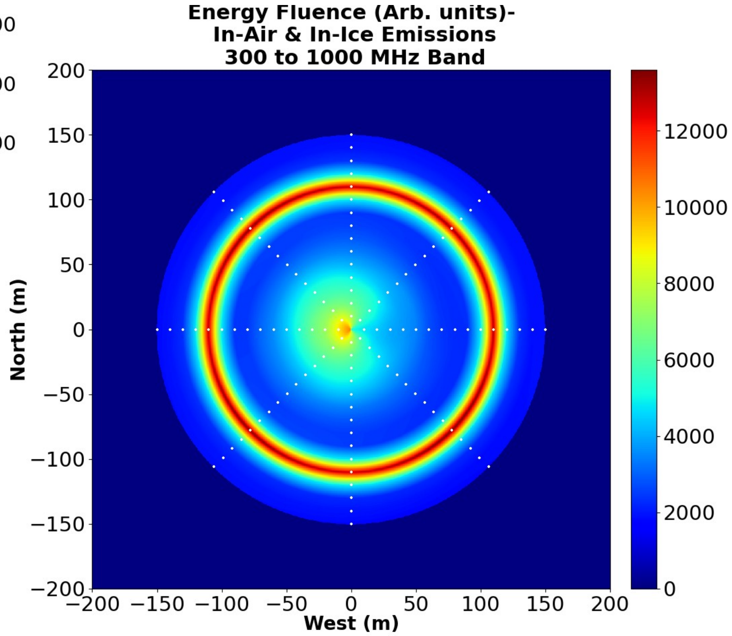
$$E_s = \vec{E}.\vec{e}_S \rightarrow E'_s \quad (1)$$

$$E_p = \vec{E}.\vec{e}_P \rightarrow E'_p \quad (2)$$

The Radio Footprint In Varying Radio Bands

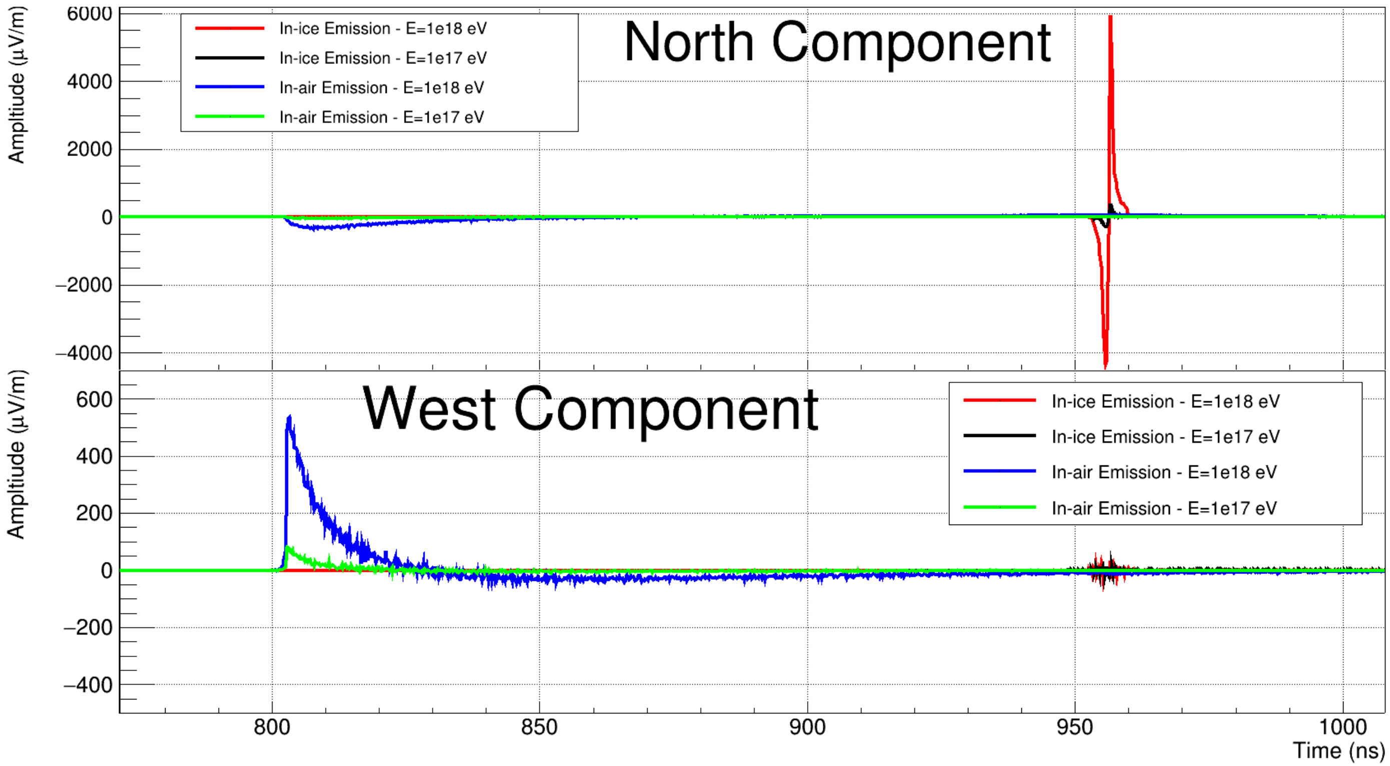




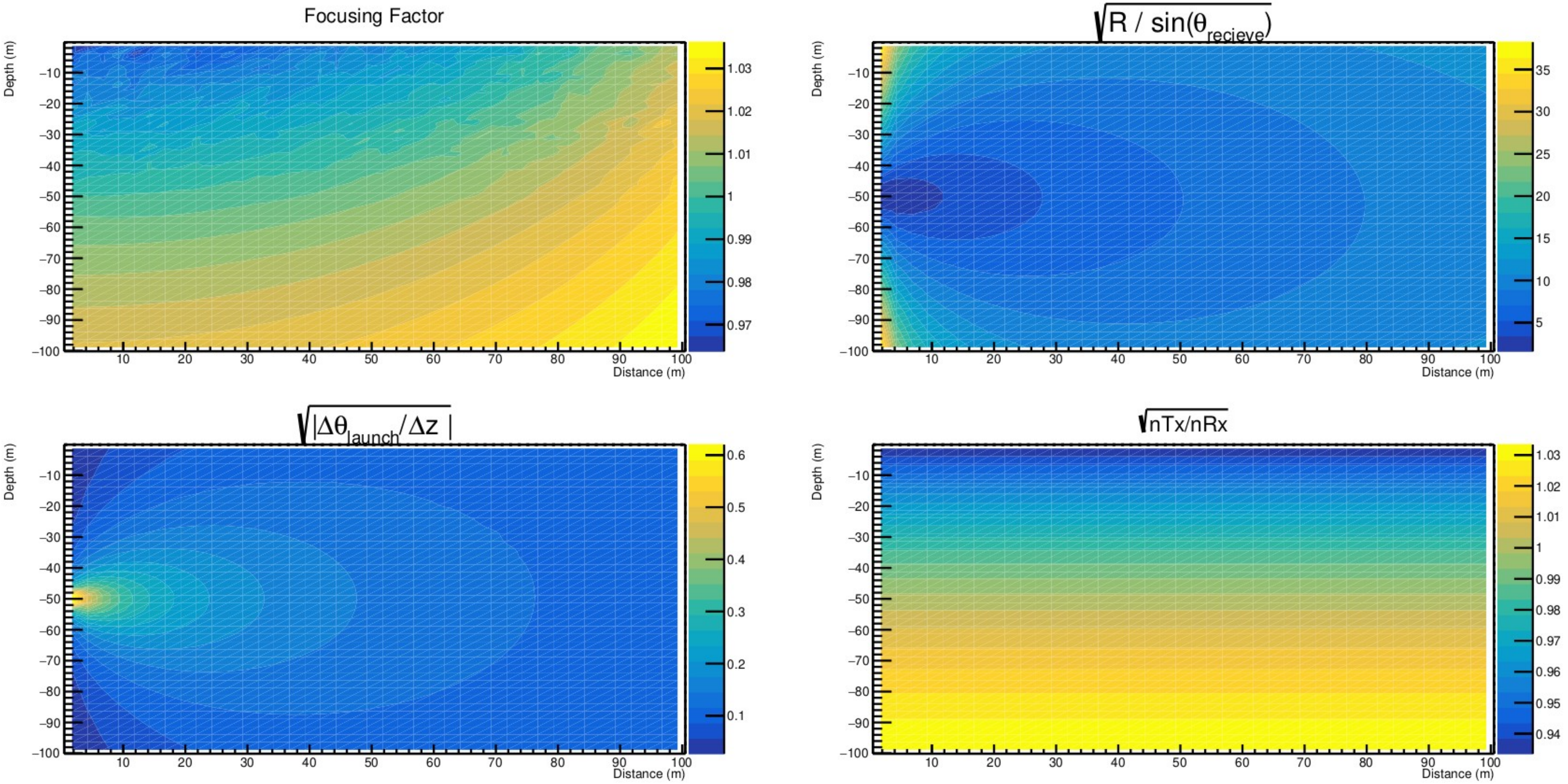


Energy Scaling

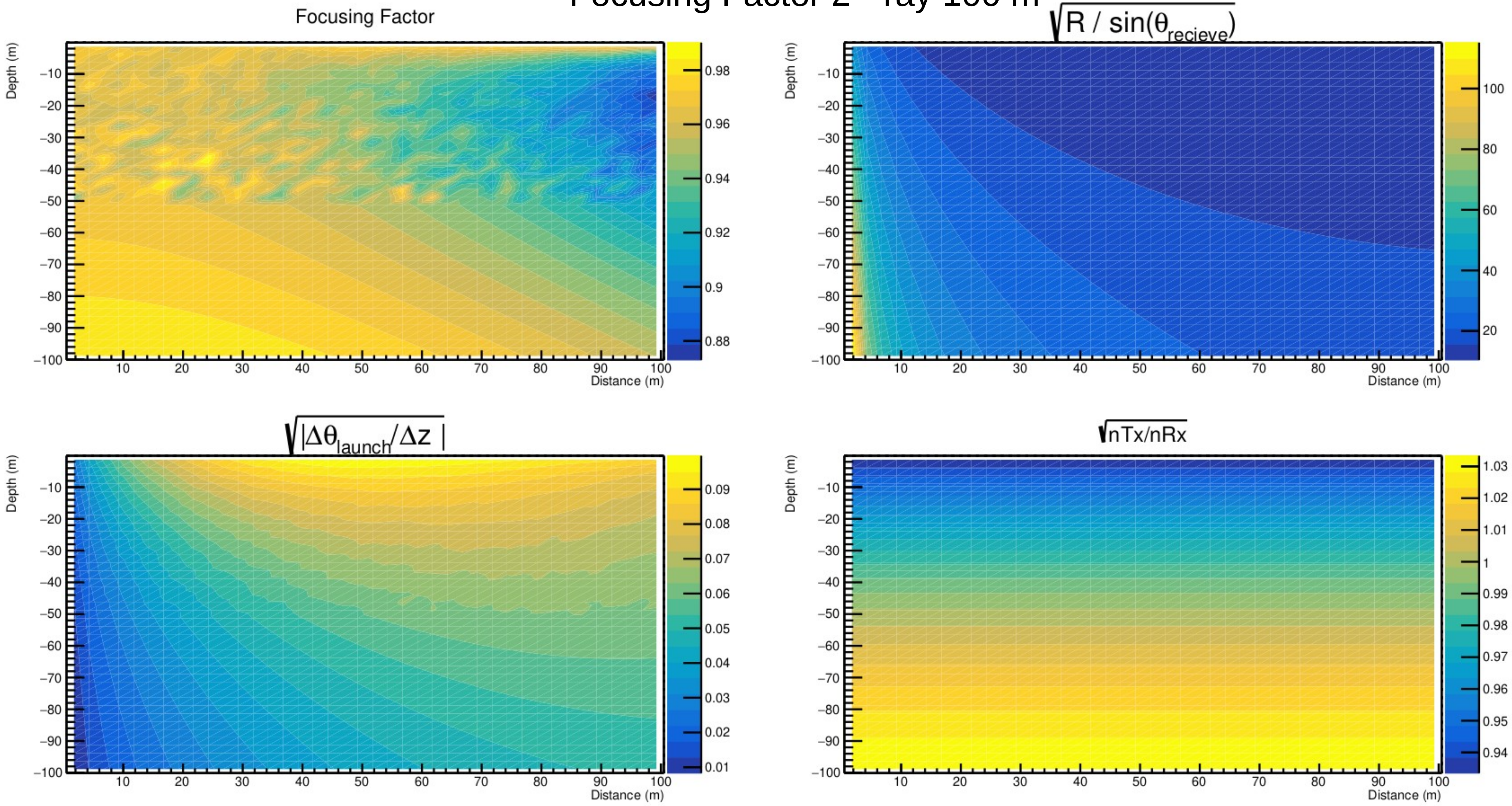
- The in-ice and in-air radio signal amplitudes scale linearly with the energy of the primary cosmic ray particle.
- Here we see a 10x increase in amplitude for 1e18 eV shower as compared to 1e17 eV shower.



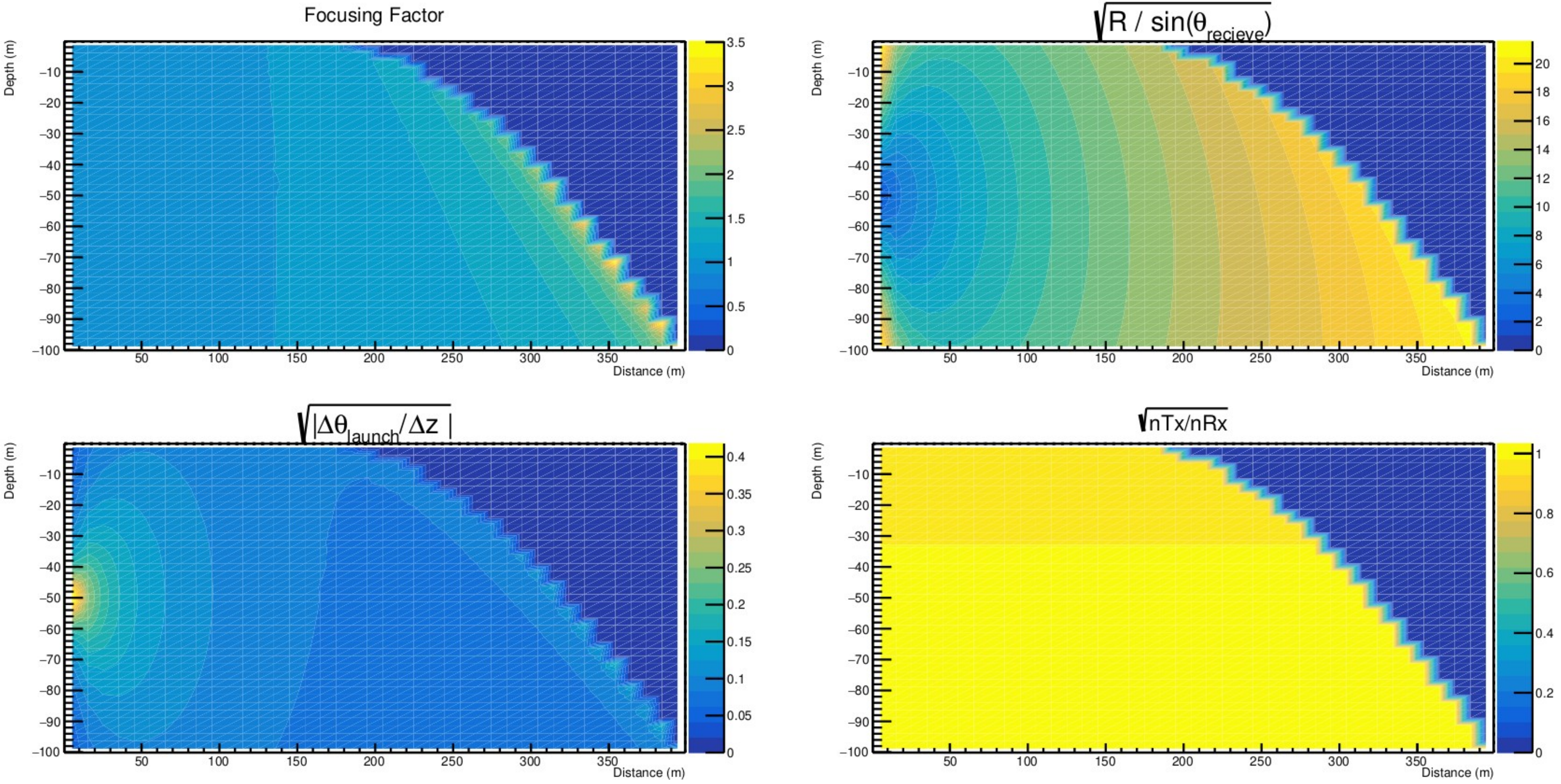
Focusing Factor 1st ray 100 m



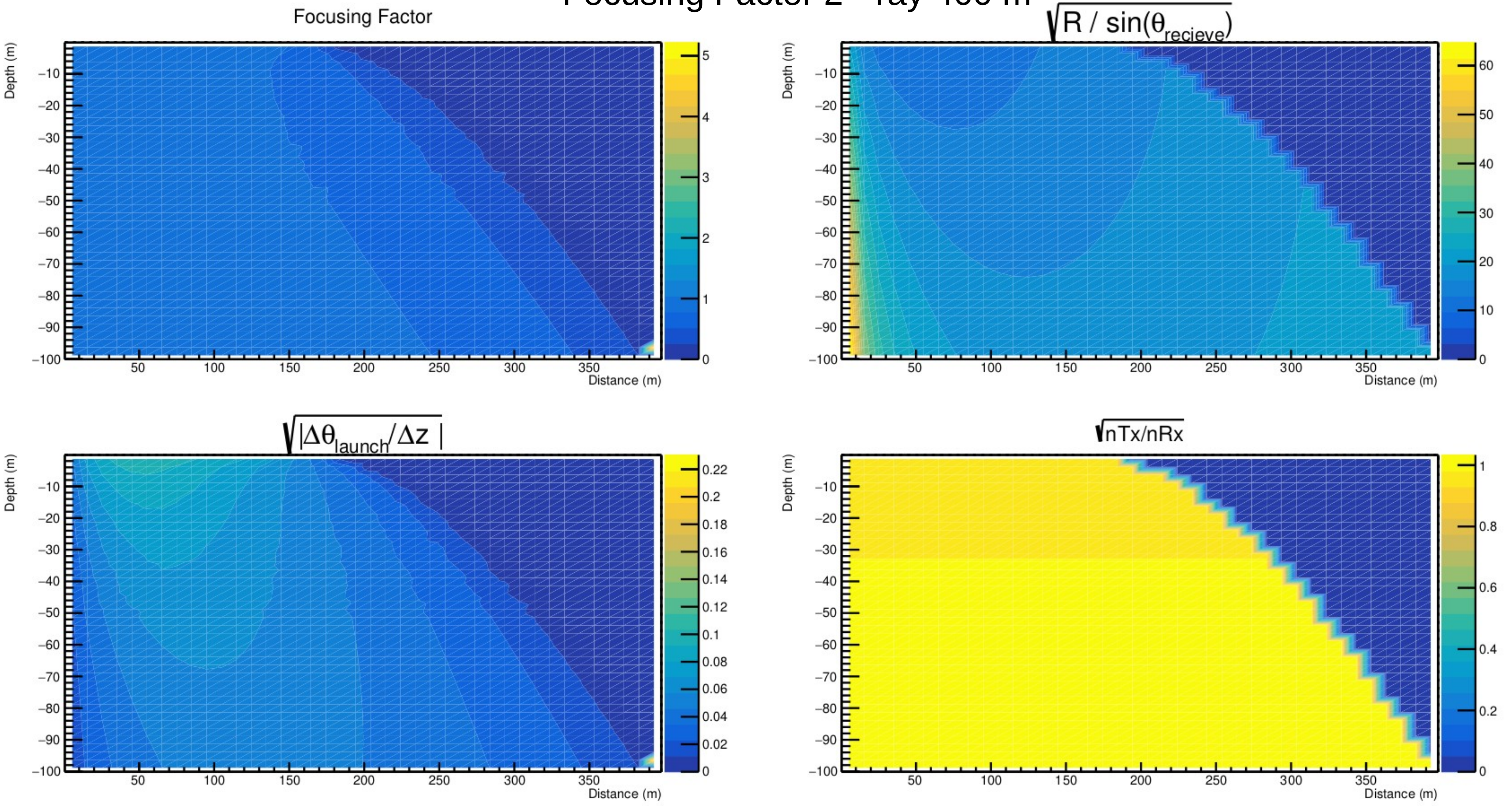
Focusing Factor 2nd ray 100 m



Focusing Factor 1st ray 400 m



Focusing Factor 2nd ray 400 m



WHY DOES THE BOOSTFACTOR MATTER?

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

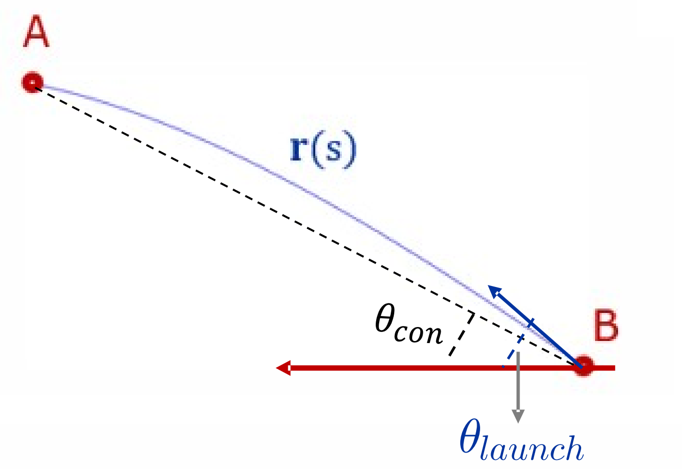
$$\vec{E}_{\pm}(\vec{x},t) = \pm \frac{1}{\Delta t}\frac{q}{c}\left(\frac{\hat{r}\times[\hat{r}\times\vec{\beta}^{*}]}{(1-n\vec{\beta}^{*}\cdot\hat{r})R}\right)$$

$(1-n\vec{\beta}^{*}\cdot\hat{r}) \rightarrow Boost\,factor^{-1}$

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