Simulating UHECRs in COREAS for ARA

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Introduction

- I have been working on using for CoREAS for UHECR simulations as a part of my thesis.
- Going to use CoREAS for template generation and then using those templates to find UHECRs in ARA data.
- CoREAS gives me the electric field as a function of time at the surface and then I propagate them manually to the antennas by raytracing in ice.
- I give CoREAS the a star shape observer configuration on the ice surface and then use Thin Plate Spline interpolation to get the complete footprint.
- I plan to then move footprint around the ice which is equivalent to simulating multiple showers and calculate the efficiency of ARA detector.

The steps for simulating a 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 16 points on the ice where (assuming emitted radiation is colinear with shower directions) radiation enters the ice surface such that it gets refracted through the ice to hit each of the ARA antennas.

3) Adjust the interpolated shower foot print around those 16 incident points on ice.

4) Convert the E-fields from the Cartesian coordinate system to spherical coordinates.

5) Propagate the E-field down using my analytic raytracing solution.

6) Convolve the E-fields with the antenna height effective (which is the complex antenna response function) to find the voltage induced on the antennas.
   - I get the gain from XFDTD which gives I convert to effective height.

7) Apply the ARA system response on the voltage waveforms to obtain the final waveforms as they should be observed in the data.

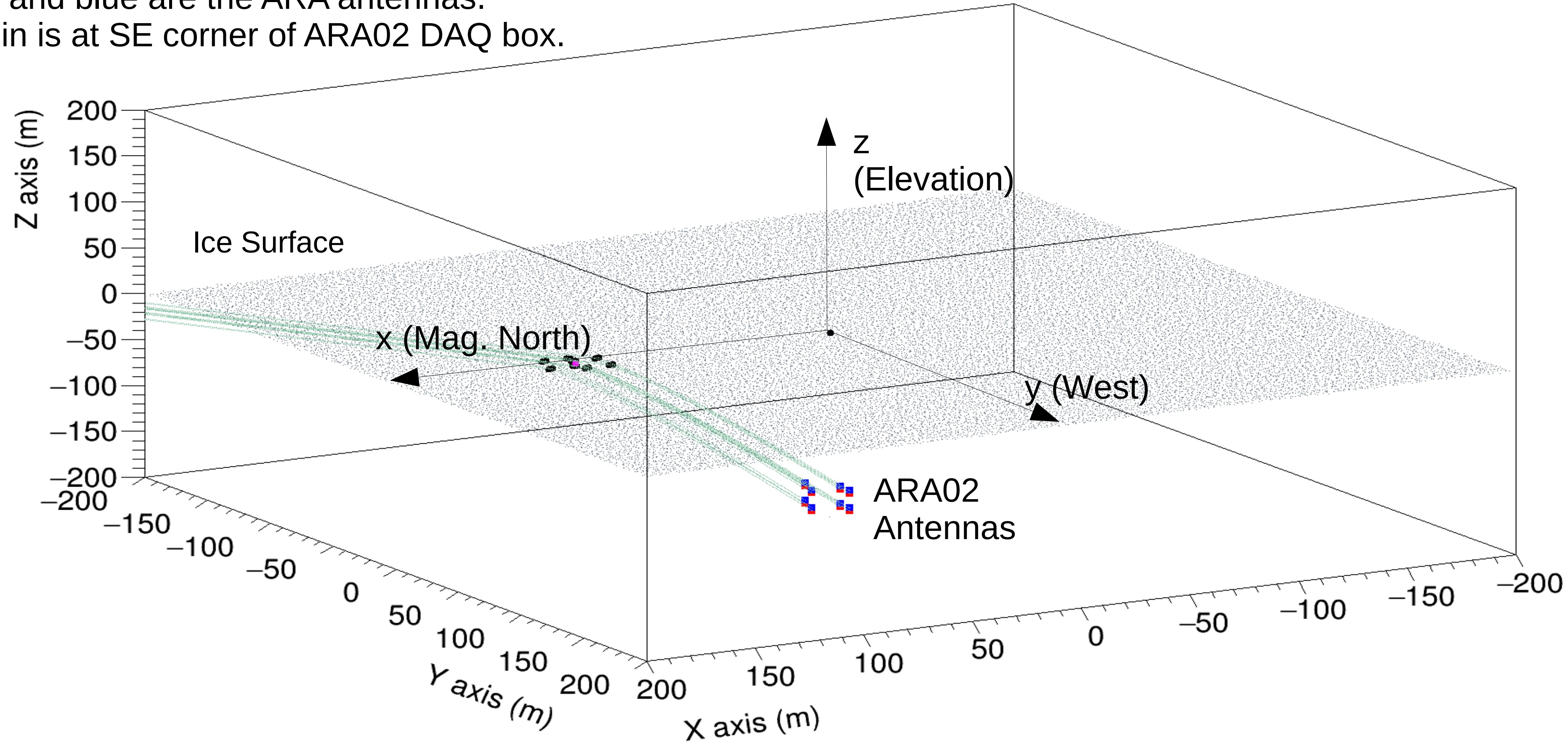
8) Time the waveforms correctly to show which channels triggered first and also to take into account the cable delays.

9) Use Power SNR and ARA trigger timing condition to see if theshower triggers the station or not

Overall Picture-I : The 16 incident points on the ice

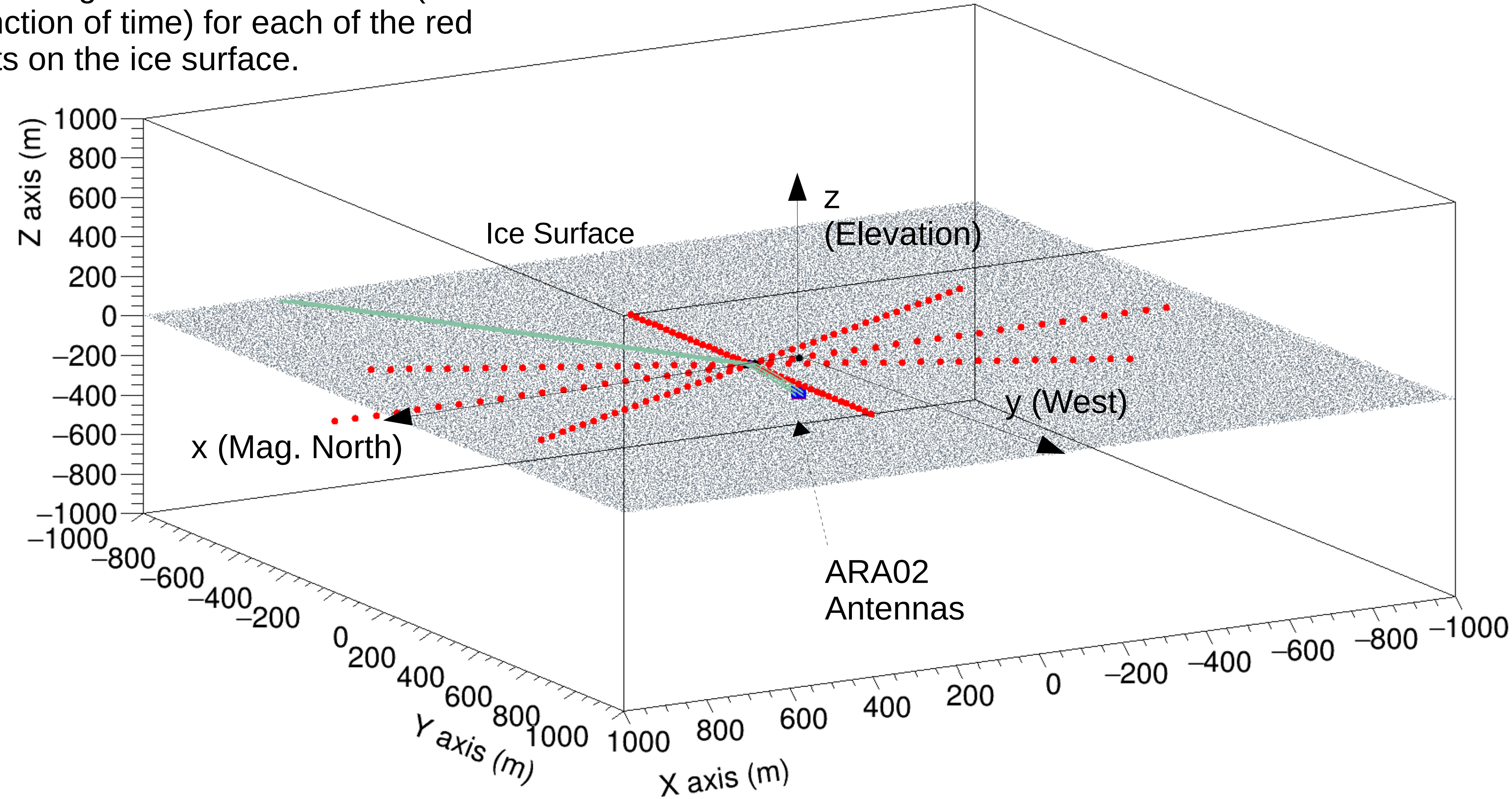
Pink dot is the shower core.
Black dots are where it enters the ice.
Red and blue are the ARA antennas.
Origin is at SE corner of ARA02 DAQ box.

Shower θ=60 deg and φ=360 deg.



Overall Picture-II : The 160 observer positions in the star pattern

COREAS gives an E-field vector (as a function of time) for each of the red points on the ice surface.



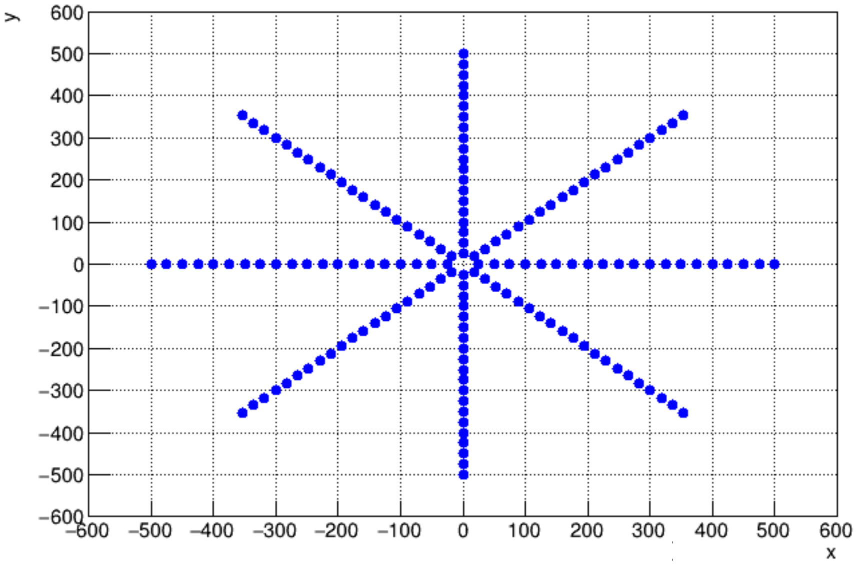
The Star Shaped Pattern

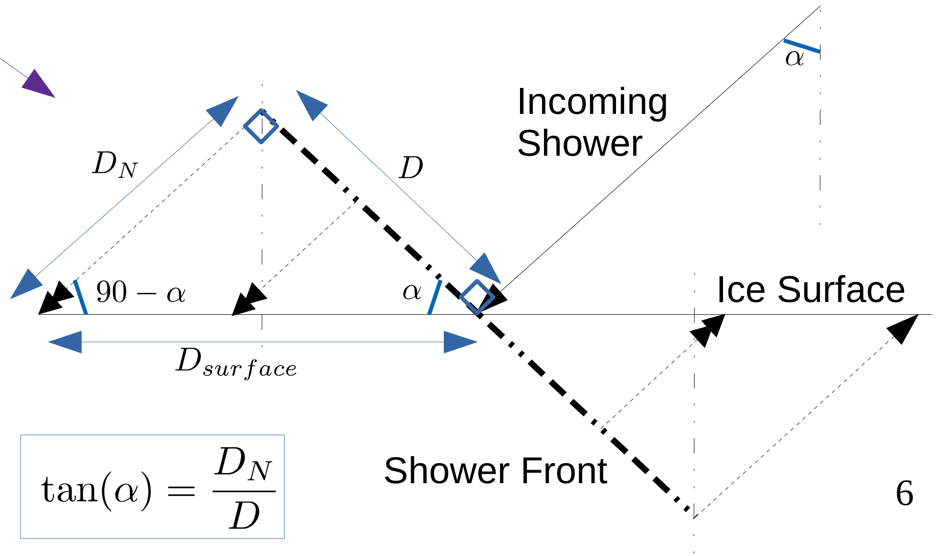
- The Star has:
  - 8 arms
  - 160 positions (20/arm)
  - Each arm 500 m long (25 m dist. btw each observer position.)

- The positions on the star have to be projected on the ground to include the “stretching” that happens due to a non-zero zenith angle.

- If there is an incoming shower at zenith angle α any point on the shower front with a distance D will have the following distance from the shower axis on the ice surface:

$$D_{surface} = D\left(\frac{\sin(\alpha)^2}{\cos(\alpha)} + \cos(\alpha)\right)$$





Analytic Raytracing

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

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

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

Finding the 16 hit points on the ice

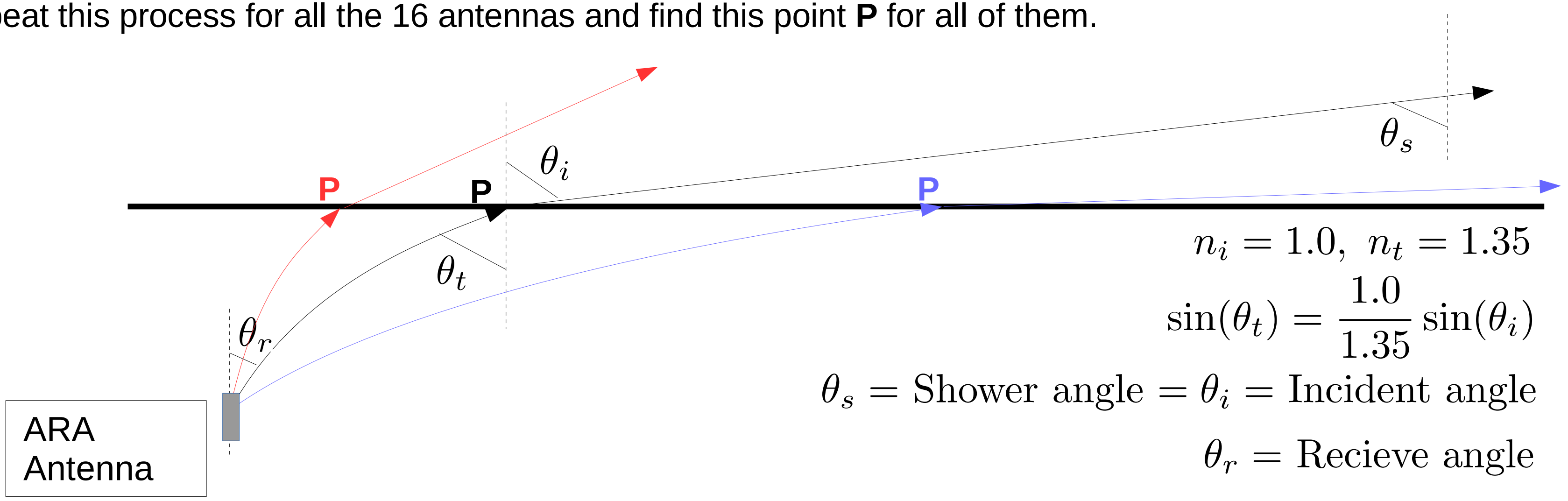
- Depending on the direction of the incoming Shower this point **P** (on the ice surface) can be further or nearer to the receiving antenna.

- 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_r. First I find the value of θ_s 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.



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

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

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

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

Thin Plate Spline interpolation

- The idea for 2-D interpolation here is that a surface should be able to pass through all the data with the least amount of required bending.
  - It produces smooth surfaces, which are infinitely differentiable.
  - There are no free parameters that need manual tuning

- It basically gives us the following function which is used for the interpolation:

$$f(x,y) = a_1 + a_2 x + a_3 y + \sum_{i=1}^{P} w_i U(||(x_i, y_i) - (x,y)||)$$

here $U(r) = r^2 \log(r)$ where r is the distance the two points.

Finding the TPS Coefficients and Weights

We have to solve the matrix equation: $L^{-1}V = (W|a_1a_2a_3)^T$, 163x1

$$L = \begin{bmatrix} K & P \\ P^T & 0 \end{bmatrix}, 163\text{x}163$$

$$V = \begin{bmatrix} v_1 \\ v_2 \\ \dots \\ v_P \end{bmatrix}, 160\text{x}1$$

Contains the z-values of all the points.

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \dots \\ w_P \end{bmatrix}, 160\text{x}1$$

Weights

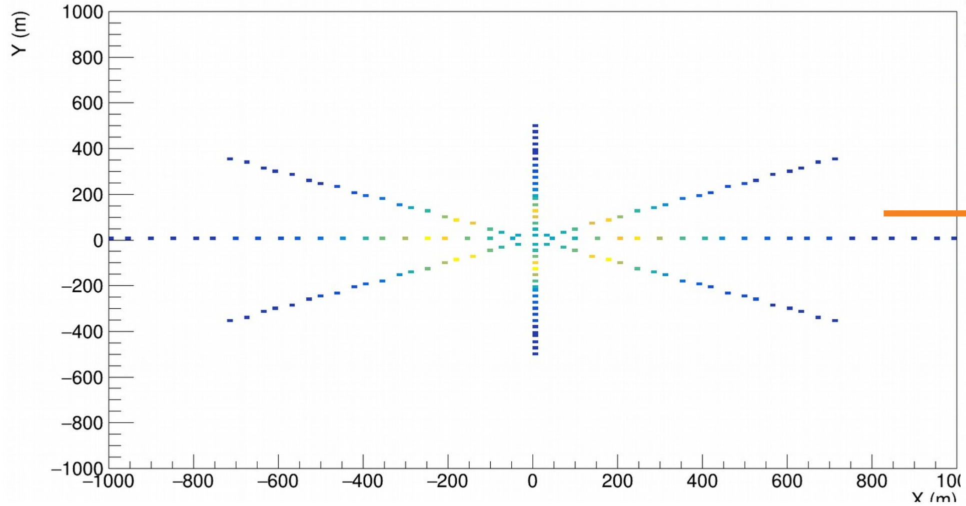
$$P = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ \dots & & \\ 1 & x_P & y_P \end{bmatrix}, 160\text{x}3$$

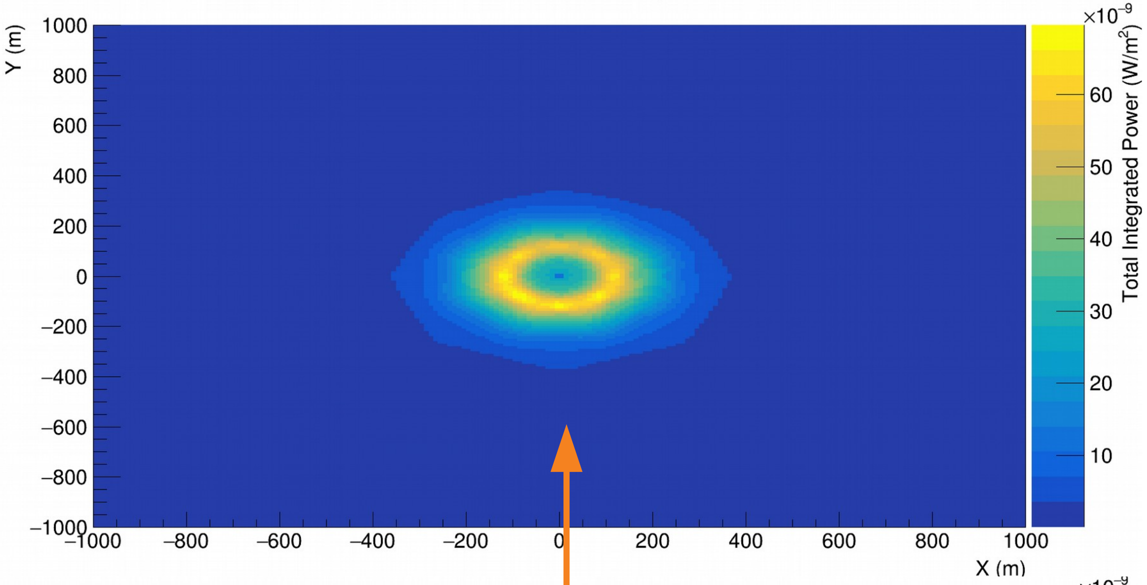
The x and y coordinates of all the data points.

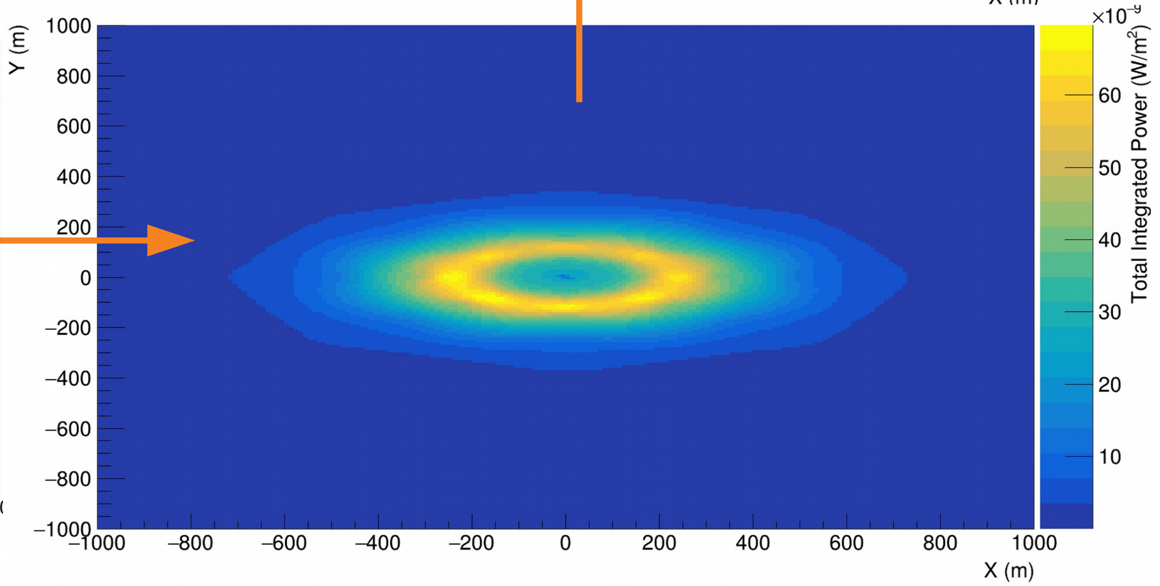
$$K = \begin{bmatrix} U(r_{11}) & U(r_{12}) & \dots \\ U(r_{21}) & U(r_{22}) & \dots \\ \dots & \dots & U(r_{PP}) \end{bmatrix}, 160\text{x}160$$

Contains values of the function U(r) for all the different data points.

Interpolation results





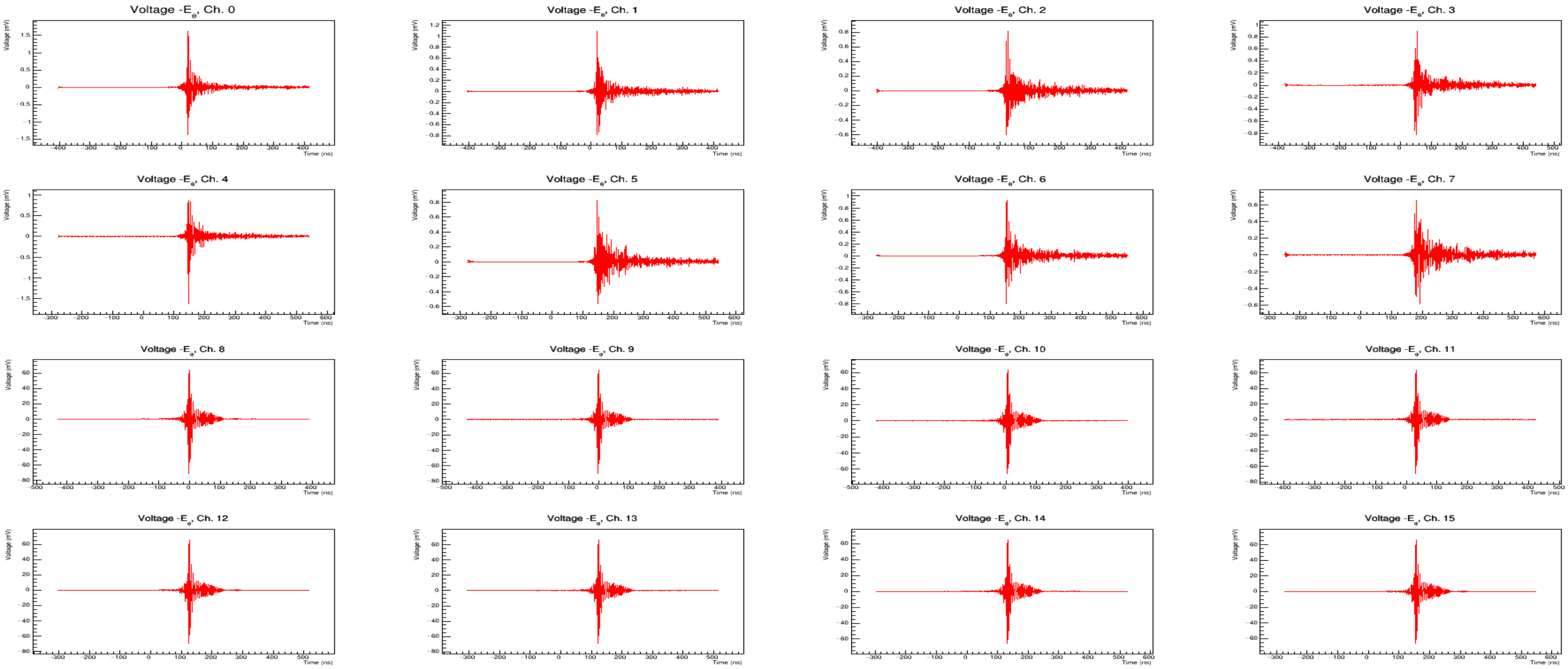


CR Voltage Waveforms

<u>Note:</u>
- X axis is in mV
- Y axis is in ns

- Shower simulated with theta=60 deg, phi=360 deg and 10^18 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 have stronger signal which is expected as most of the geomagnetic emission happens in Hpol at SP.

S1 **S2** **S3** **S4**



TV

BV

TH

BH

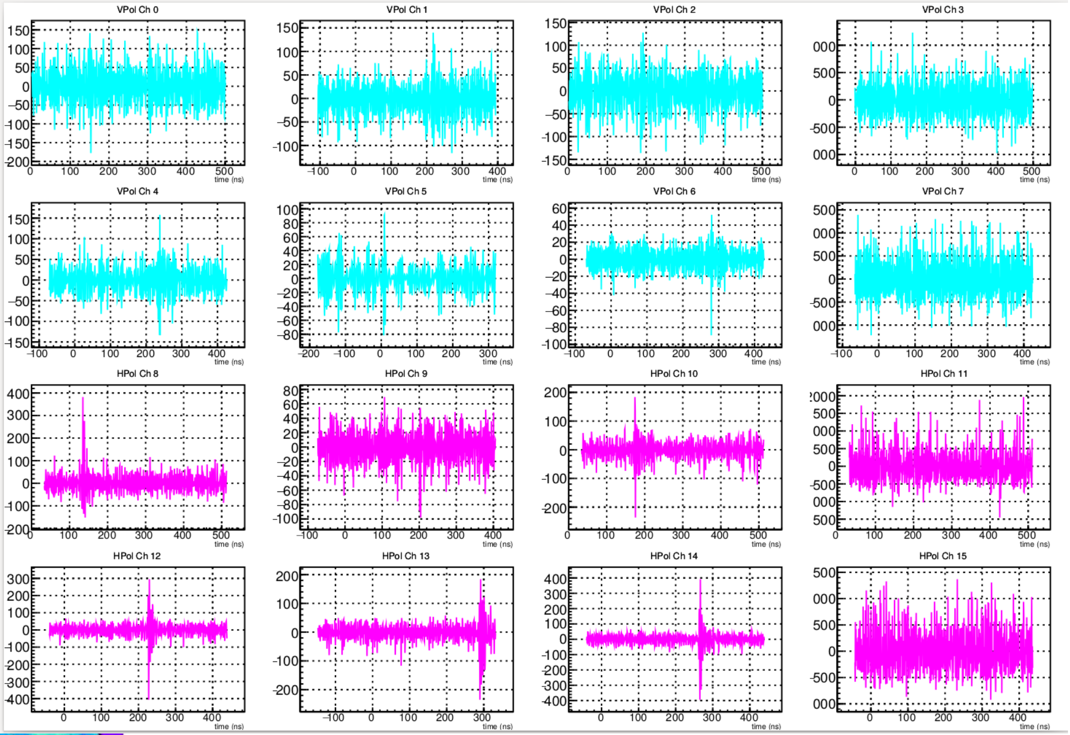
A couple of CR events

- Dave B. did rough quick search for CRs using the template matching method in the <2018 dataset.
  - The search was conducted two years ago and required
    - Waveform Power HPol > Waveform Power VPol,
    - and ii) at least 4 hits in HPol.
  - Just last week used four templates provided by me for Vpol and Hpol for shower coming at 30 deg and 60 deg Zenith and at an azimuth of 90 deg.

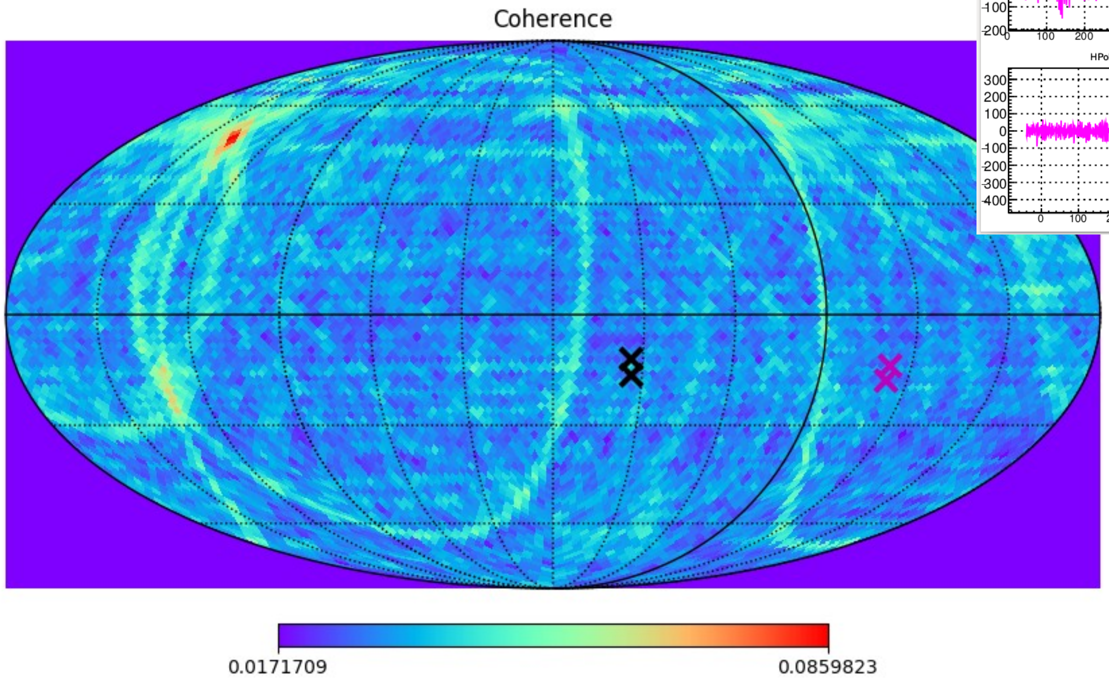
- He found a couple of candidates in the ARA 2 and ARA 3 data
  - A) ARA2, Year: 2017, Unixtime: 1488423054, run 8763, event 98649
    - 03/02/2017 @ 2:50am (UTC) – Windspeed: 6.1 m/s (not high)
  - B) ARA3, Year: 2014, Unixtime: 1408979533, run 3158, event 72641
    - 08/25/2014 @ 3:12pm (UTC) – Windspeed: 14.9 m/s (very high)
  - C) ARA3, Year: 2016, Unixtime: 1456249534, run 6426, event 88573
    - 02/23/2016 @ 5:45pm (UTC) – Windspeed: 11.0 m/s (high in compare with other values at that day)

- All of them have really strong Hpol content.
  - Event A reconstructs to the South Pole station
  - Event C reconstructs to the ICL/WT3
  - Event B seems to be coming from the direction of WT3 but has really steep zenith angle which indicates that the source is probably nearer than WT3.

Event B



Reconstruction just using Hpol channels:
Zenith: 40.2976 ,Azimuth: 228.333 ,
Radius: 200 ,MaxCoherence: 0.0859823



Could be a:

- CR
- Anthropogenic event
- Wind-generated-static

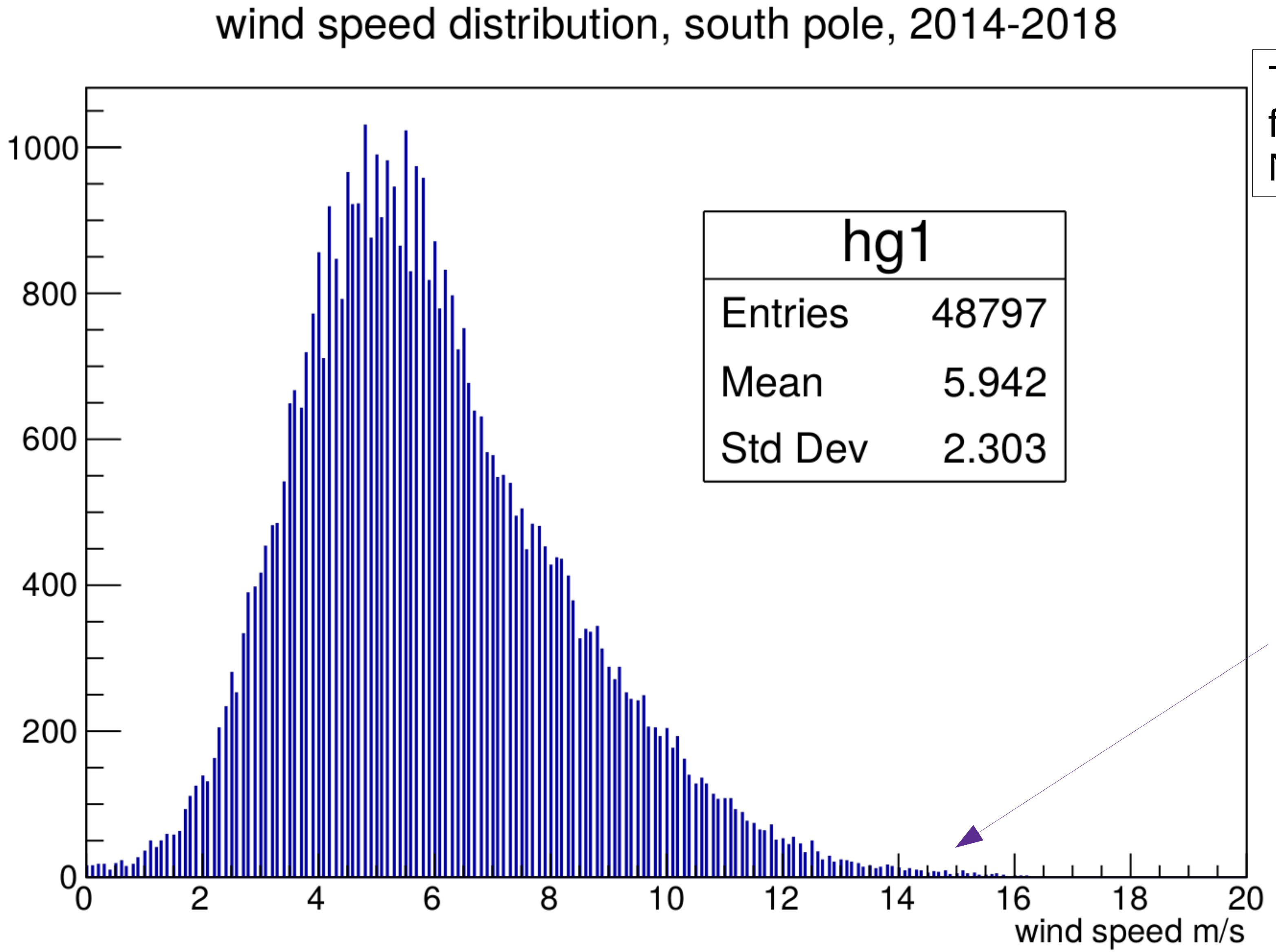
The Triboelectric effect

This was taken from Alisa Nozdrina

- Triboelectric effect is the appearance of electrical charges in the material due to the friction.
  - A strong wind cause a friction on the ice surface, which can create static surface charge.
  - Any contact between electrically charged material with an uncharged conductive object may lead to an electrical discharge via spark.
  - Spark cause the emission of the EM waves, which extend from the radio frequency to a visible light

- It can be a dangerous background for the cosmic rays analysis, since both of these signals propagate downwards to ARA stations.

- Alisa Nozdrina observed slight correlation of event rate of ARA02 with wind speed though no correlation observed between RMS voltage and wind speed.



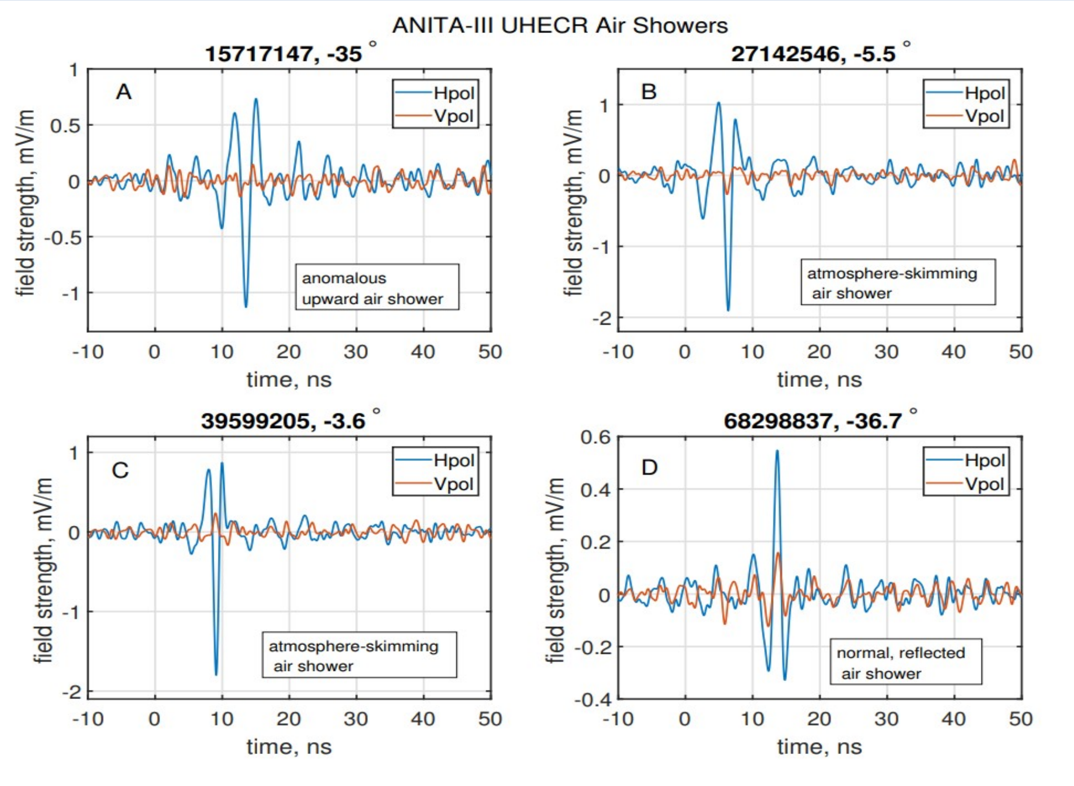
This was taken from Alisa Nozdrina

Wind speeds for the days of all 3 of those events come in the larger than average values

Event B was in excess of 14 m/s, corresponding to the 99.975% percentile

Anita "Mystery" Events

- ANITA's balloon flights have seen several UHECR (~100 in total) and a couple of mystery events:
  - ANITA-I
    - 12 Ref. , 3 Dir., 1 Myst. Event , E_{avg}=2.9 EeV
  - ANITA-III
    - 18 Ref. , 2 Dir. , 1 Myst. Event
  - At 1 EeV, the SM neutrino L_{int} is of order 1600 km water-equivalent and the flux is attenuated by a factor of 10^−5, effectively excluding a neutrino origin for this event.
    - Event implies a chord distance of 3x10^4 km
  - Estimates indicate that a SM cross-section suppression factor of ∼ 3 − 4 is required to make this event a plausible ν_τ candidate
- They could be possibility explained by the triboelectric effect or the charge extinction mechanism.



arXiv:1603.05218v5 [astro-ph.HE], arXiv:1803.05088v1 [astro-ph.HE]

Things still left to do

- Do interpolation across the whole frequency spectrum of electric fields across the whole footprint area.
- Integrate raytracing within CoREAS (if possible?)
  - This still needs to be discussed with Tim.
- Do the efficiency calculation for ARA.
- After generating a shower library start the template matching process and look for cosmic rays.

Backup

Antenna Coordinates for COREAS

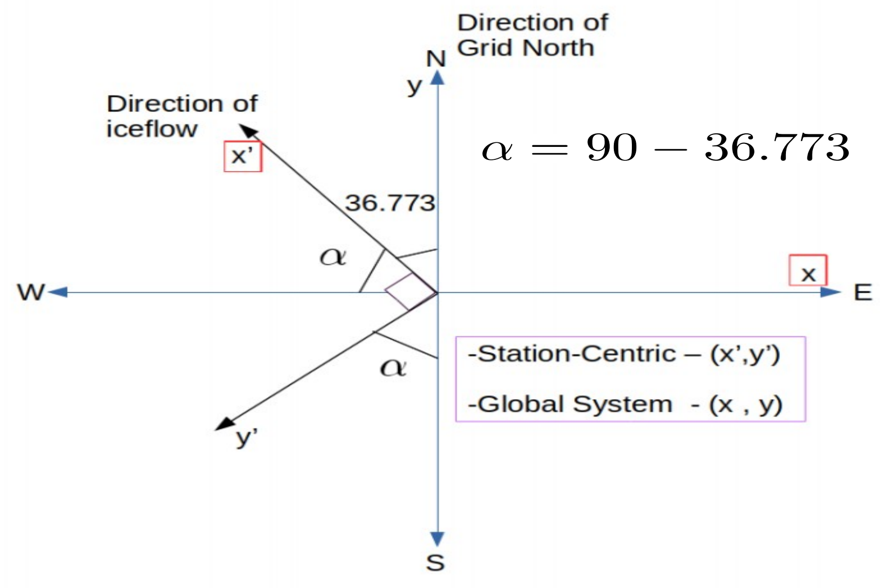
- First we need to get the ARA station coordinates in the CORSIKA coordinate system.

- ARA station coordinates are in terms of ARA Station Centric coordinate system.
  - At the South Pole the ice flows along a line near 40 W longitude by about 10 m/year.
  - The ARA coordinate system is set in the ice such that it also moves with the ice flow i.e the x-axes points in the direction of flow

- In CORSIKA the x-axes points towards the Magnetic north.

- So we basically have to do 2 rotations (on the next slide).

1. ASC to Grid (or Global) coordinate system

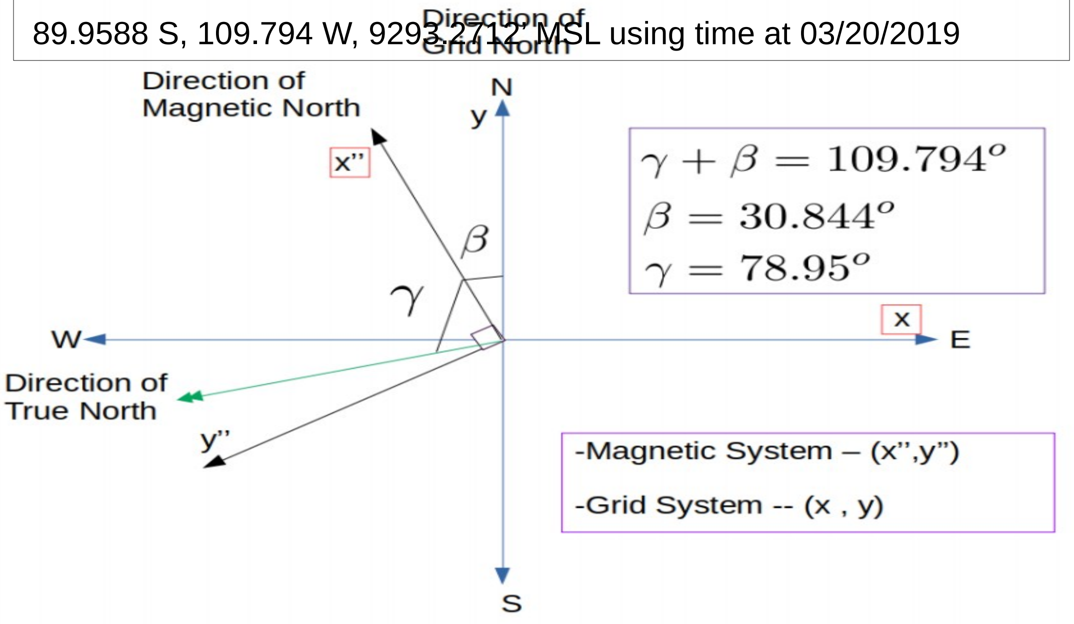


$$x = -(x' \cos(\alpha) + y' \sin(\alpha))$$
$$y = x' \sin(\alpha) - y' \cos(\alpha)$$

2. Grid to Magnetic North coordinate system

γ is the angle of declination calculated using the IGRF12 model using GeographicLib B-field calculator (https://sourceforge.net/projects/geographiclib/) for the parameters for ARA2 DAQ SE corner:

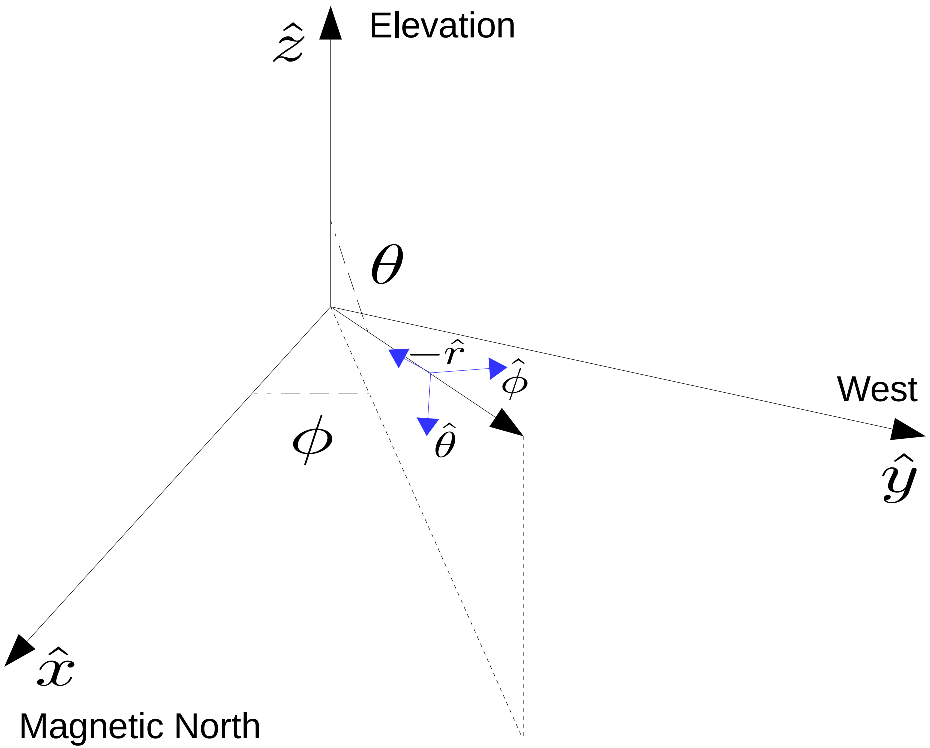
89.9588 S, 109.794 W, 9293.2712' MSL using time at 03/20/2019



$$x'' = y \cos(\beta) - x \sin(\beta)$$
$$y'' = -y \sin(\beta) - x \cos(\beta)$$

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: $\boxed{\vec{E}(t) = E_r(t)\ \hat{r} + E_\theta(t)\ \hat{\theta} + E_\phi(t)\ \hat{\phi}}$

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.

- For cases when $\mu_1 \approx \mu_2 \approx \mu_0$

$$n_1 = 1,\ n_2 = 1.35$$
$$\theta_i = \ \text{Angle of incidence}$$

  – 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

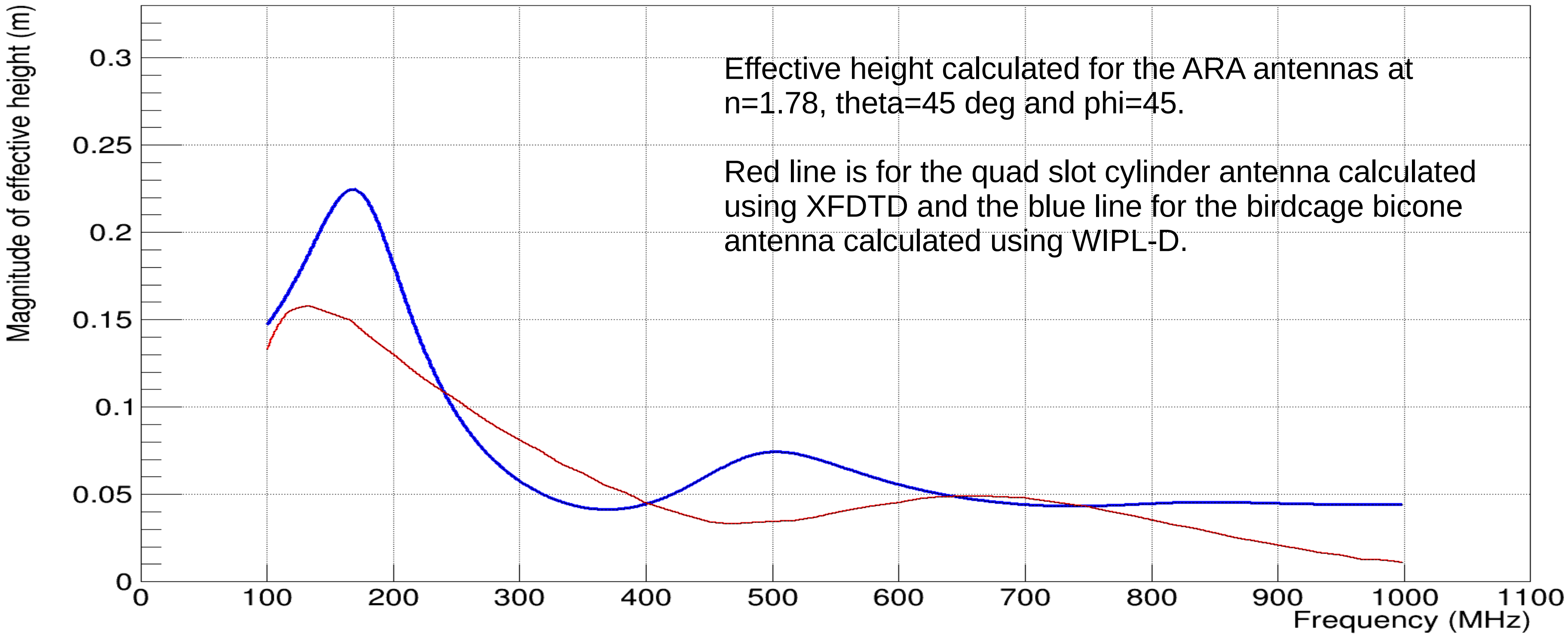
-Substituting $A_{eff} = \frac{\lambda^2 G(\theta,\phi)}{4\pi}$ into $|\vec{h}_{eff}|$

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

Note:Gain is in linear units.

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

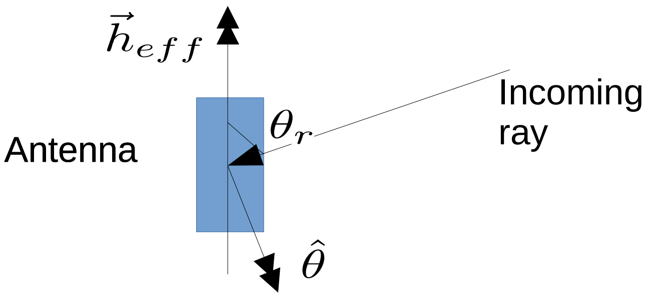
The effective height magnitude (m) vs frequency (MHz)



H_{eff} vector direction

For ARA Bicone Vpol antennas:

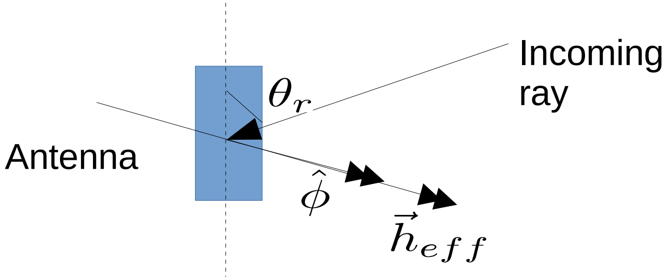
$$\vec{h}_{eff} = |\vec{h}_{eff}|\ \hat{z}$$



WIPL-D model used for Vpol antennas

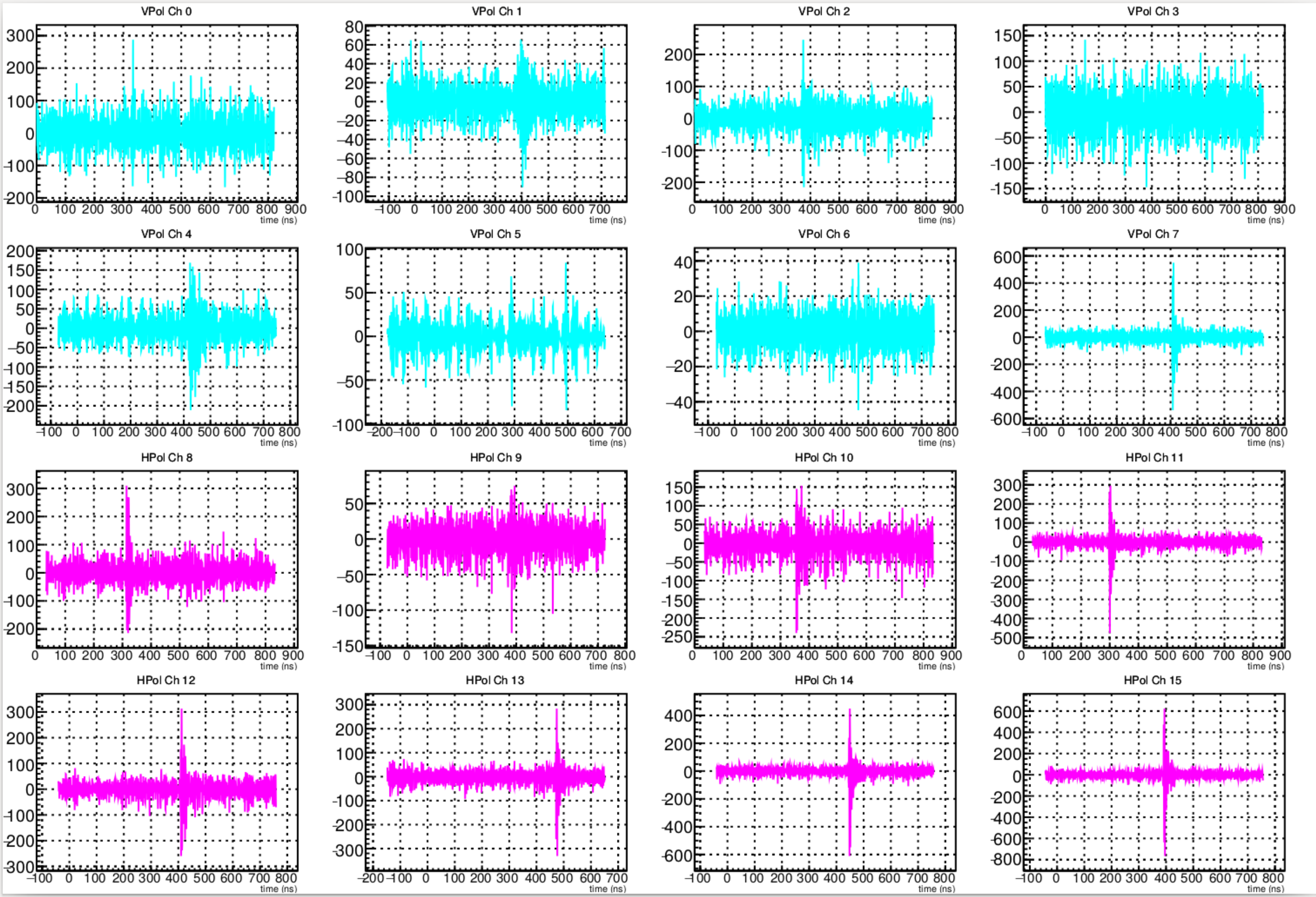
For ARA Quad Slot Cylinder Hpol antennas (due to azimuthal symmetry) :

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

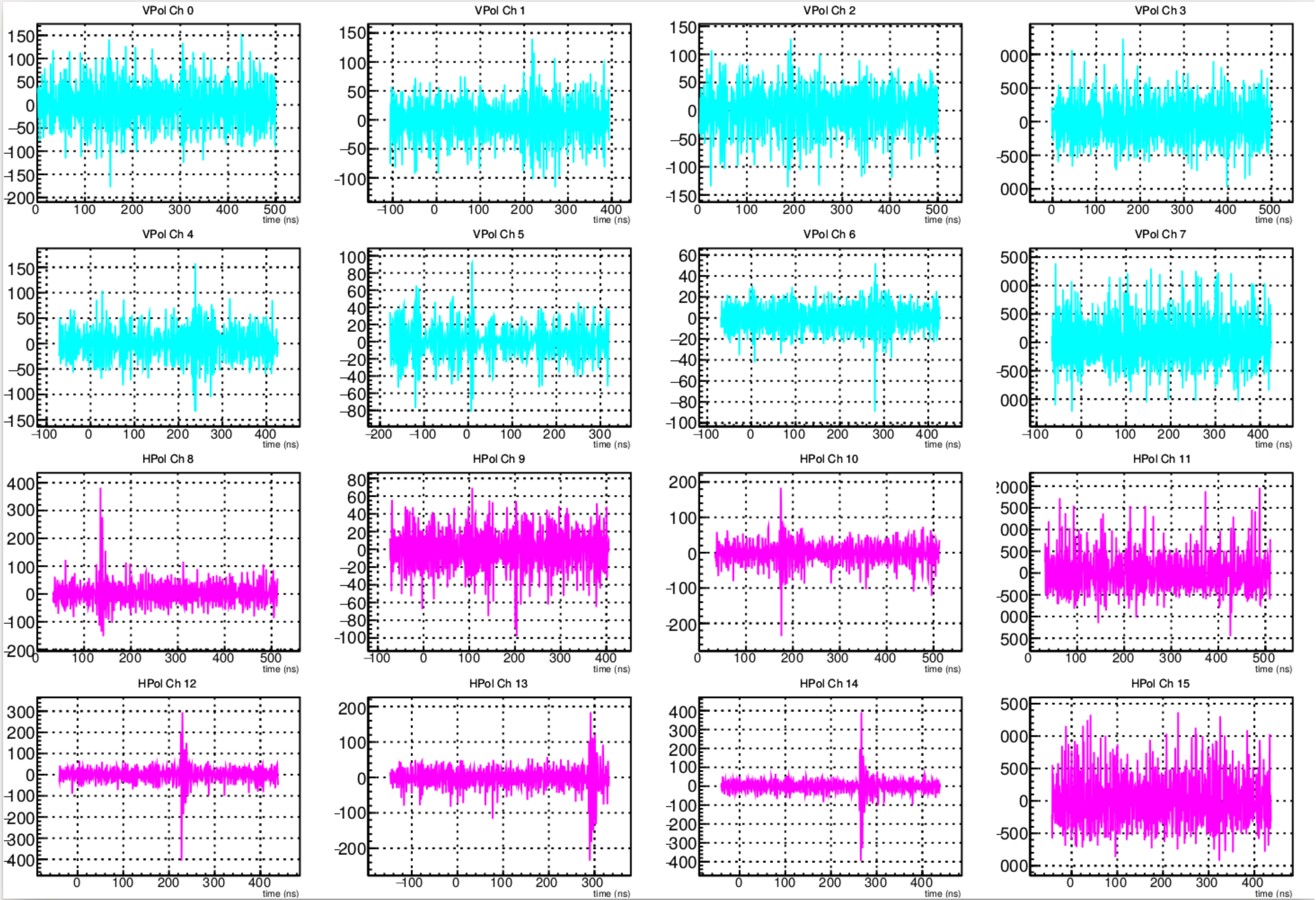


XFDTD model used for Vpol antennas

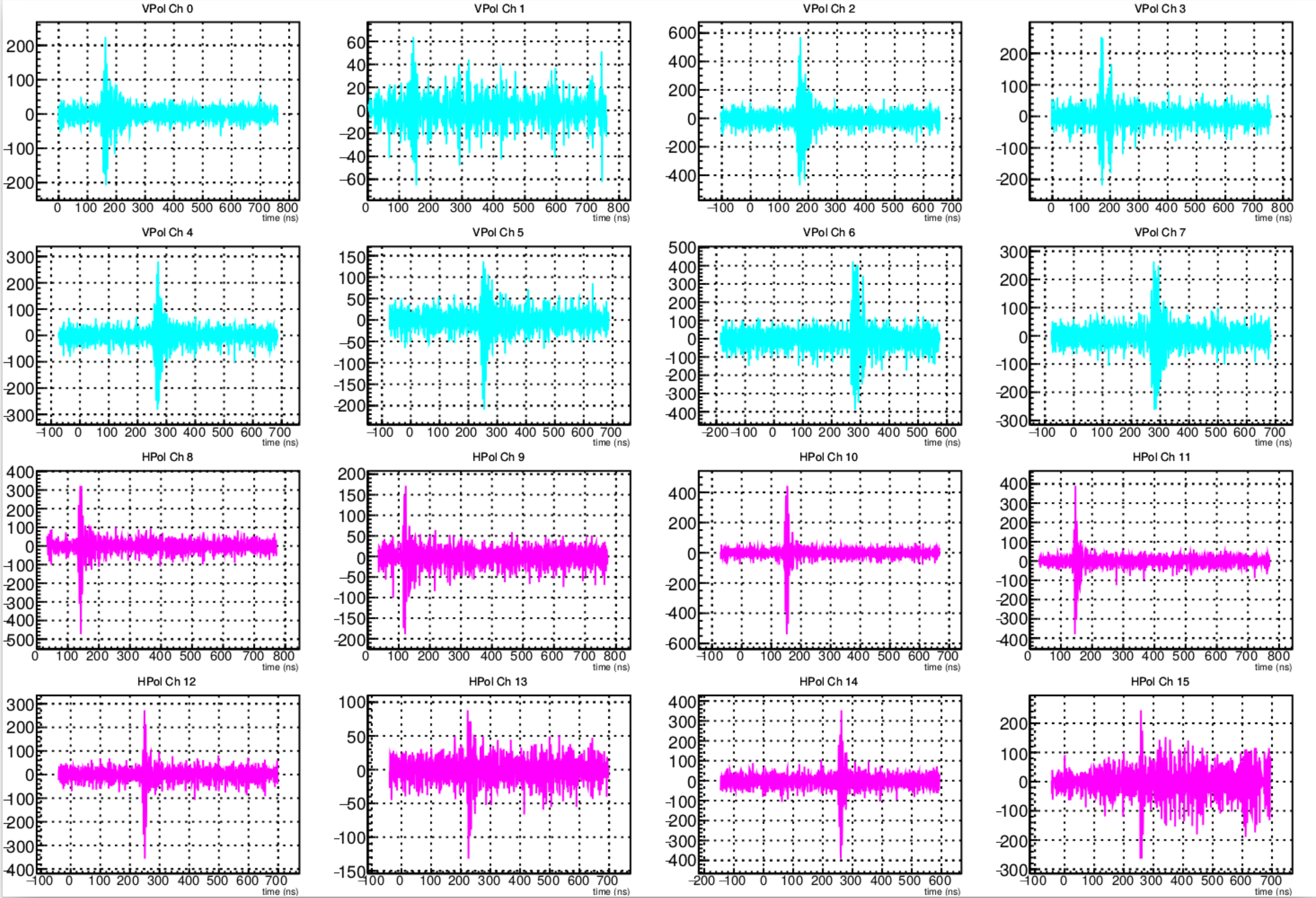
Run 6426,
Evt 88573



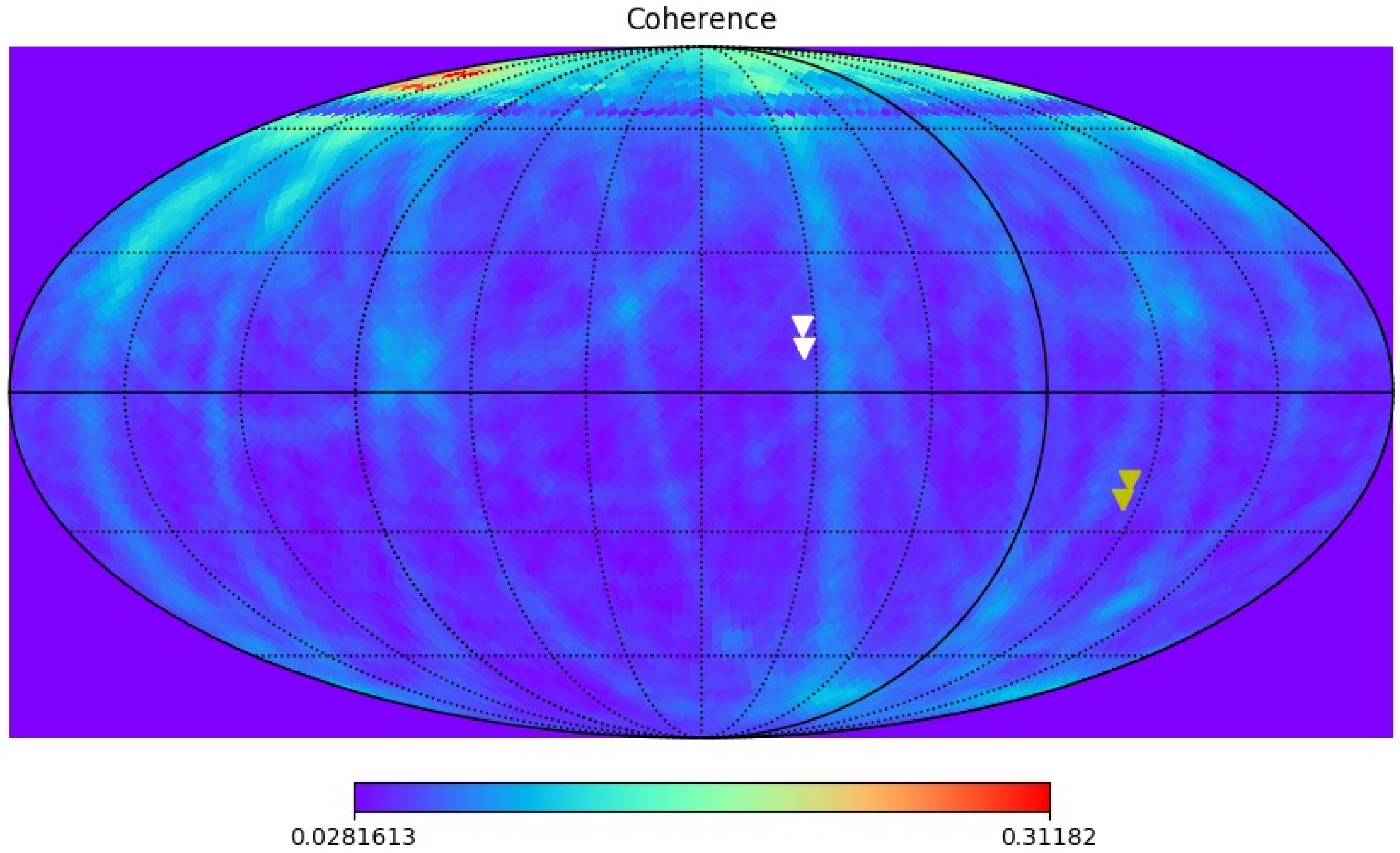
Run 3158,
Evt 72641



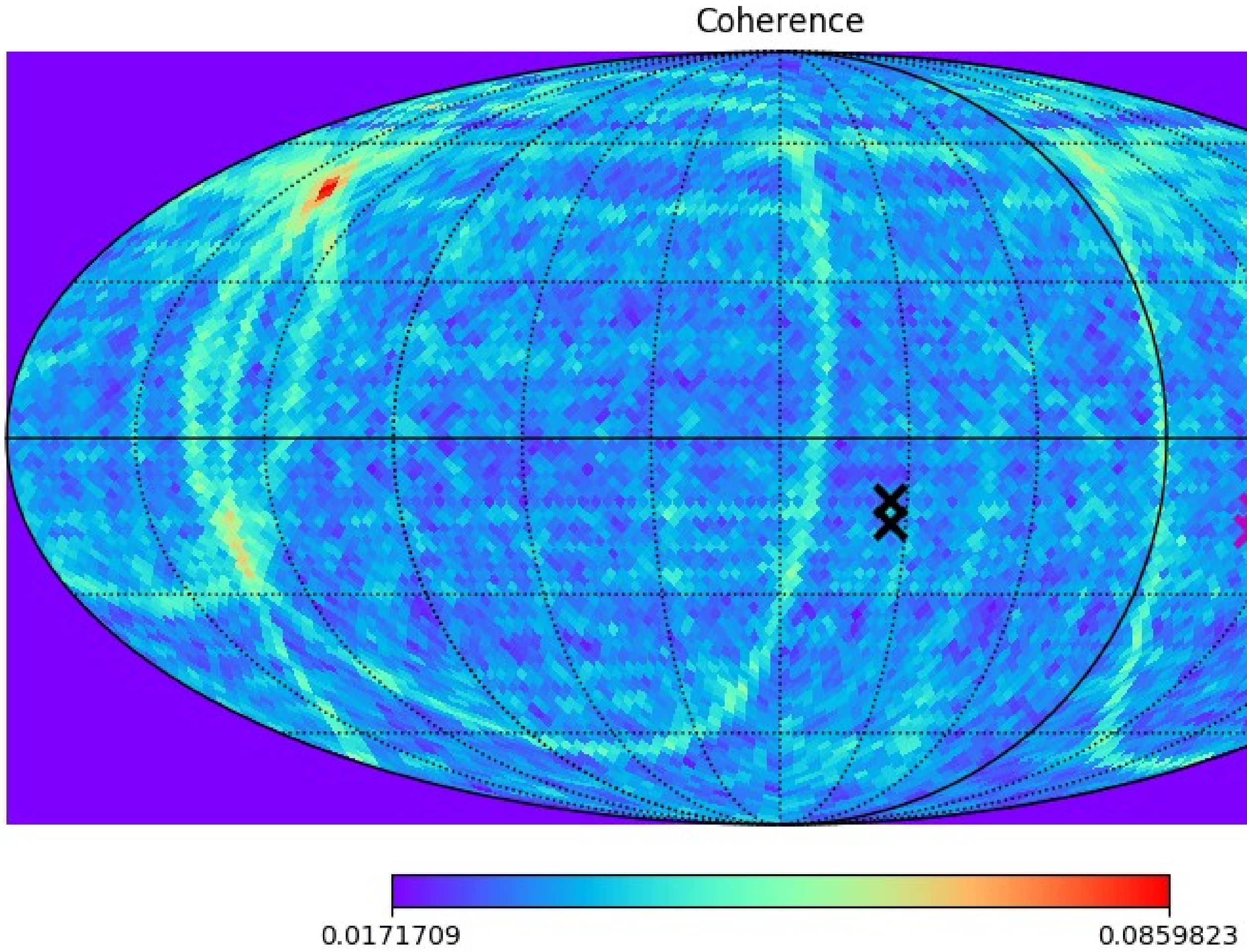
Run 8763,
Evt 98649



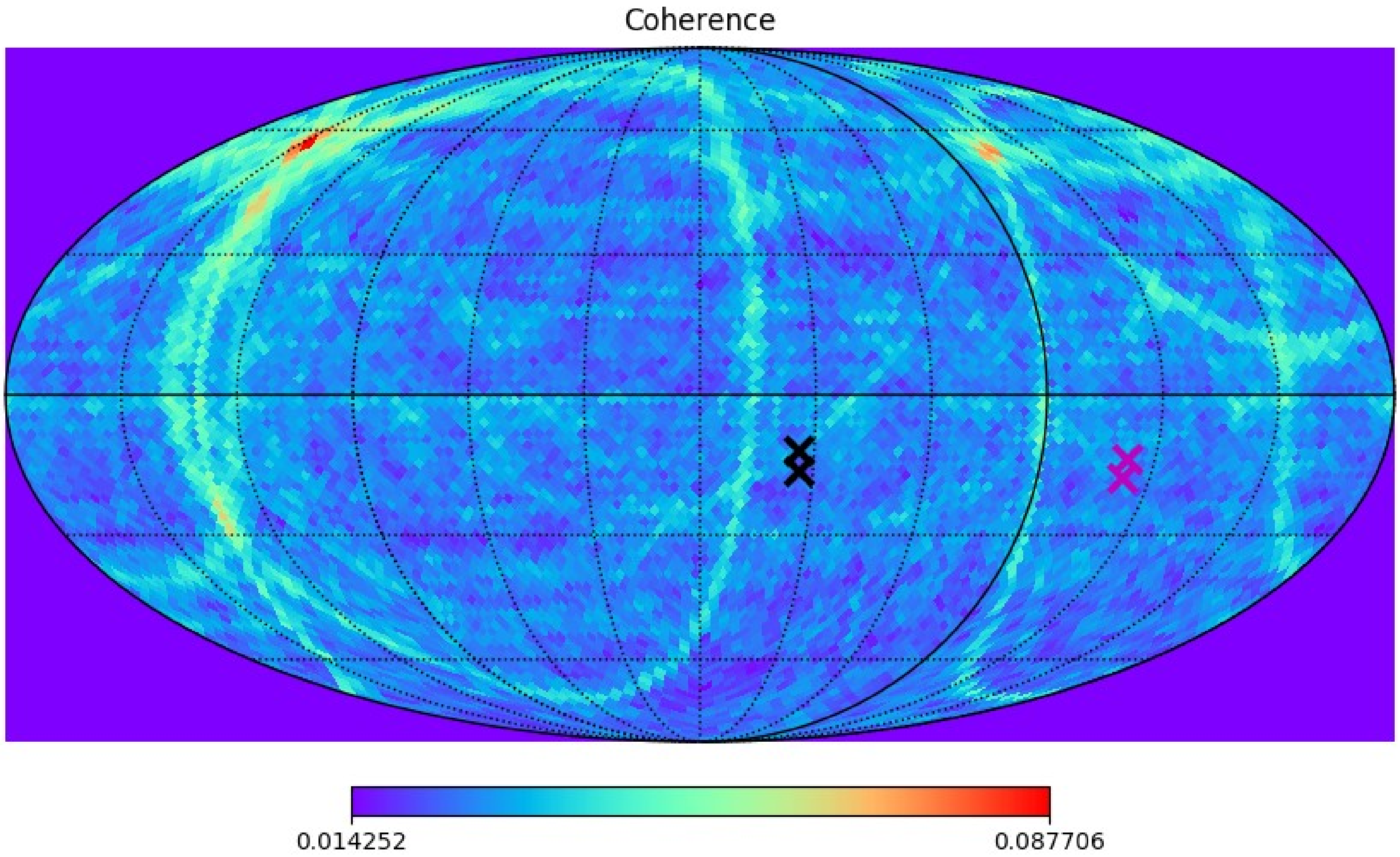
- ARA2, Run 8763, EventNumber: 98649, Unixtime: 1488423054 , **Hpol** reco.
- Zenith: 13.1865 ,Azimuth: 255 ,Radius: 200 ,MaxCoherence: 0.31182

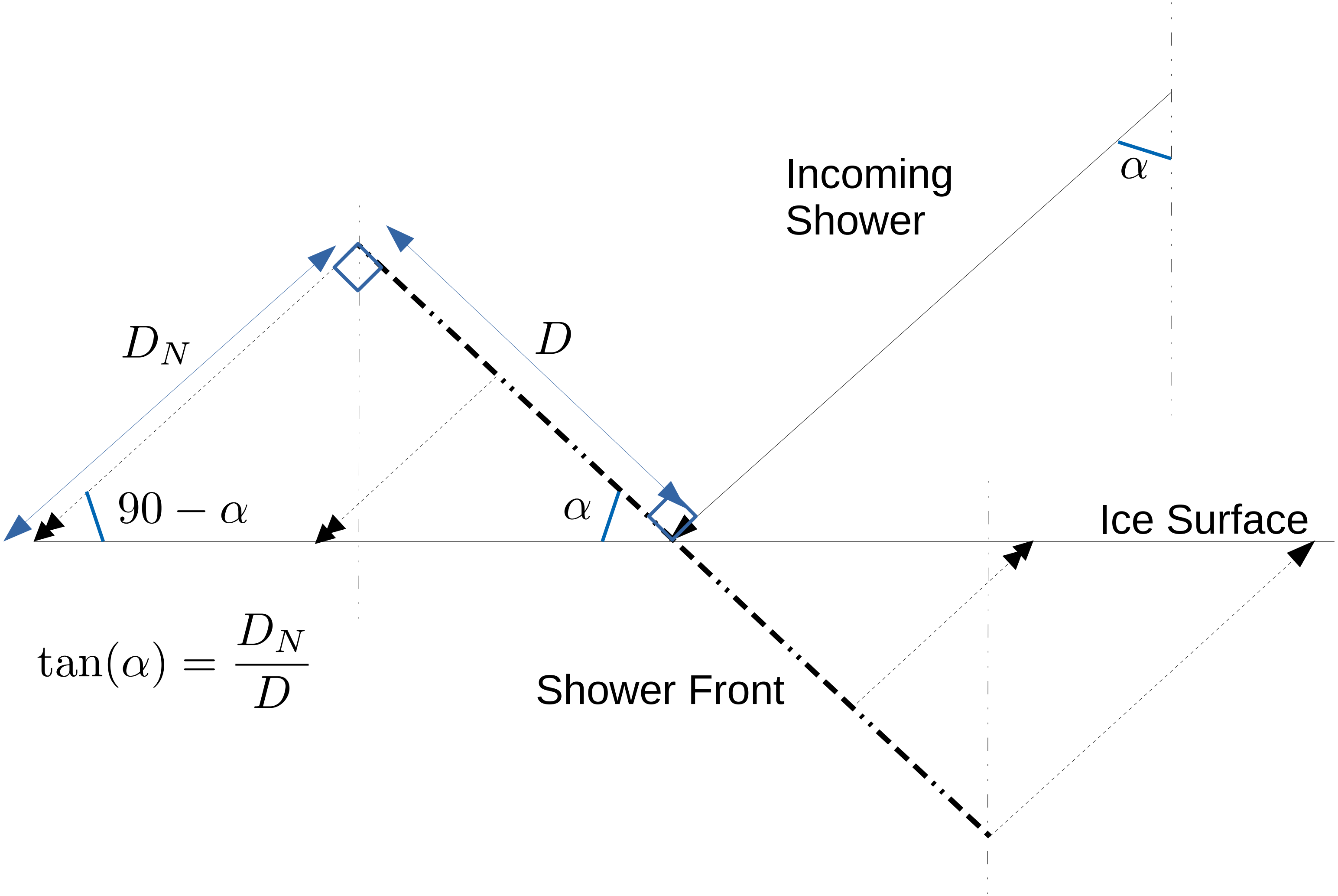


- ARA3, Run 3158, EventNumber: 72641, Unixtime: 1408979533 , **Hpol** reco.
- Zenith: 40.2976 ,Azimuth: 228.333 ,Radius: 200 ,MaxCoherence: 0.0859823



- ARA3, Run 6426, EventNumber: 88573, Unixtime: 1456249534 , **Hpol** reco.
- Zenith: 32.6005 ,Azimuth: 239.318 ,Radius: 40 ,MaxCoherence: 0.087706





$$\tan(\alpha) = \frac{D_N}{D}$$