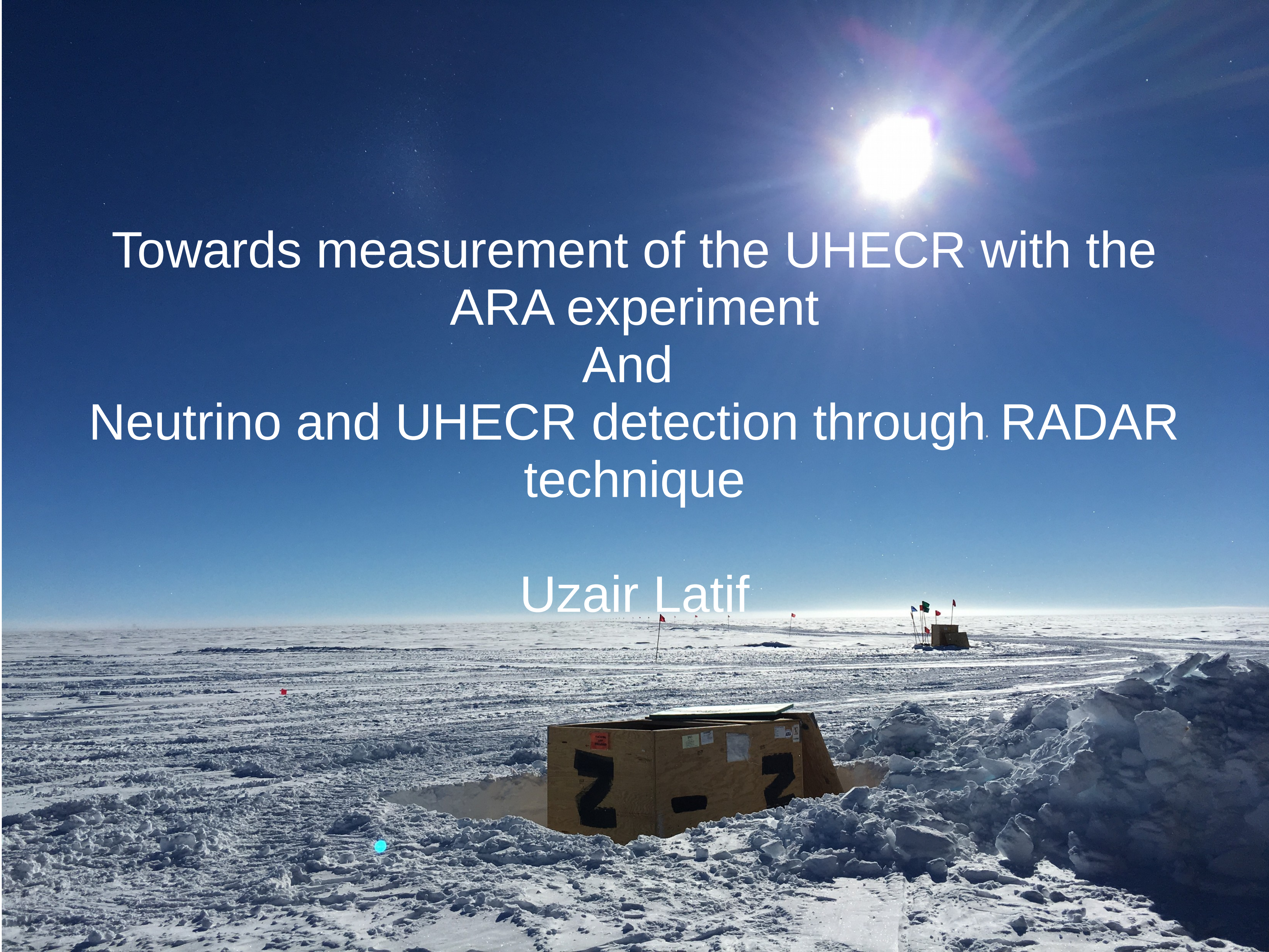
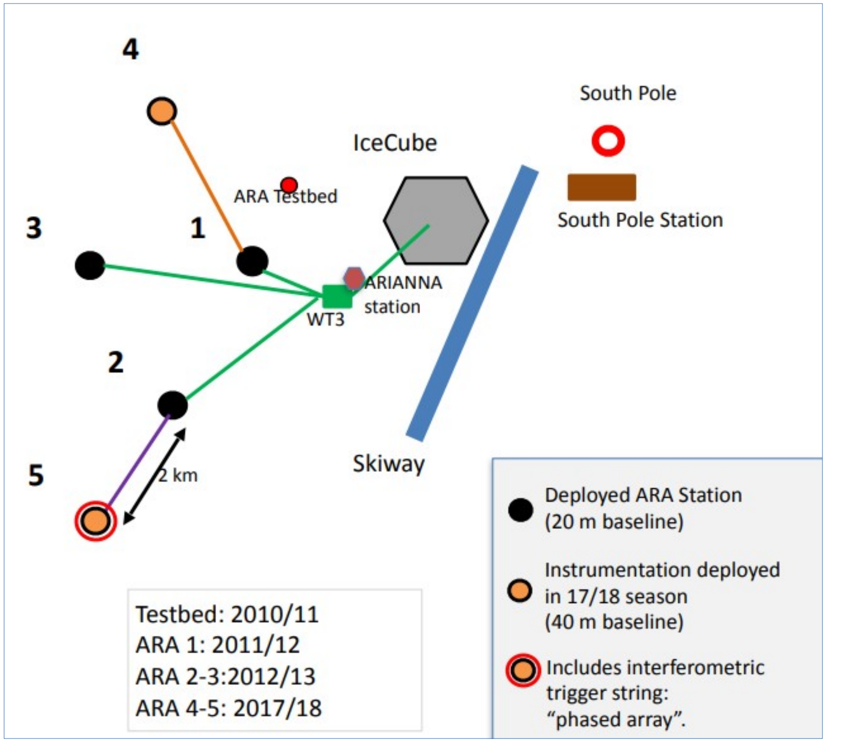
Towards measurement of the UHECR with the ARA experiment
And
Neutrino and UHECR detection through RADAR technique

Uzair Latif

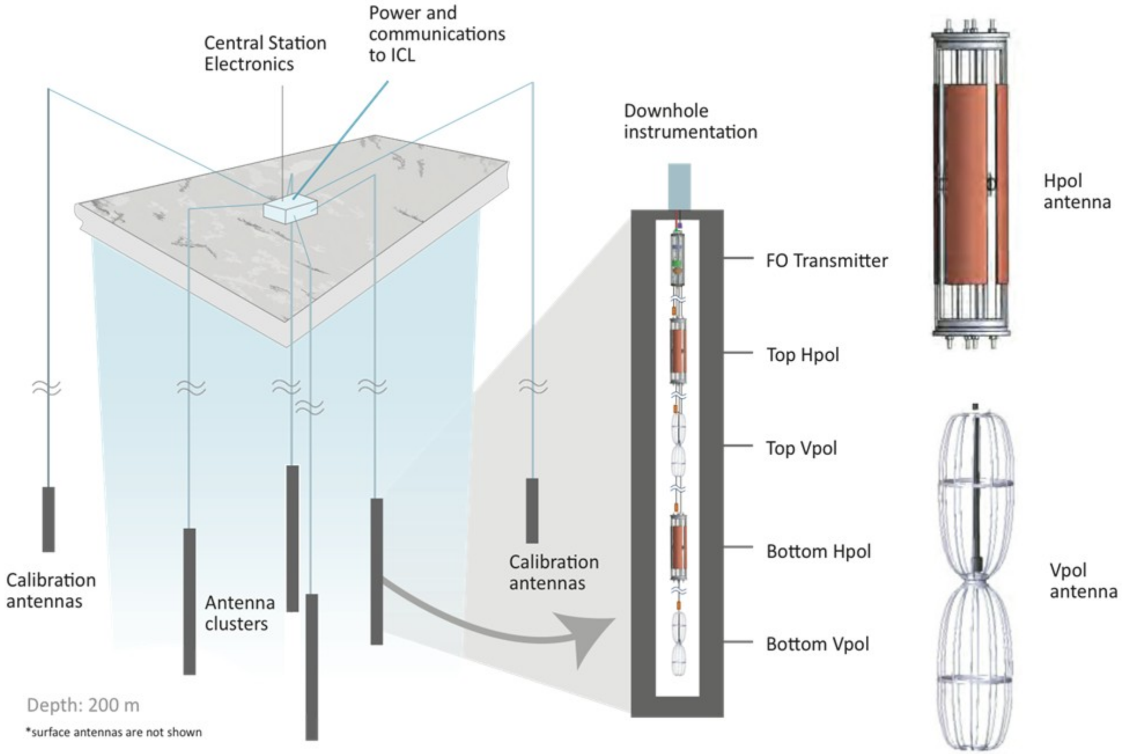


ARA & UHECR

- I have been primarily working for Askaryan Radio Array for the last 3 years.
  - Planned Hexagonal Array of 37 stations in the ice sheet 200 m deep (Area: O(100 km^2)).
  - 5 of 37 planned stations currently deployed plus ARA testbed.
  - Bandwidth: 150 to 850 MHz
  - Aims to detect GZK neutrinos using Askaryan emission from neutrino showers in ice:
    - <1 in 10 months of livetime for ARA37
- Ultra-High Energy Cosmic rays
  - CRs with energy >PeV
  - Initiate air showers which cause radio emissions that serve as a background for ARA
  - Sources are still not well known.



Current configuration of ARA stations at the South Pole

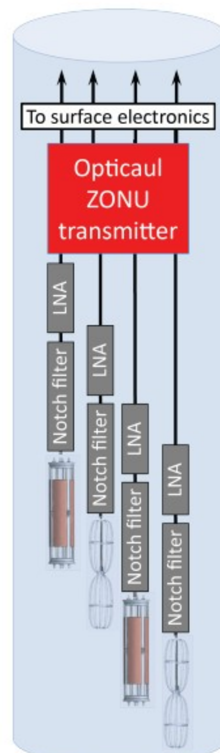


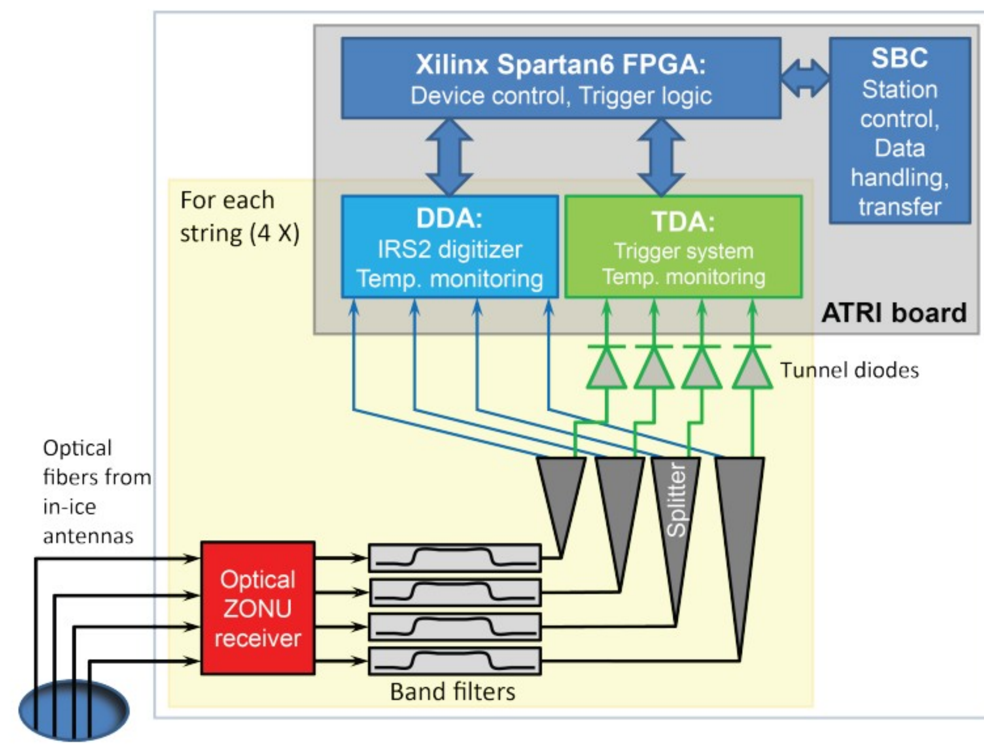
ARA station layout

- 4 strings with 4 antennas in each
  - 2 Hpol, 2 Vpol
- 2 cal. pulser strings
- DAQ box in the center

ARA signal chain

- Notch filter at 450 MHz to cut SP radio comm.
- RFoF takes signal to the surface from the antenna.
- Trigger condition: 3 of 8 of one pol. in 170 ns.
- 80 dB of amplification in total





CoREAS simulation

- CoREAS (CORSIKA-based Radio Emission from Air Showers) is a Monte Carlo code for the simulation of radio emission from extensive air showers.

- Implements the endpoint formalism for the calculation of EM radiation directly in COsmic Ray SImulations for KAscade (CORSIKA).
  - Particle motion is described via a series of discrete, instantaneous acceleration events, or ‘endpoints’, with each such event being treated as a source of emission
  - In the final step, the radiation from all particles is superimposed, resulting in the macroscopically observed radio pulse.
  - The electric fields for the endpoint formalism can be directly calculated from the Lienard-Wiechert potentials

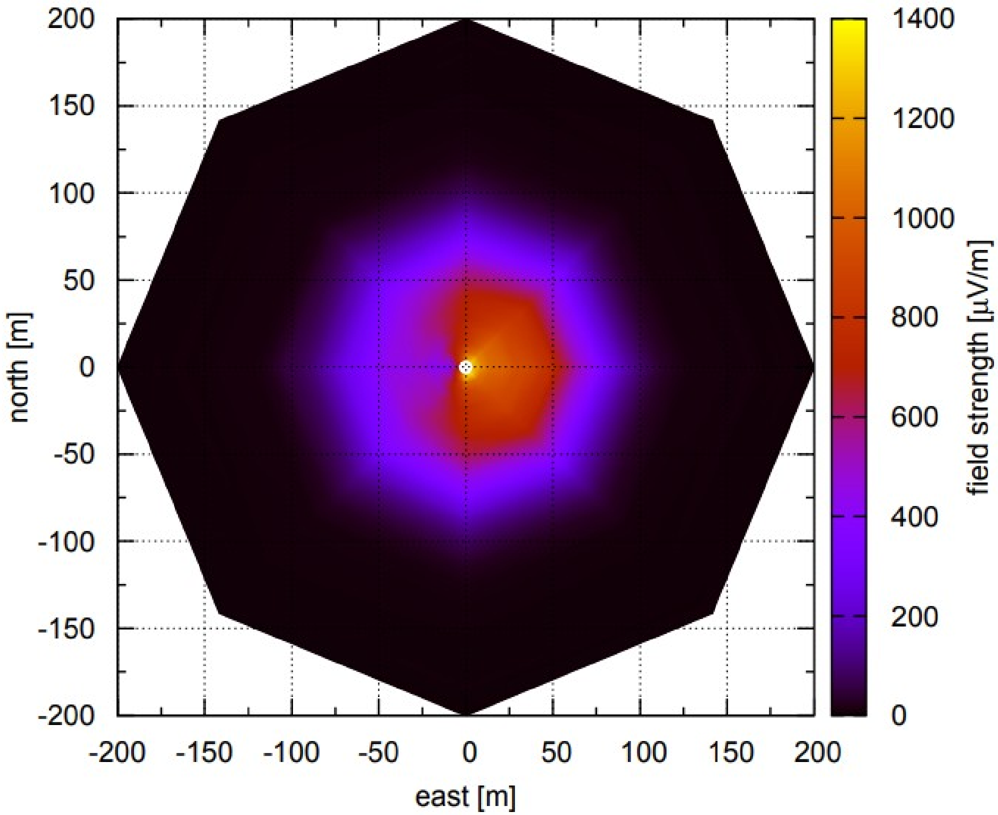
- Makes no assumptions about the emission mechanism

- Takes into account the complete complexity of the electron and positron distributions as simulated by CORSIKA

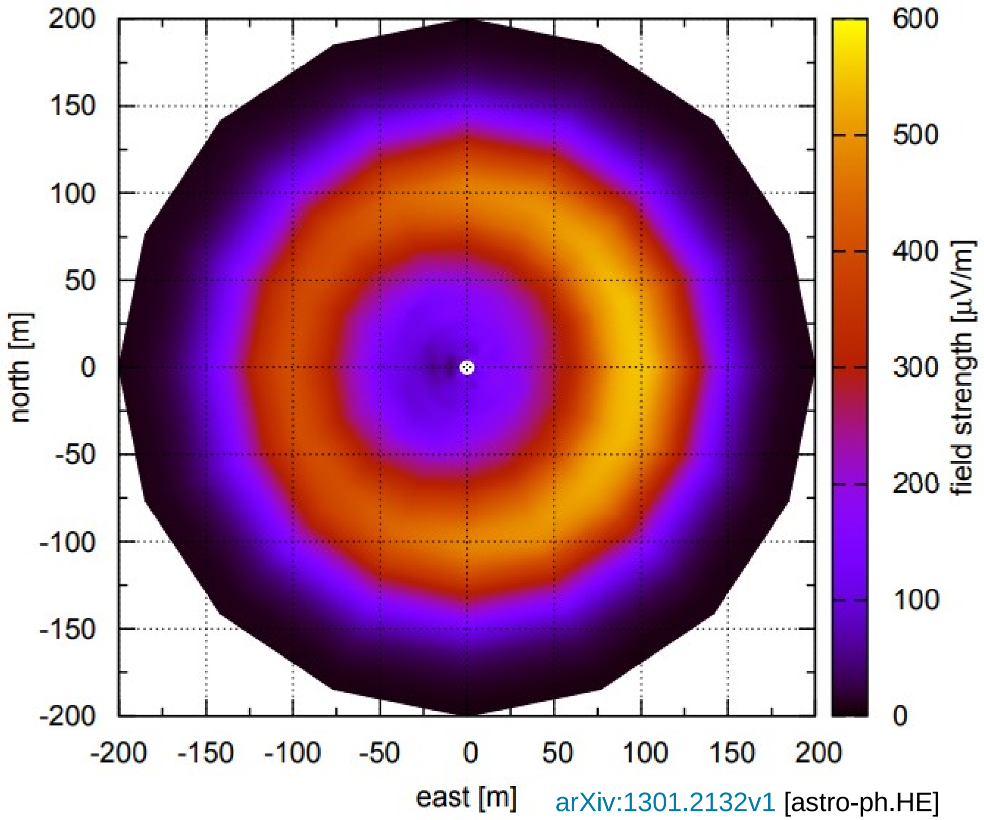
- Takes into account the refractive index profile of the atmosphere which is relevant for the radio emission.

Showers Simulated in CoREAS (300-1200 MHz)

Proton, 10^17 eV, vertically down



Iron, 10^17 eV, vertically down



arXiv:1301.2132v1 [astro-ph.HE]

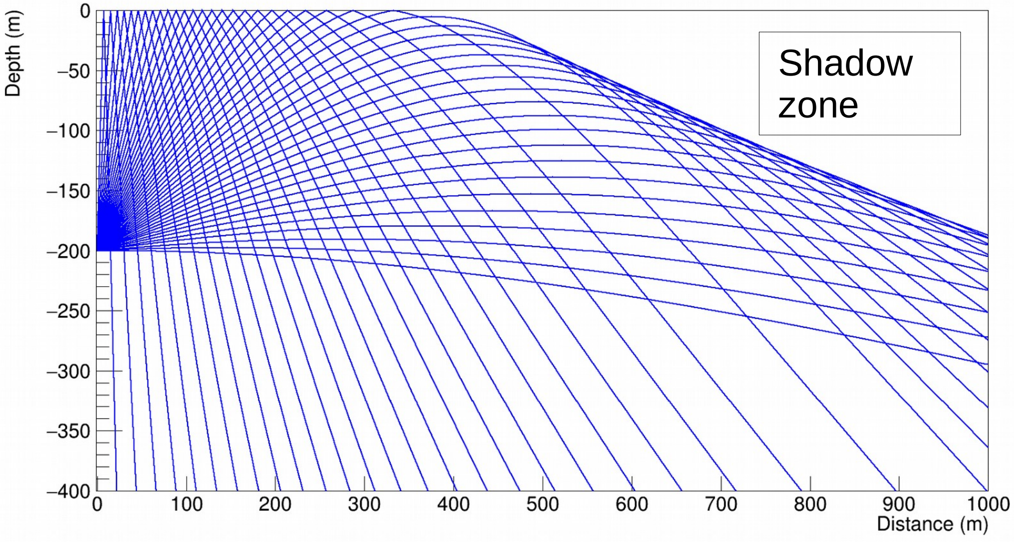
- Asymmetric nature of the emission is clearly visible for both cases.

- The expected Cherenkov ring is also visible for the iron shower but not for the proton one
  - Xmax of the iron shower is much shallower as compared to the protonic shower
  - Therefore ring for proton very close to the central shower axis and gets mixed up with geomagnetic emission

- At lower frequencies, no ring is expected, and the 2-D profile of both showers will be similar to that shown on the left.

Raytracing

- CoREAS gives us E-fields at observer positions on the ice surface
- For propogating rays to ARA antennas we have to understand the propagation mechanism of rays in ice.
- For this we need to perform raytracing.
- It helps in the neutrino vertex reconstruction in-ice required to perform energy reconstruction of the neutrino.
- Rays are refracted in the ice sheet owing to the depth-dependent density, and therefore index of refraction.
- The refractive index profile for SP ice:



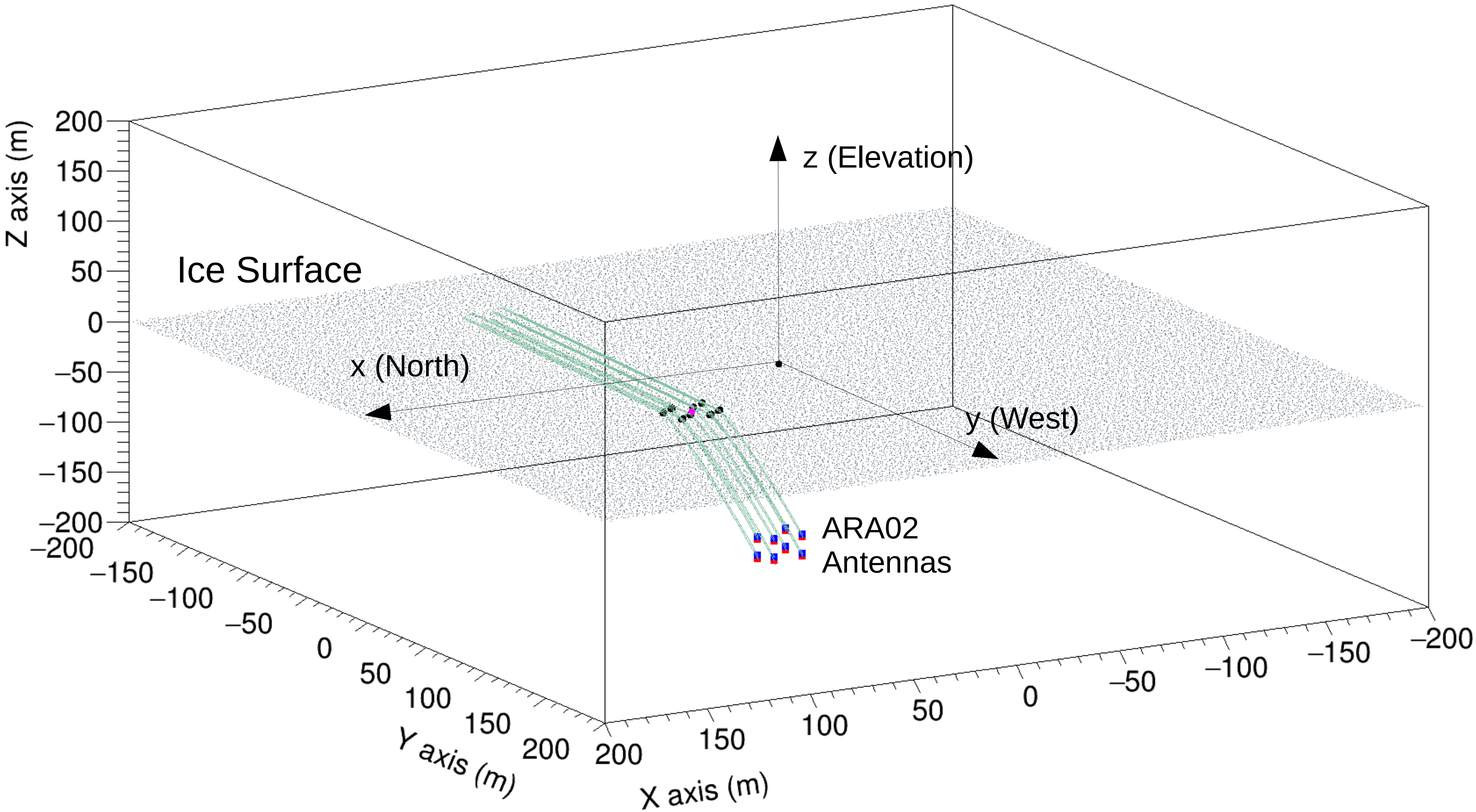
Ray paths for a source at a depth of 200 m. The bending causes the formation of ‘shadow zones’.

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

Overall Picture: Simulating EAS for ARA using CoREAS

Pink dot is the shower core.
Black dots are where it enters the ice.
Red and blue are the ARA antennas.
Origin is at SE corner of ARA02 DAQ box.

So I simulated a shower with E=10^17 eV , θ=45 deg and φ=35 deg.



The steps for simulating the shower and obtaining the voltage WFs

1) Decide on the shower's zenith and azimuthal (θ_s, ϕ_s) angles and its energy.
2) Find the points (observer) on the ice where a shower of that (θ_s, ϕ_s) needs to intersect such that radiation travels and gets refracted through the ice to hit each of the ARA antennas.
3) Convert the E-fields from the Cartesian coordinate system to spherical coordinates.
4) Propagate the E-field down using raytracing manually.
5) Convolve the E-fields with the antenna height effective (which is the complex antenna response function) to find the voltage induced on the antennas.
6) Apply the ARA system response on the voltage waveforms to obtain the final waveforms as they should be observed in the data.
7) Add noise to the waveforms.
8) Time the waveforms correctly to show which channels triggered first and also to take into account the cable delays.

Obtaining the voltage waveforms

- Taking the dot product of effective height (m) with the E-Field (V/m) vectors in frequency space.

  - <u>Effective height</u>: It is a measure of the voltage induced on the open-circuit terminals of the antenna when a wave impinges upon it.

$$\vec{h}_{eff}(f,\theta,\phi) = h_{eff,\theta}(f,\theta,\phi)\ \hat{\theta} + h_{eff,\phi}(f,\theta,\phi)\ \hat{\phi}$$

  - Take the DFT of Electric fields to take them in Fourier space and take the following complex dot product:

$$\tilde{V}_{OC}(f) = \tilde{\vec{E}}(f,\theta,\phi).\tilde{\vec{h}}^{*}_{eff}(f,\theta,\phi)$$

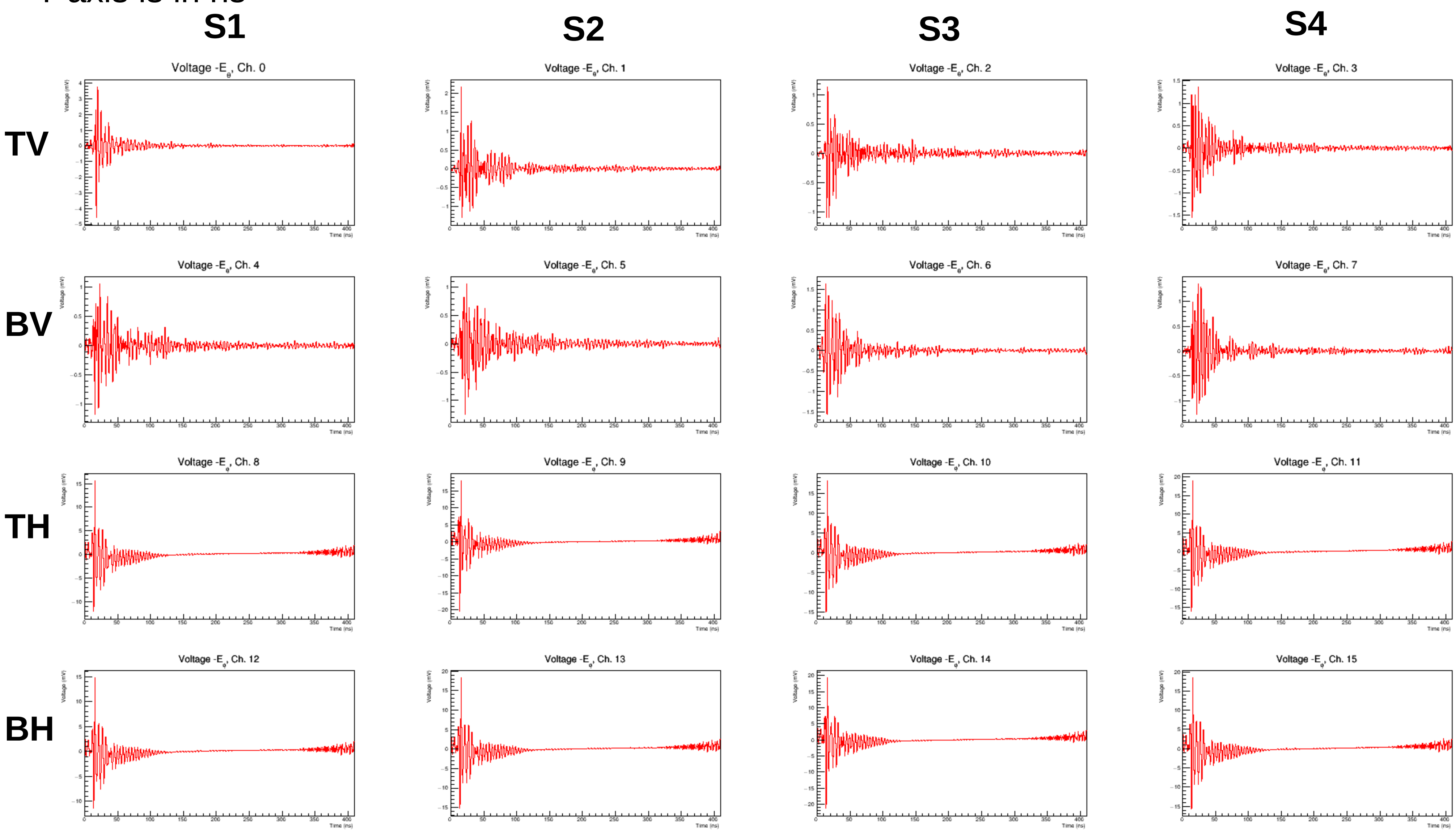
  - We assume conjugate impedance matching which basically means that for simple antennas such as dipoles the induced voltage into a matched receiver load is given by

$$\tilde{V}_{induced}(f) = \frac{\tilde{V}_{OC}(f)}{2}$$

Final Waveforms after passing through the ARA detector response

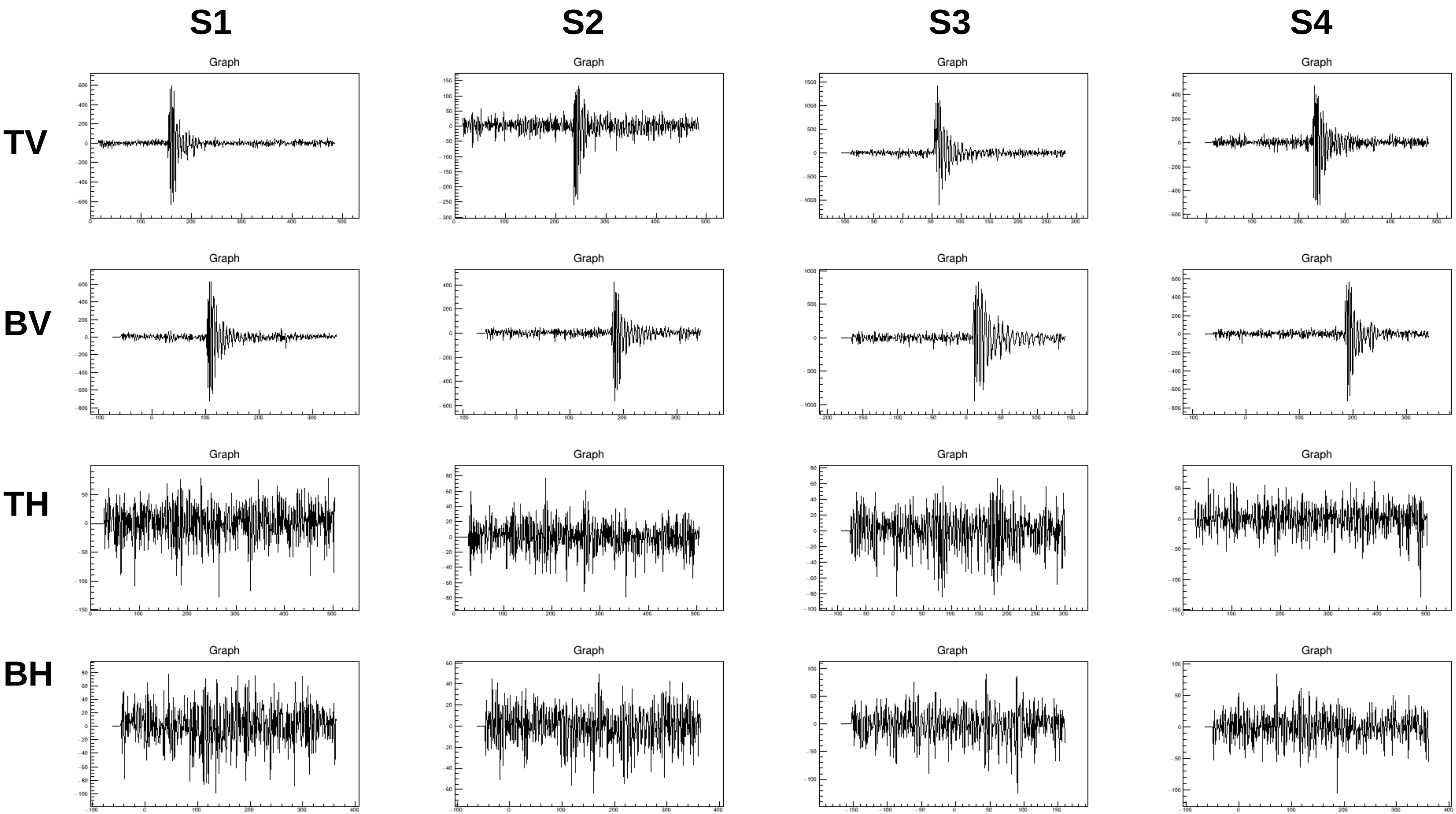
Note:
- X axis is in mV
- Y axis is in ns

- Shower simulated with theta=45 deg, phi=35 deg and 10^17 eV.
- The hadronic models use are QGSJETII.04 for high energy showers and UrQMD 1.3 for low energy showers.
- Thinning was ON, with a thinning fraction of 10^-6.
- Hpol waveforms are slightly stronger which is expected as most of the geomagnetic emission happens in Hpol.



ARA02 2016, Run 7625, Event 2412
Calpulser event waveform

Vpol axes on the order of 500 mV
Hpol axes on the order of 40 mV



Rough Road Map for obtaining UHECR events from ARA

- Look at data from ARA 2-3 from 2013 to 2016.
- Eliminate events in periods of
  - high anthropogenic activity like austral summers
  - Deep and shallow pulser studies
  - Storms (?)
- Eliminate upward coming events:
  - There might be some ambiguity near the Critical angle of ice-air boundary

$$\theta_C = \arcsin(1.00/1.35) = 47.8^o$$

- Make voltage WF templates for UHECR events taking into account:
  - Direction
  - Energy
  - Species
- Do template-matching or cross correlations with data and try to to filter out CR events.
  - Have not done this yet. Will definitely like more feedback on this.
- Do an expected CR background calculation and check and verify your final event number.

Radar Detection in Ice

- You can have shower particles in ice:
  - When UHECR air showers penetrate ice
  - When GZK neutrinos create particle showers in ice.

- These traversing shower particles eject cold ionization electrons from atoms in the bulk, forming a tenuous particle-shower plasma (PSP), distinct from the energetic shower front particles responsible for ionization.

- This plasma in above two mentioned cases can become dense enough to reflect radiowaves.

- The lifetime of this plasma can be at the order of 1-10 ns depending on the temperature and purity of ice.
  - Simulations indicate coherent radar returns with a PSP lifetime as short as 0.1 ns.
  - 90% of the shower particles are contained within 1 Moli`ere radius from the shower axis, which for ice is order 10 cm.

The RADAR mechanism

- Stolen from Steven's Paper: https://arxiv.org/pdf/1710.02883.pdf

$$\mathbf{E_A} = \frac{\alpha E_I}{R} \hat{n} \times \hat{n} \times \hat{\epsilon_{\mathbf{A}}}$$

$$\alpha = -\frac{q^2 \omega}{c^2 m(\omega + i\nu_c)}$$

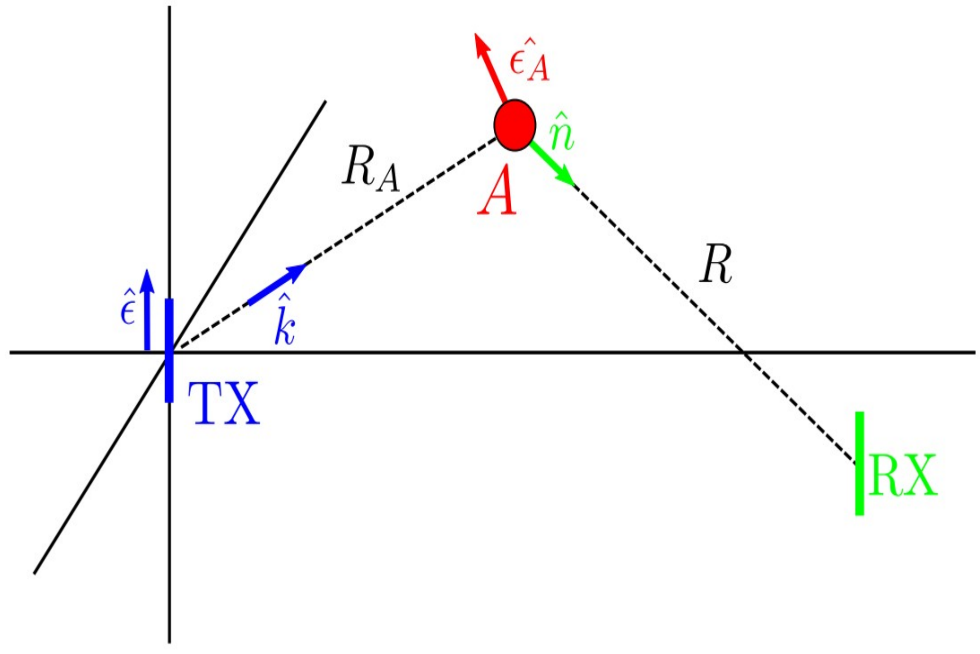


Figure 1: The angles used in the derivation of the invidual particle scattering contribution presented in the text. The direction of the wave vector $\hat{k}$ points from transmitter (TX) to the charge A. $\hat{n}$ points from the charge A to the receiver (RX). The polarization of the source is labeled $\hat{\epsilon}$, and the polarization of field at charge A is $\hat{\epsilon_A}$, which is perpindicular to $\hat{k}$ and lies in plane with $\hat{\epsilon}$.

An event from RadioScatter simulation

Chirp Signal

- The chirp signal is very distinctive and unliked any anthropogenic impulsive background.
  - It is a simple consequence of doppler shifting

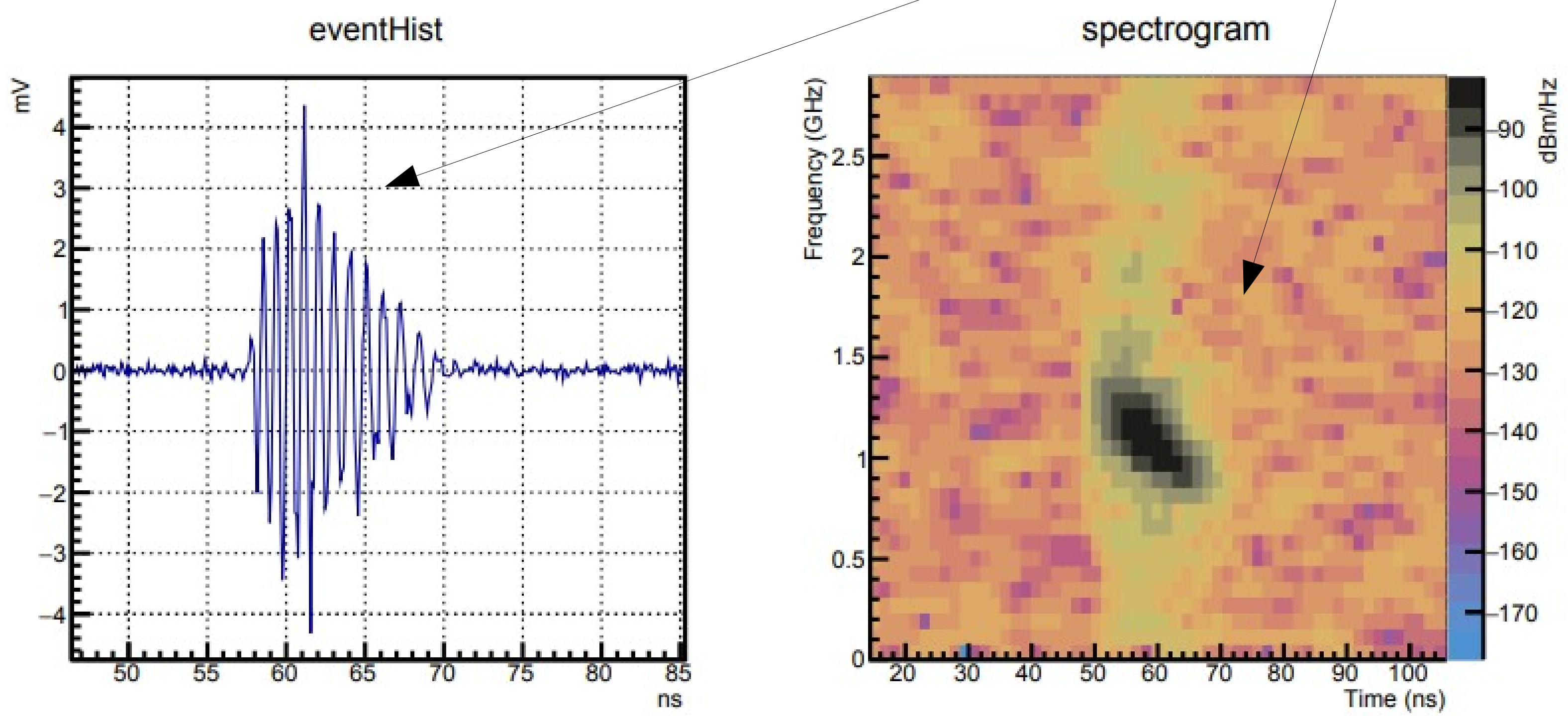
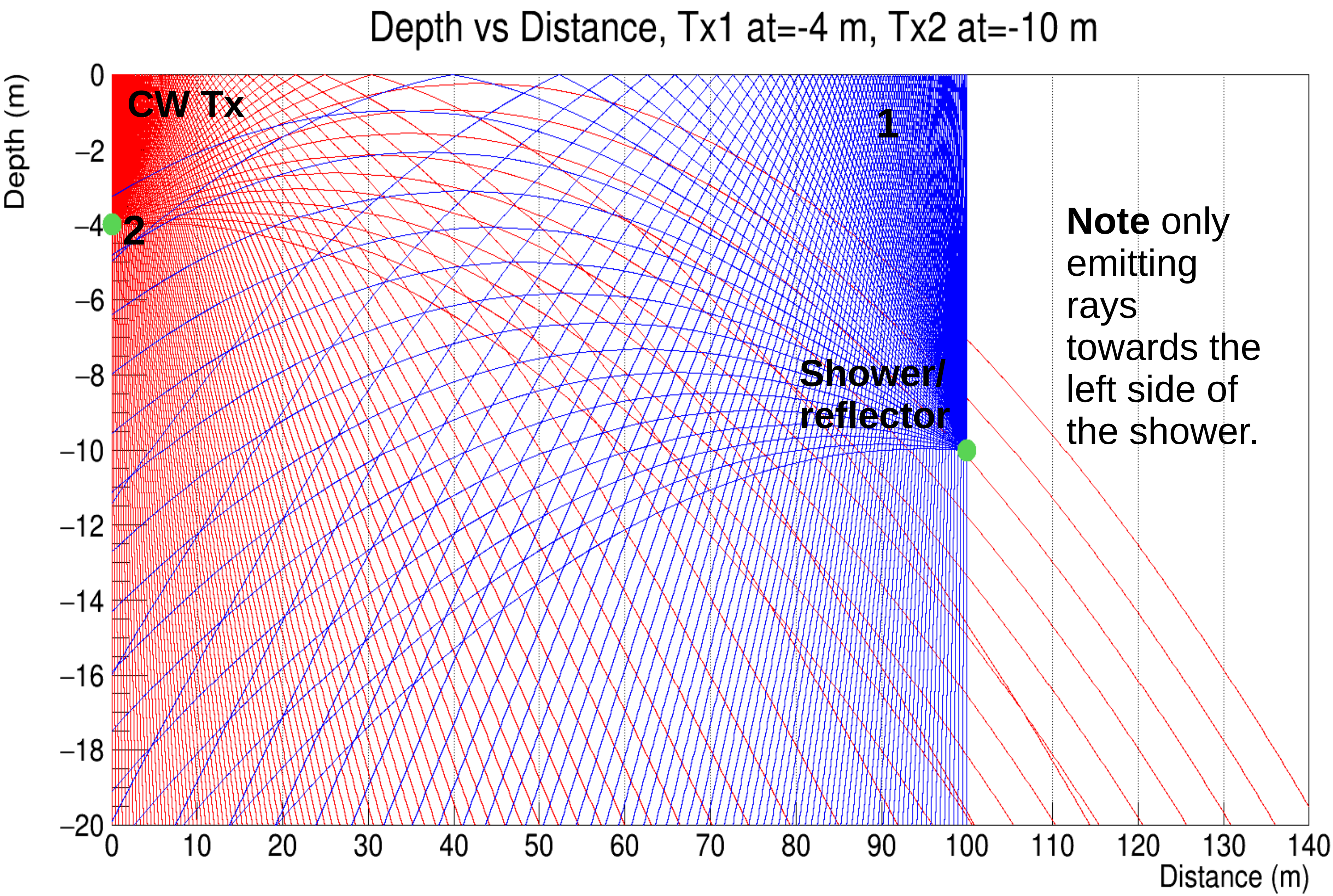


Figure 8: Simulated radio reflection for a 5 GHz bandwidth receiver, from an electron-initiated plasma consisting of 10^9 13.6 GeV primaries, superimposed upon thermal noise, with a sounding frequency of 1.15 GHz CW. The transmitter output power is 10 W and the plasma lifetime is 0.1 ns. The observed chirp-like signal is a function of the TX-PSP-RX geometry.

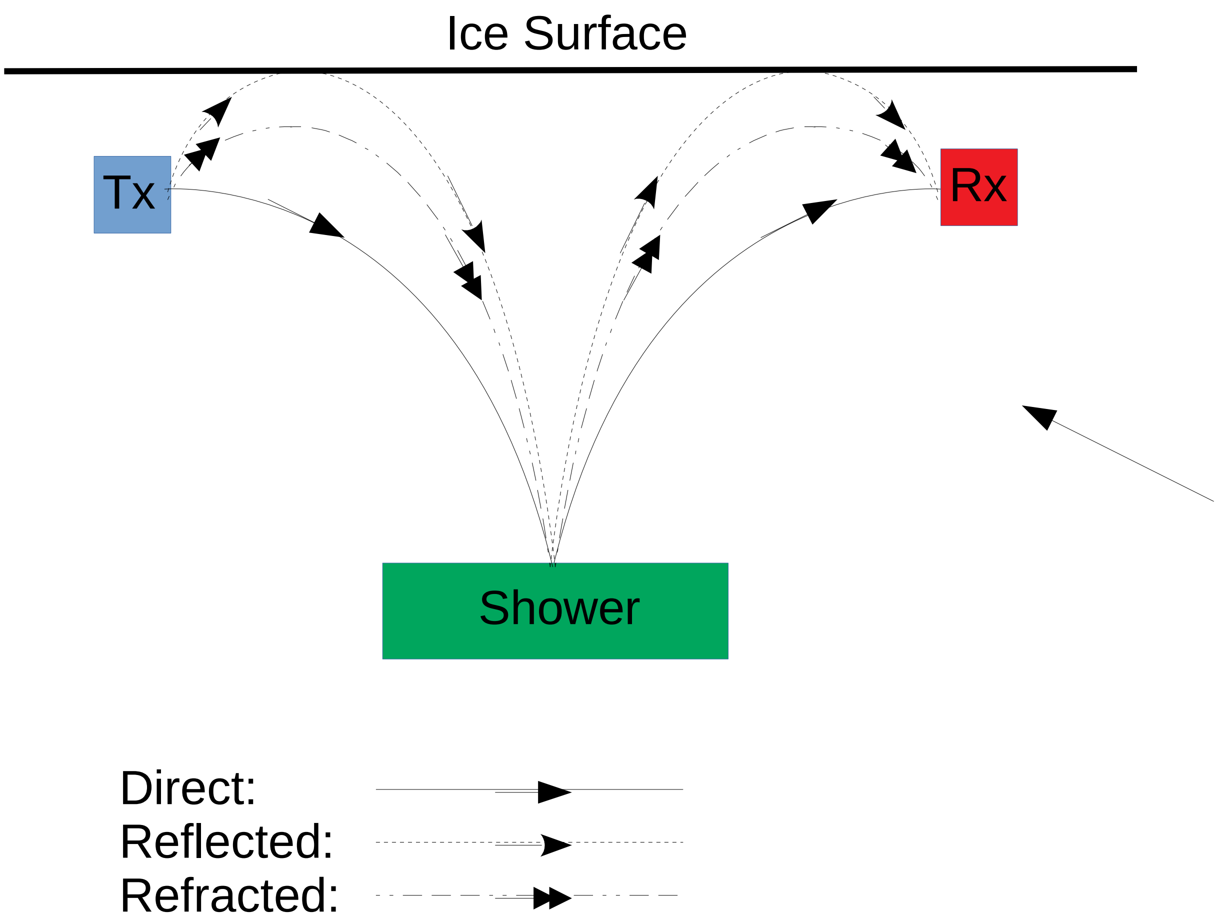
Simulated reflection off GEANT4 shower in a High-Density PolyEthylene (HDPE). Plasma lifetime is set to 0.1 ns.

1 and 2 are just one of the many possible positions for our recievers. If we are in 1 we would not see the CW transmitter but only the shower (or the reflector)



Note only emitting rays towards the left side of the shower.

All possible ray paths btw Tx and Rx



For any given source and target positions you have 2 possible rays paths which can happen in any of the following ways:

1. Direct, Reflected
2. Direct, Refracted
3. Refracted, Reflected.

In the radar configuration you can have:

1. D, R’
2. D, D’
3. R, D’
4. R, R’

This gives you 4 pulses and makes the reflected signal at the reciever extremely unambiguous.

The T576 experiment at SLAC - May 2018

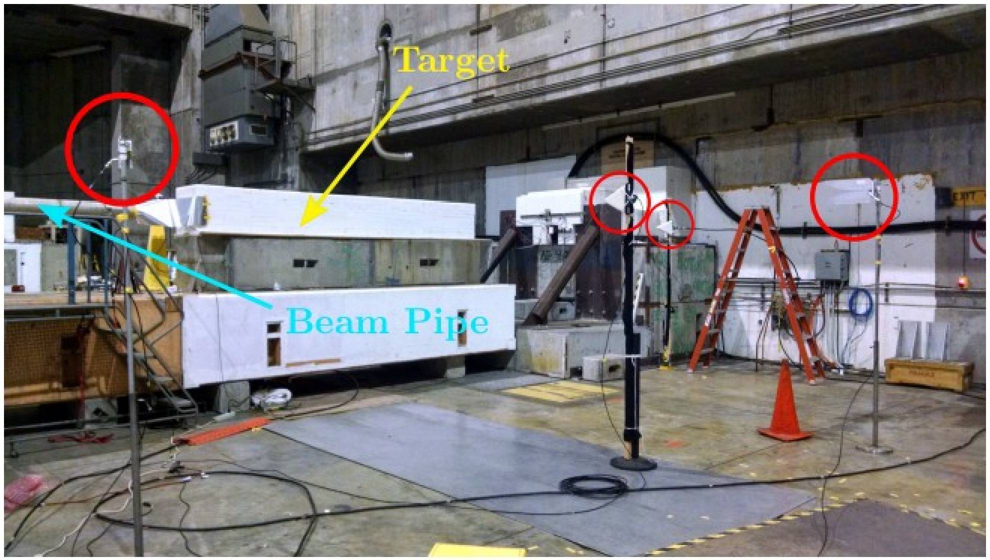
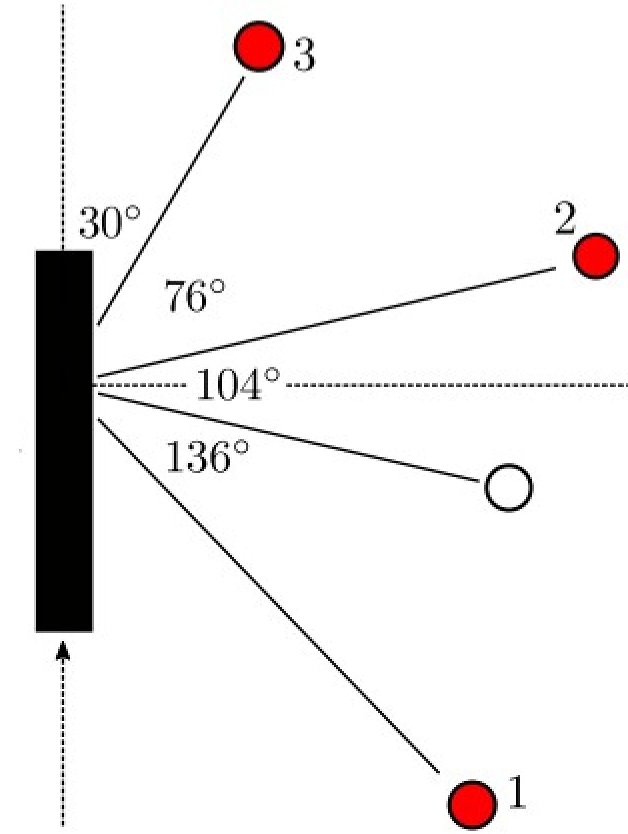


FIG. 1: The T576 experimental setup. The large white rectangular polyhedron at the center is the HDPE target. The beam enters from the left, with the entry point shielded by aluminum sheeting in an effort to mitigate transition radiation (TR). The circles (red online) indicate the receiver/transmitter antennas. Second from left is the transmitter, the others are receivers.



https://arxiv.org/pdf/1810.09914.pdf

A T576 event

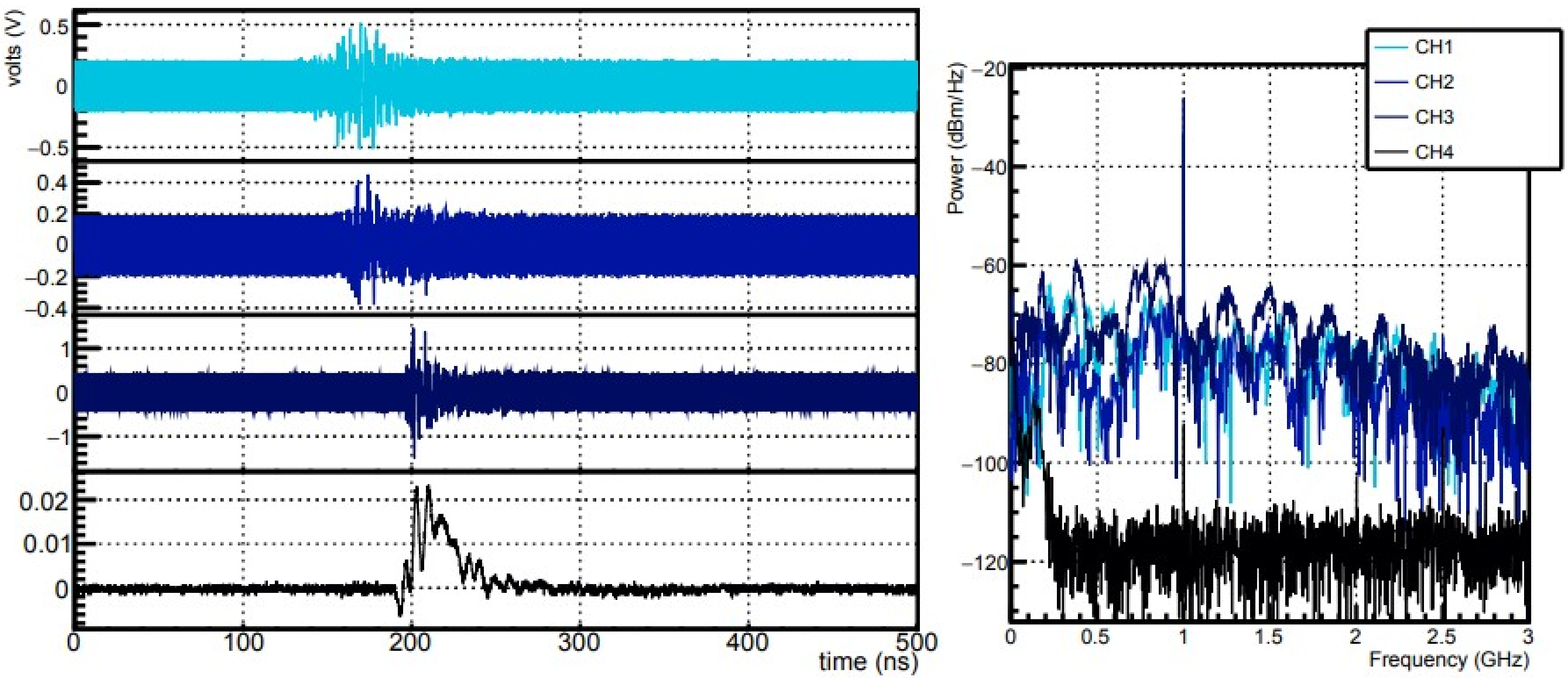
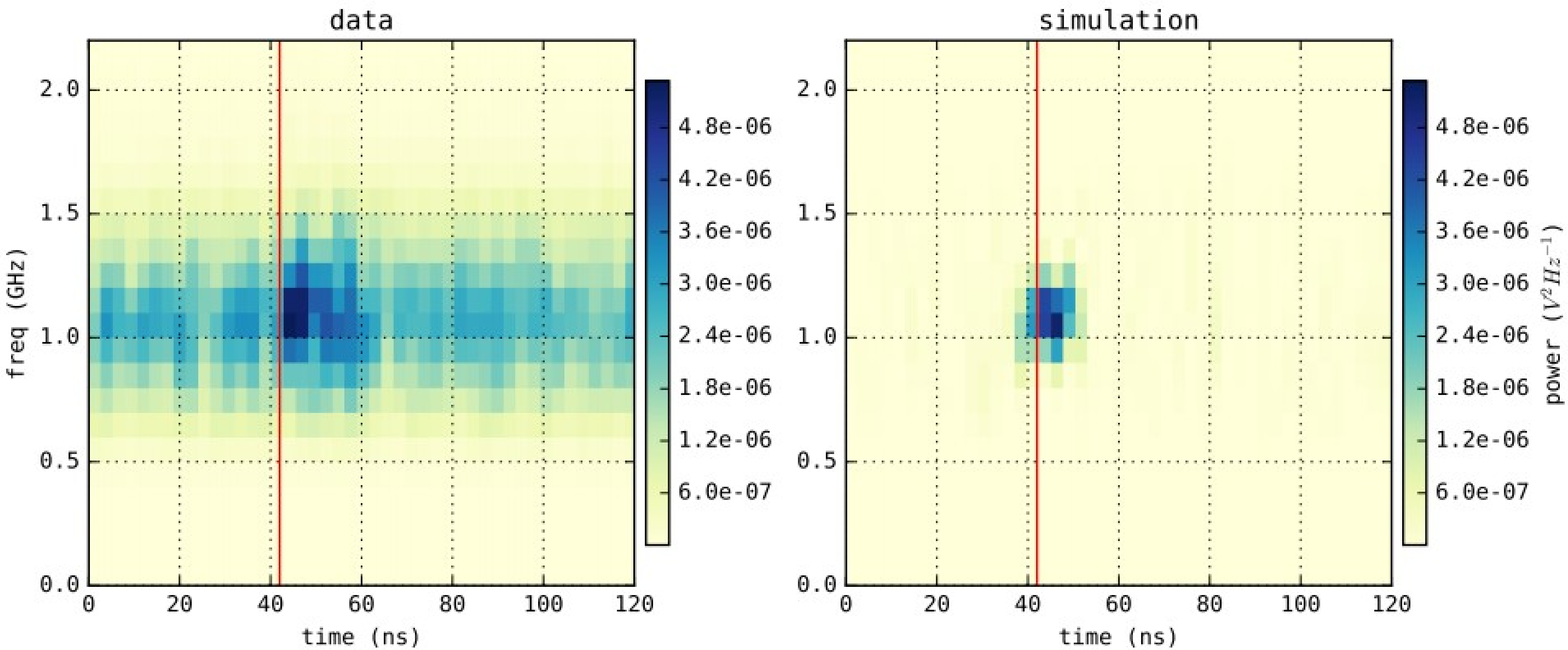


FIG. 5: A typical T576 event. The 4 left panels are channels 1-4 from top to bottom, respectively, and the right panel shows their associated PSD. The offsets on the x-axis are due to air and cable propagation delays.

Possible reflection signal after using SVD to remove background



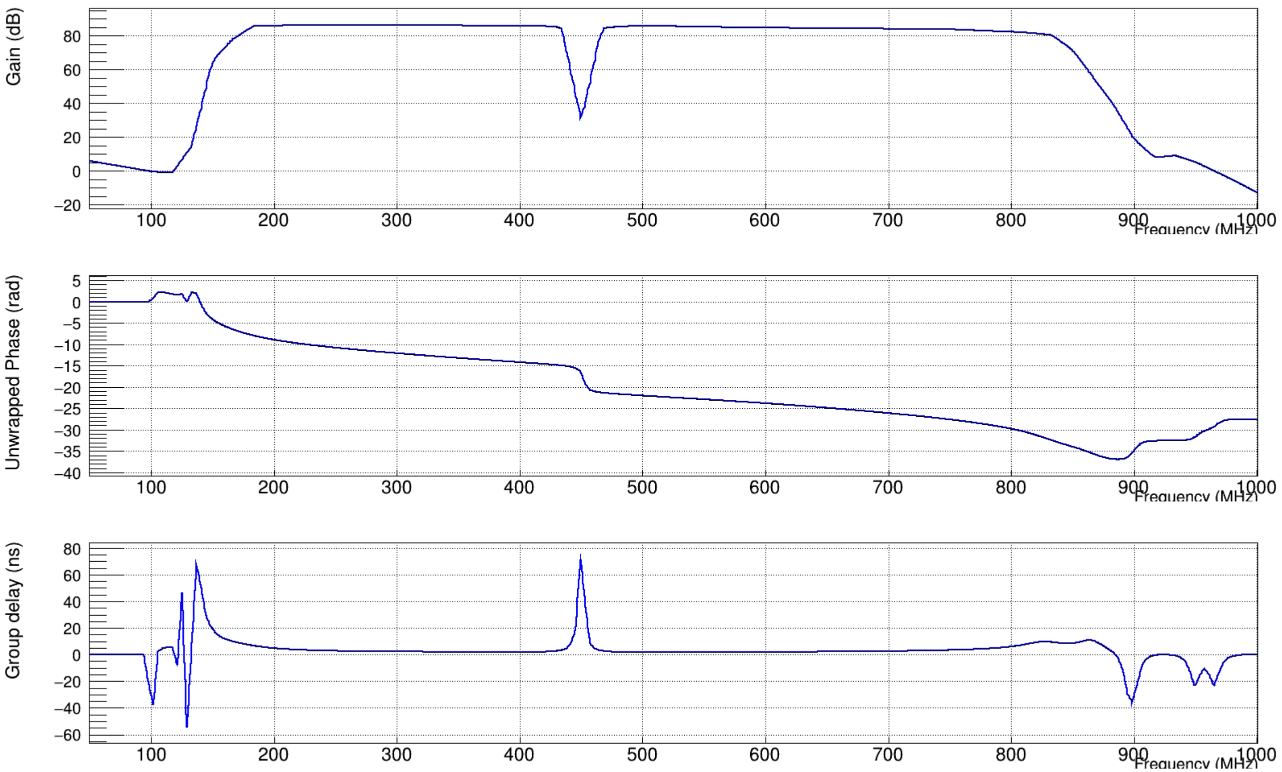
Simulation plot has used a plasma lifetime of 10 ns.
The solid red line indicates the approximate signal onset point.
Signal has an SNR=2 in line with RadioScatter's prediction.

- Right now we are using SVD (Singular Valued Decomposition) to extract our low SNR from our data.
- Is there a way we can use ML for that somehow?

Thank you!

Backup

ARA detector response



- To do this we multiply the complex gain by the complex voltage in frequency space:
- $$\tilde{V}_{final}(f) = \tilde{V}_{induced}(f).\tilde{G}_{ARA}(f).\frac{1}{\sqrt{2}};$$
- here the 1/sqrt(2) factor arises from the splitter. This complex gain takes into account all the amplification and filtration that happens in the ARA signal chain.

Converting E-fields from Cartesian to Spherical coordinates-1

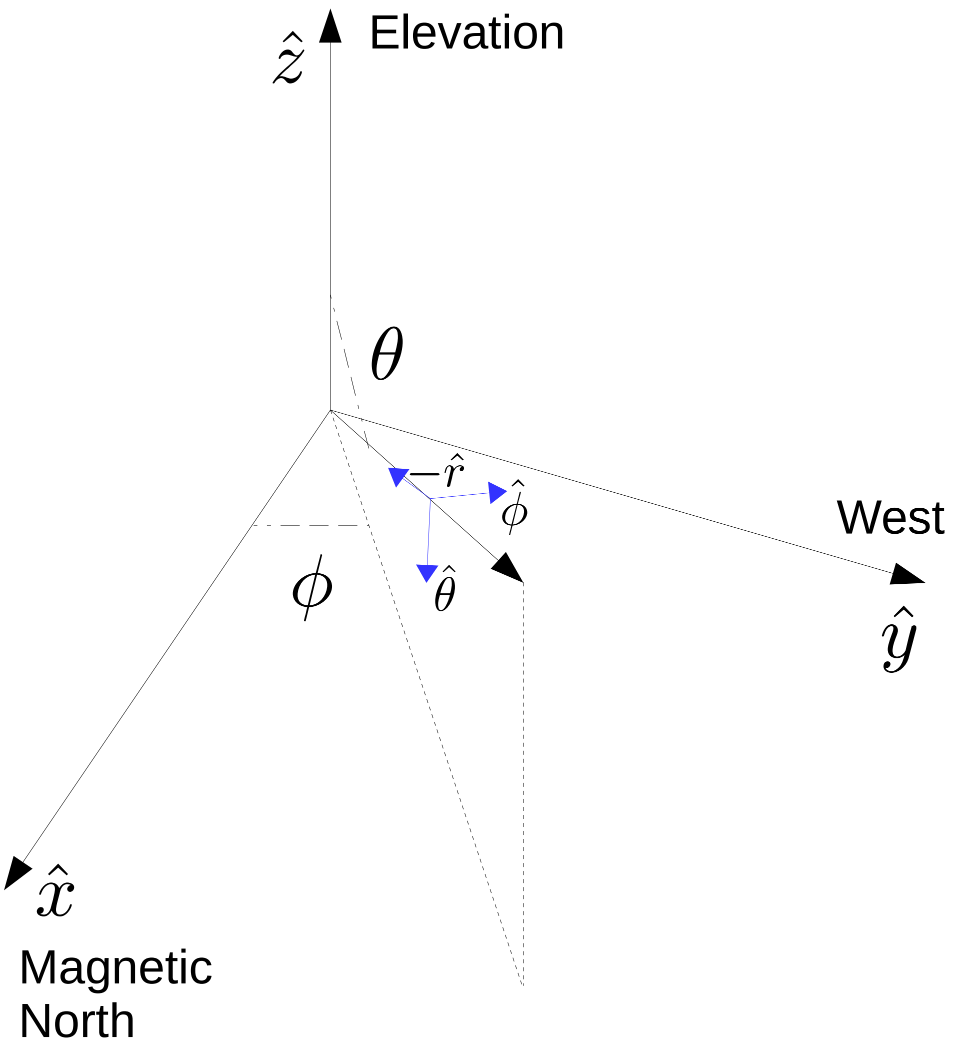
- This makes
  - propagation in ice much more convenient.
  - Calculation of Voltage waveforms also becomes convenient.

- I convert the Cartesian E-field to get it in terms of:
  - $\vec{E}(t) = E_r(t)\ \hat{r} + E_\theta(t)\ \hat{\theta} + E_\phi(t)\ \hat{\phi}$

- The Er component is ignored as that is in the direction of propagation itself.

- Only the E_θ and E_φ components are propagated in the ice.

- Note: The θ and Φ angles are fixed by the incoming shower direction.



Converting E-fields from Cartesian to Spherical coordinates-2

$$\vec{E}(t) = E_x(t)\ \hat{x} + E_y(t)\ \hat{y} + E_z(t)\ \hat{z}$$

Note: The θ and Φ angles are fixed by the incoming shower direction.

-By substituting the following in the equation above:

$$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} = \begin{bmatrix} \sin(\theta)\cos(\phi) & \cos(\theta)\cos(\phi) & -\sin(\phi) \\ \sin(\theta)\sin(\phi) & \cos(\theta)\sin(\phi) & \cos(\phi) \\ \cos(\theta) & -\sin(\theta) & 0 \end{bmatrix} \begin{bmatrix} \hat{r} \\ \hat{\theta} \\ \hat{\phi} \end{bmatrix}$$

-I get the E-field components in spherical coordinates:

$$E_r(t) = E_x(t)\sin(\theta)\cos(\phi) + E_y(t)\sin(\theta)\sin(\phi) + E_z(t)\cos(\theta)$$

$$E_\theta(t) = E_x(t)\cos(\theta)\cos(\phi) + E_y(t)\cos(\theta)\sin(\phi) - E_z(t)\sin(\theta)$$

$$E_\phi(t) = -E_x(t)\sin(\phi) + E_y(t)\cos(\phi)$$

-And thus I get the E-field itself: $\vec{E}(t) = E_r(t)\ \hat{r} + E_\theta(t)\ \hat{\theta} + E_\phi(t)\ \hat{\phi}$

Raytracing-II

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

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

$L = n(z_0)\sin(\theta_0)$, 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 $\frac{dx}{dz} = \tan(\theta) = \tan\left(\arcsin\left(\frac{L}{A+Be^{Cz}}\right)\right)$

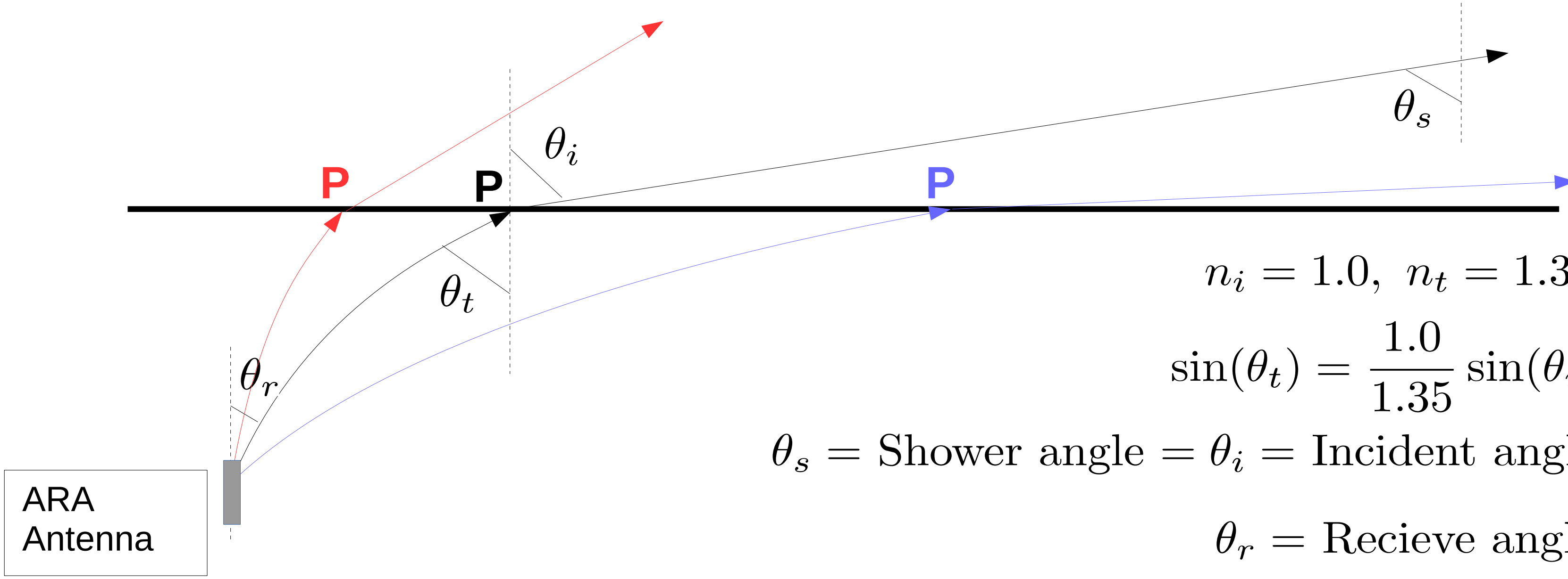
- Depending on the direction of the incoming Shower this point **P** (on the ice surface) can be further or nearer to the receiving antenna.

- Once I fix the incoming shower zenith angle I can use my raytracing code and find this point **P** for that antenna.
  - We know the coordinates for the ARA antenna and the angle θ_t at which the ray enters (or leaves) the ice for fixed shower elevation θ_s. First I find the value of θ_r or the launch angle such that:

$$f(z_0, z_1, \theta_t, \theta_r) = \tan\left(\arcsin\left(\frac{L(\theta_r, z_0)}{A + Be^{Cz_1}}\right)\right) - \tan(\theta_t) = 0,$$

  - Once I have θ_r I can find the point **P** by tracing the ray.

- I repeat this process for all the 16 antennas and find this point **P** for all of them.



$$n_i = 1.0,\ n_t = 1.35$$

$$\sin(\theta_t) = \frac{1.0}{1.35}\sin(\theta_i)$$

$$\theta_s = \text{Shower angle} = \theta_i = \text{Incident angle}$$

$$\theta_r = \text{Recieve angle}$$

Scaling the E-fields by the Transmittance on ice

- The fraction of the incident power that is reflected from the interface is given by the reflectance R, and the fraction that is transmitted is given by the transmittance T.

$$n_1 = 1,\ n_2 = 1.35$$

$$\theta_i = \text{ Angle of incidence}$$

- For cases when $\mu_1 \approx \mu_2 \approx \mu_0$
  - For s-polarisation (φ polarisation):

$$R_s = \left| \frac{n_1 \cos(\theta_i) - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2}}{n_1 \cos(\theta_i) + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2}} \right|^2 \longrightarrow T_s = 1 - R_s$$

    - So we get: $\boxed{E^*_\phi = E_\phi \sqrt{T_s}}$

  - For p-polarised (θ polarisation):

$$R_p = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2} - n_2 \cos(\theta_i)}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2} + n_2 \cos(\theta_i)} \right|^2 \longrightarrow T_p = 1 - R_p$$

    - So we get: $\boxed{E^*_\theta = E_\theta \sqrt{T_p}}$

H_{eff} magnitude in terms of Antenna Gain (from XFDTD)

$$|\vec{h}_{eff}| = 2\sqrt{\frac{\Re(Z_L)A_{eff}}{Z_0}}$$

Z_0 : Impedance of free space $= 120\pi\ \Omega$

$\Re(Z_L)$: Load impedance$= 50\ \Omega$

A_{eff} : Effective Area

-Substituting $A_{eff} = \frac{\lambda^2 G(\theta,\phi)}{4\pi}$ into $|\vec{h}_{eff}|$

-And using the fact that in dielectrics: $c \to \frac{c}{n},\ Z_0 \to \frac{Z_0}{n}$

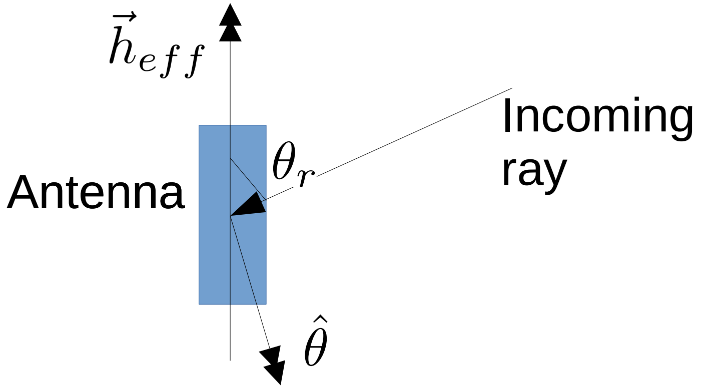
Note:Gain is in linear units.

$$=> |\vec{h}_{eff}(f,\theta,\phi,z)| = 2\sqrt{\frac{\Re(Z_L)}{(Z_0)}\left(\frac{c}{fn(z)}\right)^2\frac{G(\theta,\phi)}{4\pi}}$$

H_{eff} vector direction

For ARA Bicone Vpol antennas:

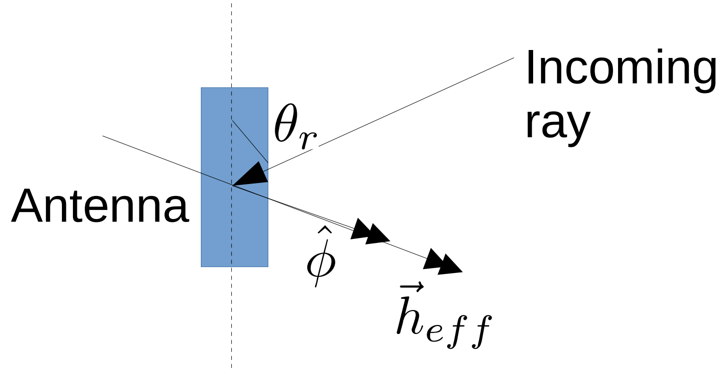
$$\vec{h}_{eff} = |\vec{h}_{eff}| \ \hat{z}$$



WIPL-D model used for Vpol antennas

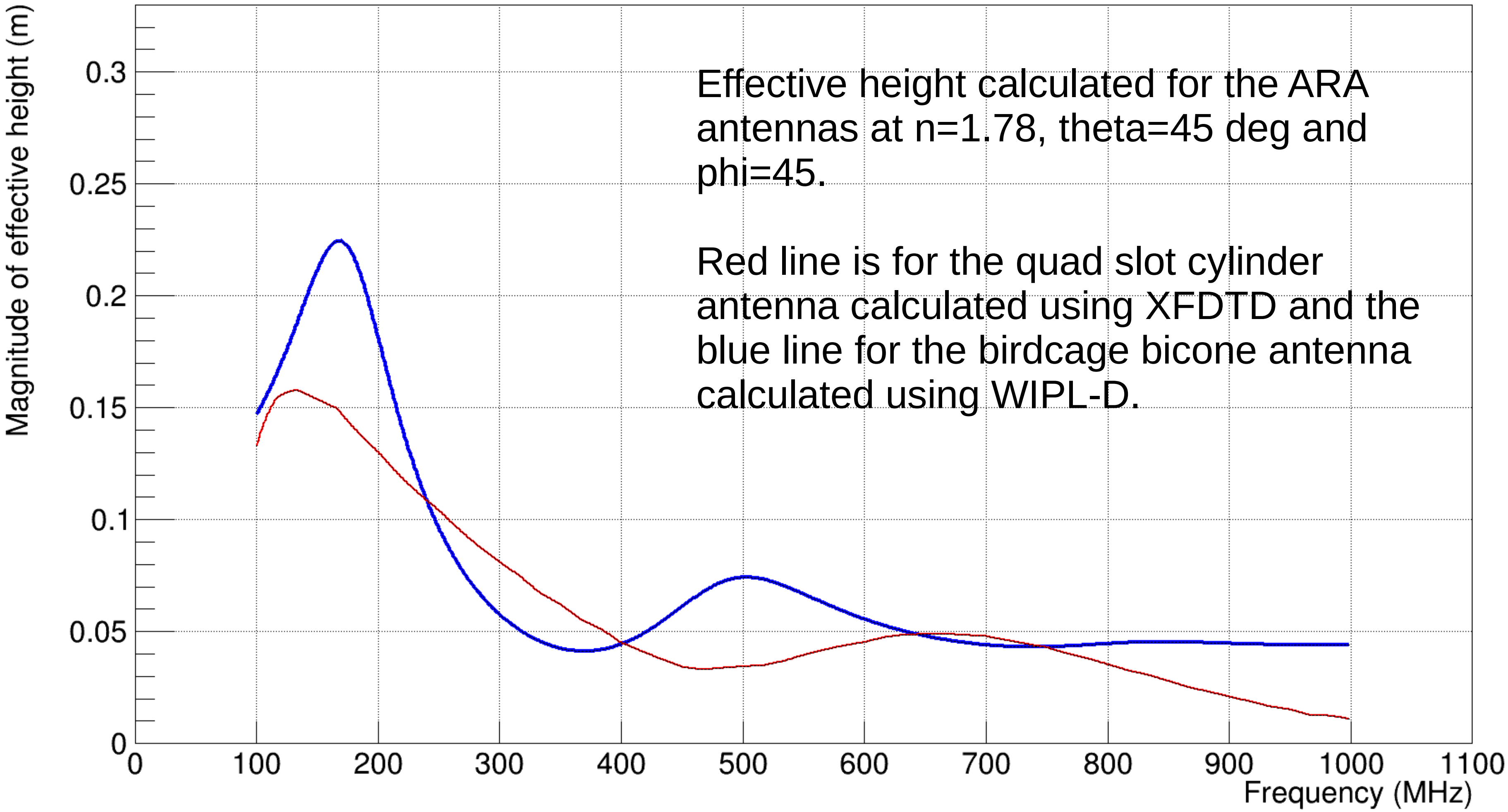
For ARA Quad Slot Cylinder Hpol antennas (due to azimuthal symmetry) :

$$\vec{h}_{eff} = |\vec{h}_{eff}| \ \hat{\phi}$$



XFDTD model used for Vpol antennas

The effective height magnitude (m) vs frequency (MHz)



Refraction through the atmosphere

- The COREAS simulation comes with an enclosed GDAS-tool that queries the GDAS (Global Data Assimilation System) atmospheric database for a given location and time and downloads a corresponding density and humidity profile.
  - The density profile is fitted to generate the 5-layer atmosphere fed to CORSIKA.
  - At the same time, a consistent, tabulated refractivity profile is fed to CoREAS.

- This allows in particular the inclusion of humidity effects in the refractive index profile.

- I got the refractivity profile for following parameter values:
  - Coordinates: lat = -89.96 deg, lon = -109.79 deg
  - Time [UTC]: Tue Aug 7 17:45:53 2018

Analytical Soln. Properties

- When A=L the solution becomes undefined. The condition A<L therefore must always be fulfilled, putting a limit on our launch angle theta_0 for a given source depth, and limiting launch angles to less than 90 deg.
  - Since ray paths are reversible, the target and the source can be swapped. Thus this technique allows us to trace rays even if the source is shallower than the target.

- This solution has two roots: one for C>0 and z<0 and the other for C<0 and z>0.

- The solution also becomes undefined when n(z)=L. This gives us a limit on the minimum depth (peak point, or turning point) that a ray launched at a certain angle will attain. This point is called z_max, which can be written as:

$$n(z_{max}) = L \;\; => \;\; z_{max} = \frac{1}{C}\log\left(\frac{L-A}{B}\right)$$