# A Complete Theoretical Framework for Antarctica based ANITA experiment and its Implication for the ANITA Anomalous Events

**HEP Seminar**

The Service de Physique des Particules Élémentaires of the
Université Libre de Bruxelles (ULB)
Inter-University Institute for High Energies IIHE (ULB-VUB)
Belgium, Europe

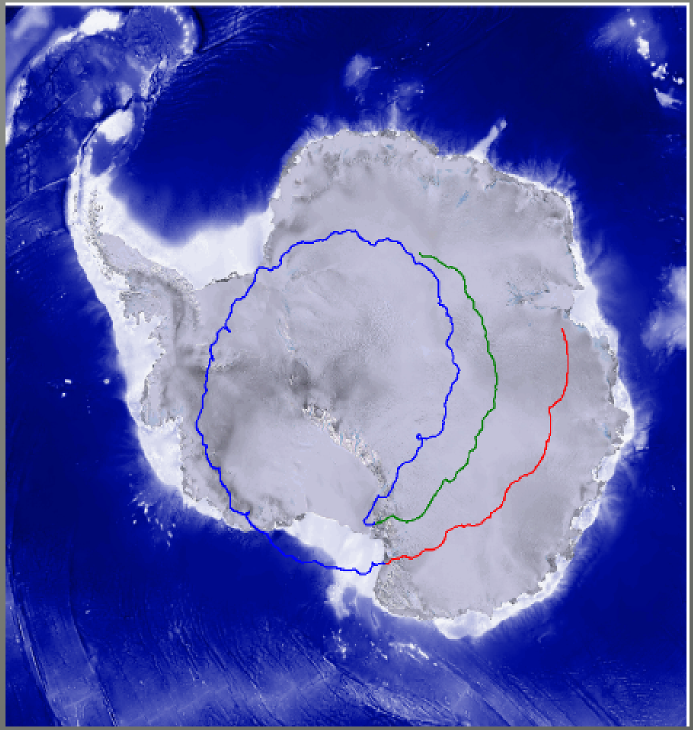
Paramita Dasgupta, IIT Kanpur, India

24th April, 2020

# The ANITA Experiment

## (ANtarctic Impulsive Transient Antenna)

**NASA long-duration balloon payload with an array of radio antennas.**



**He balloon flying at a height 37Km above Antarctica, carries array of radio antennas to detect radio signals from Cosmic Neutrinos/UHECRs**

# Goals of ANITA Mission

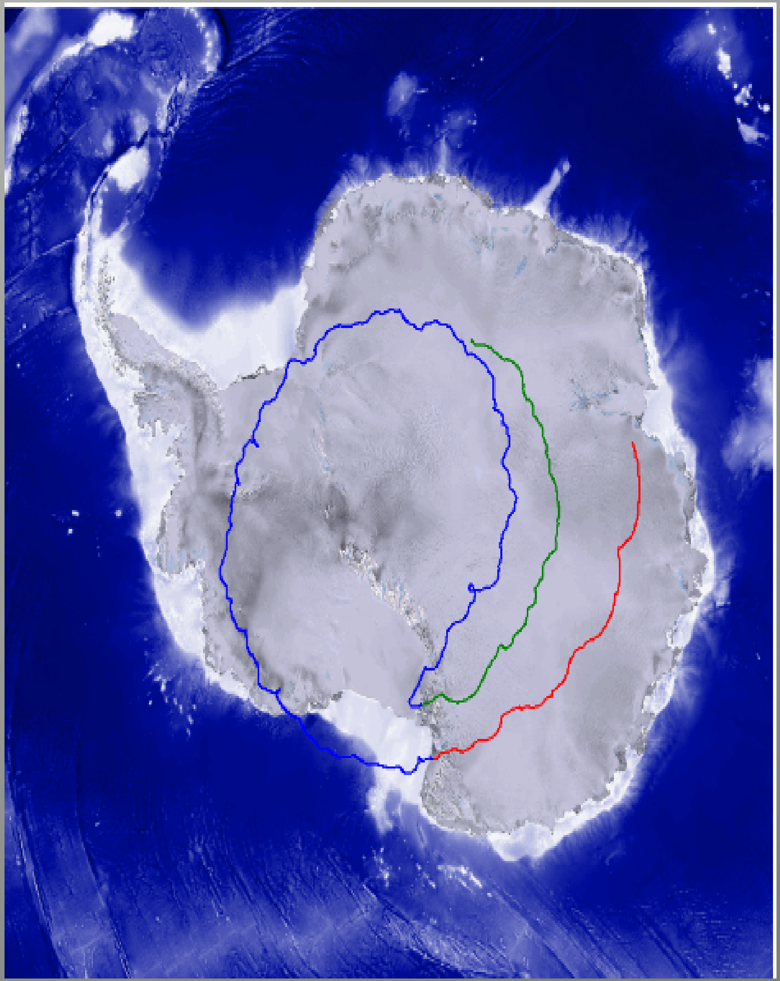
- Search for high energy cosmogenic neutrinos by detecting their impulsive radio signals emitted via the Askaryan effect in the Antarctic ice sheet ← Primary goal

- ANITA is the First Experiment to Implement Radio Technique in the EeV Energy regime (1 EeV = $10^{18}$ eV)

- UHECR induced radio emission in Air detected by balloon-borne radio antennas

# Why Antarctica?

For EeV scale detection, we need huge detector



Lots of ice ~ 1 million Km$^3$

Coverage Radius ~ 700 Km

Detector at height ~ 37 Km

Ice has Excellent RF clarity

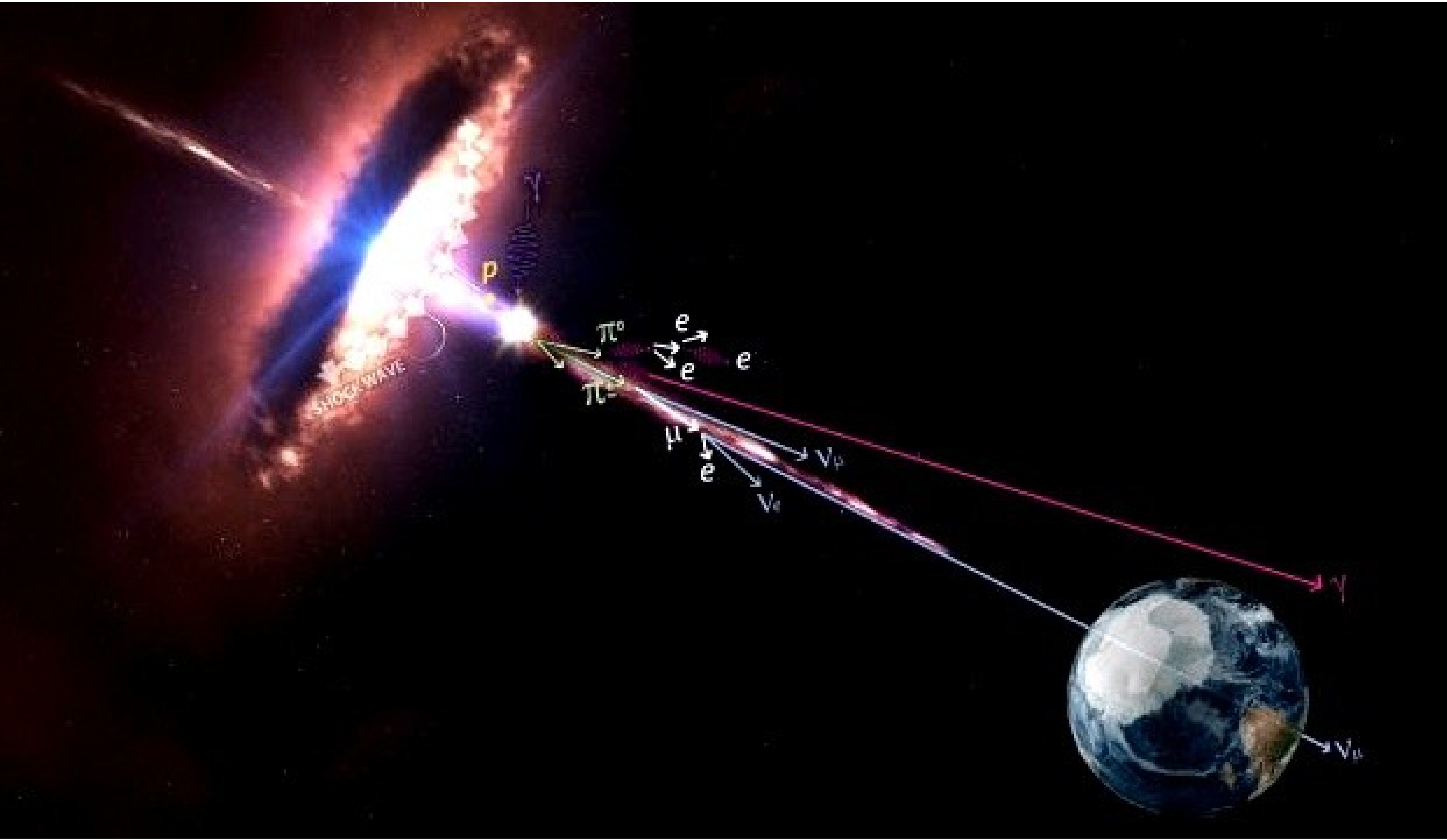
RF attenuation length: ~ 1km

Low Population, Less noise

IceCube (Energy ~ PeV), ARA, ARIANNA are other experiments in Antarctica

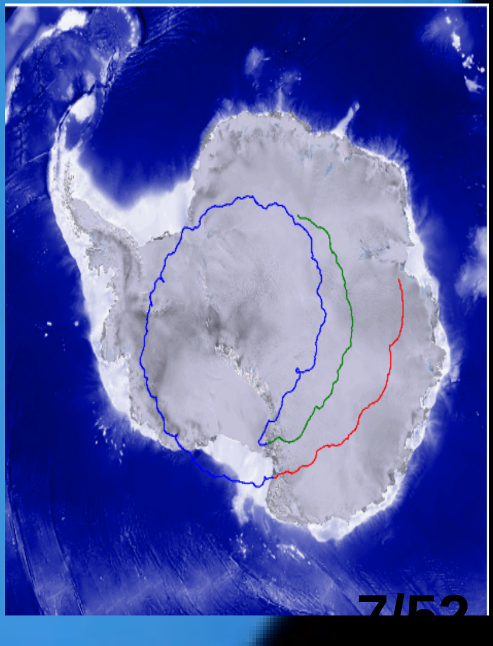
Journal of Astronomical Instrumentation VOL. 06, NO. 02 , P. Gorham, D.Z. Besson, P. Dasgupta, P. Jain et. al.

# UHE Neutrinos: The Ideal Astronomical Messengers

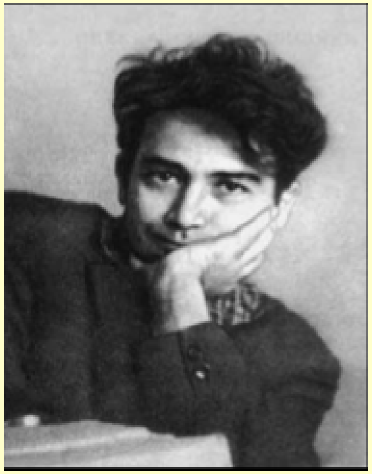


# Experimentalists During the Launch of ANITA

**28-32 days at float**



# Primary Goal of ANITA :

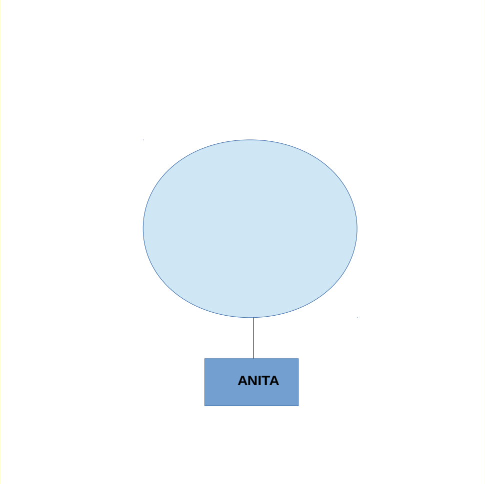


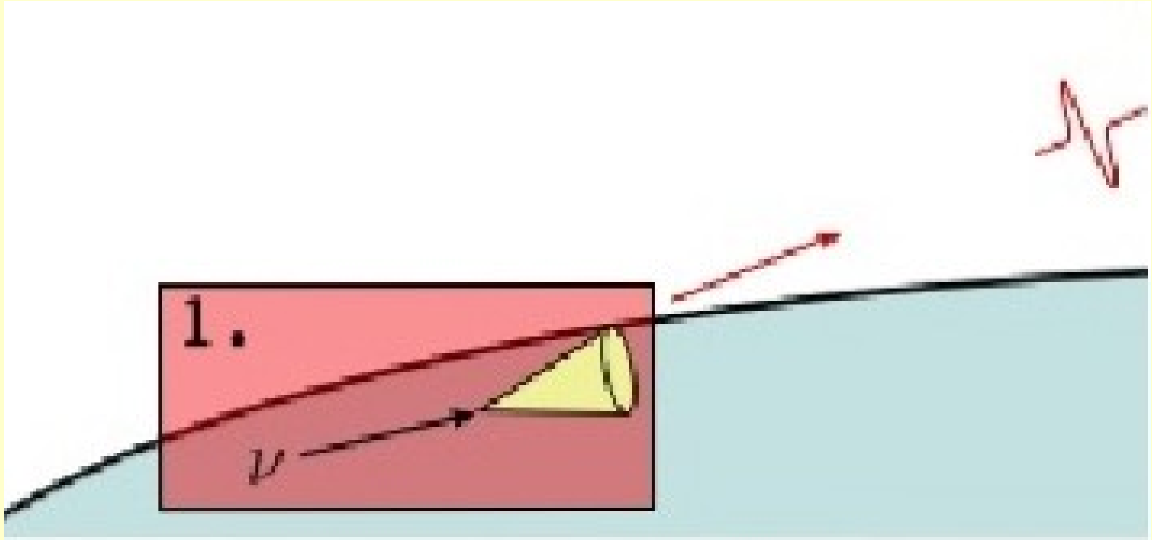
Gurgen Askaryan

## UHE ν Detection based on Askaryan Mechanism in dense medium (Antarctic ice)

ν + ice ($H_2O$) → knock-on collisions → excess $e^-$

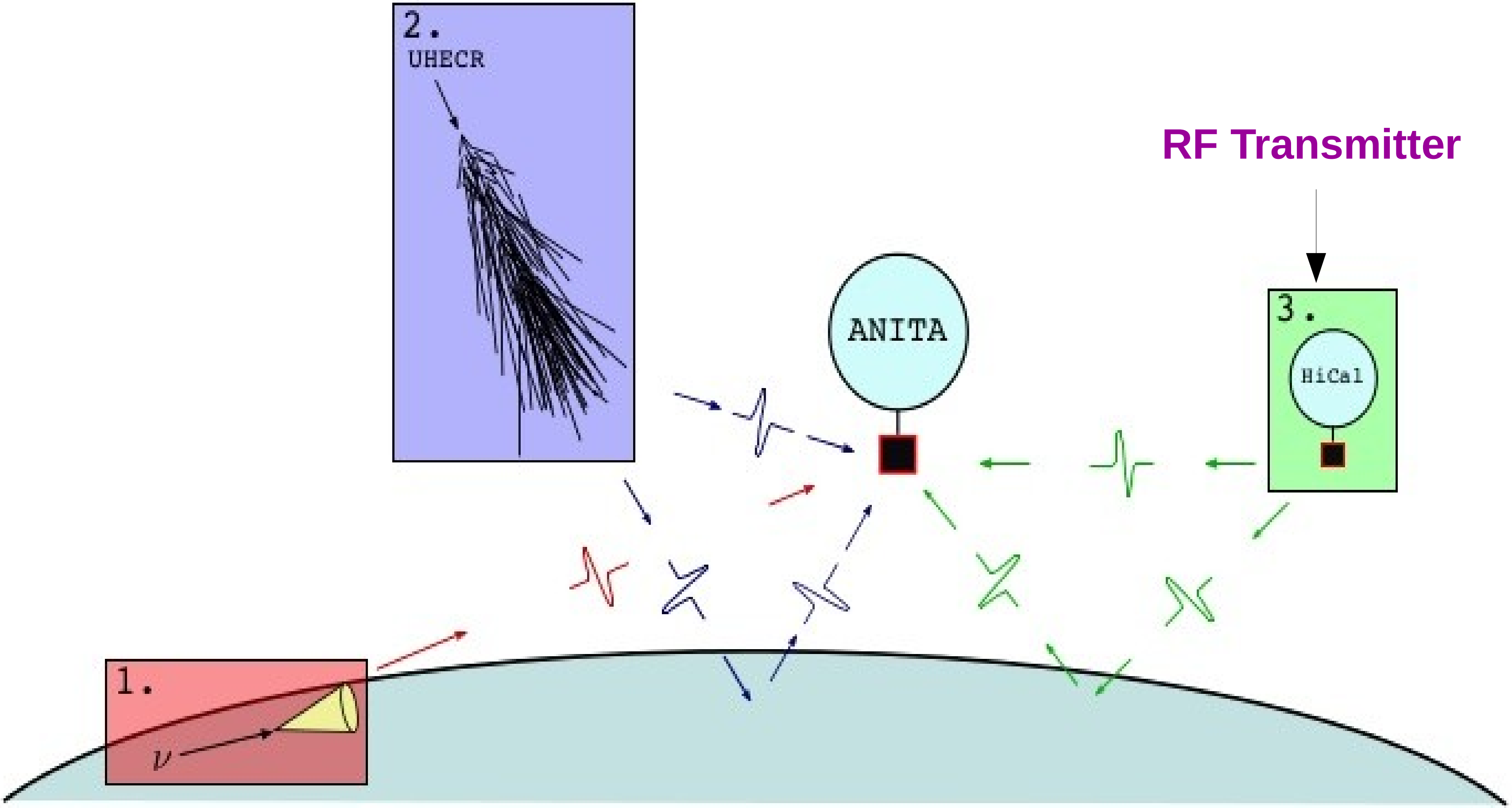
Charge excess moving with velocity greater than the velocity of light in the traversed medium → **Cherenkov Radiation**





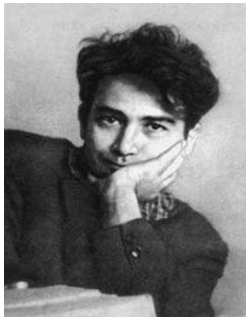
# Working Principle of ANITA

- **Detect UHE Neutrinos via Askaryan effect in ice ← Main Goal**
- **Coherent Geo-Synchrotron Radiation at Radio Frequencies from highly relativistic $e^+$-$e^-$ pair gyrating in Earth's mag. field**



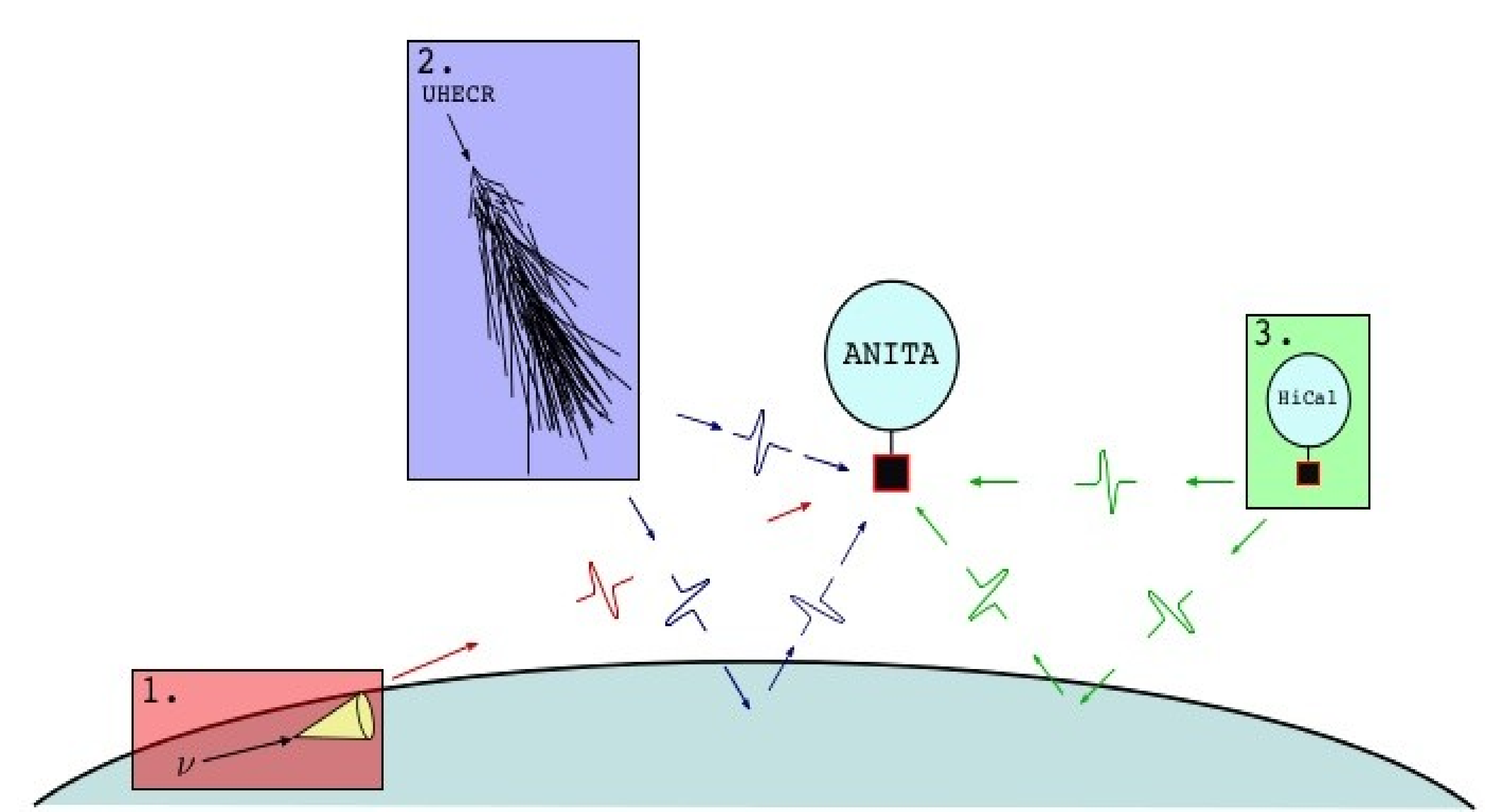
**RF Transmitter**

**Pavel Cherenkov**



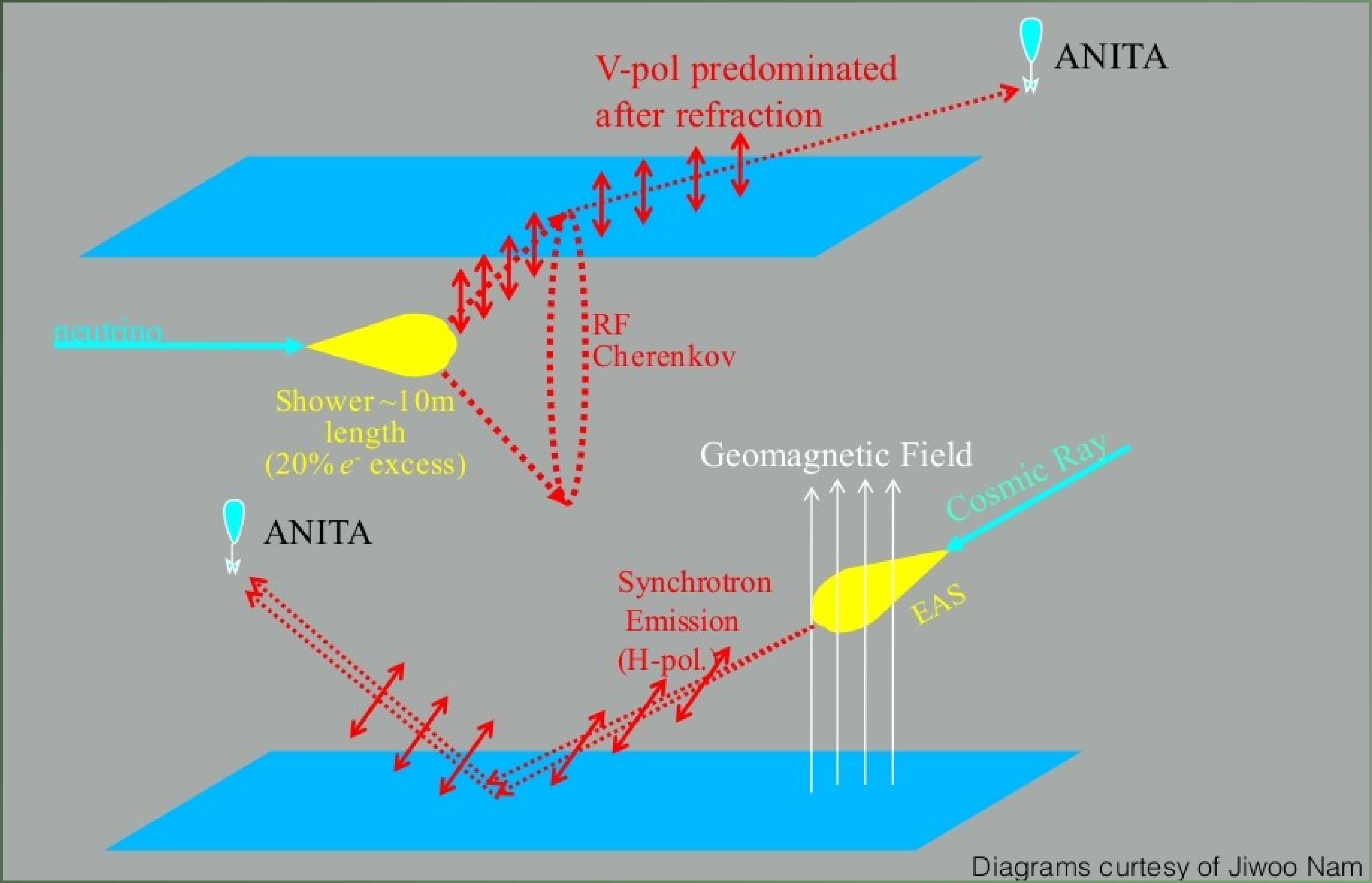
**Gurgen Askaryan**

**P. W. Gorham et al. arXiv:1710.11175**



# How to Distinguish between Neutrino Induced signals and UHECR induced signals ?

# Neutrino Signal vs. Air Shower Signal



Diagrams curtesy of Jiwoo Nam

# Contribution to ANITA Mission ?

# Using First Principle Calculation

**We developed**

**“First Complete Theoretical Framework” for ANITA**

**&**

**its successor Neutrino detection experiments**

- **Development of First Complete & General theoretical framework for reflected RF signal simulation**

  **P. Dasgupta and P. Jain (Thesis supervisor)**

- **Incorporated Antarctic Surface features & Curvature of Earth using First Principle Calculation**

- **Investigated the mystery of ANITA Anomalous Events**

- **Prof. David Besson (at the Dept. Of Physics, Univ. of Kansas, USA) & I investigated Antarctic subsurface Reflection and Transmission**

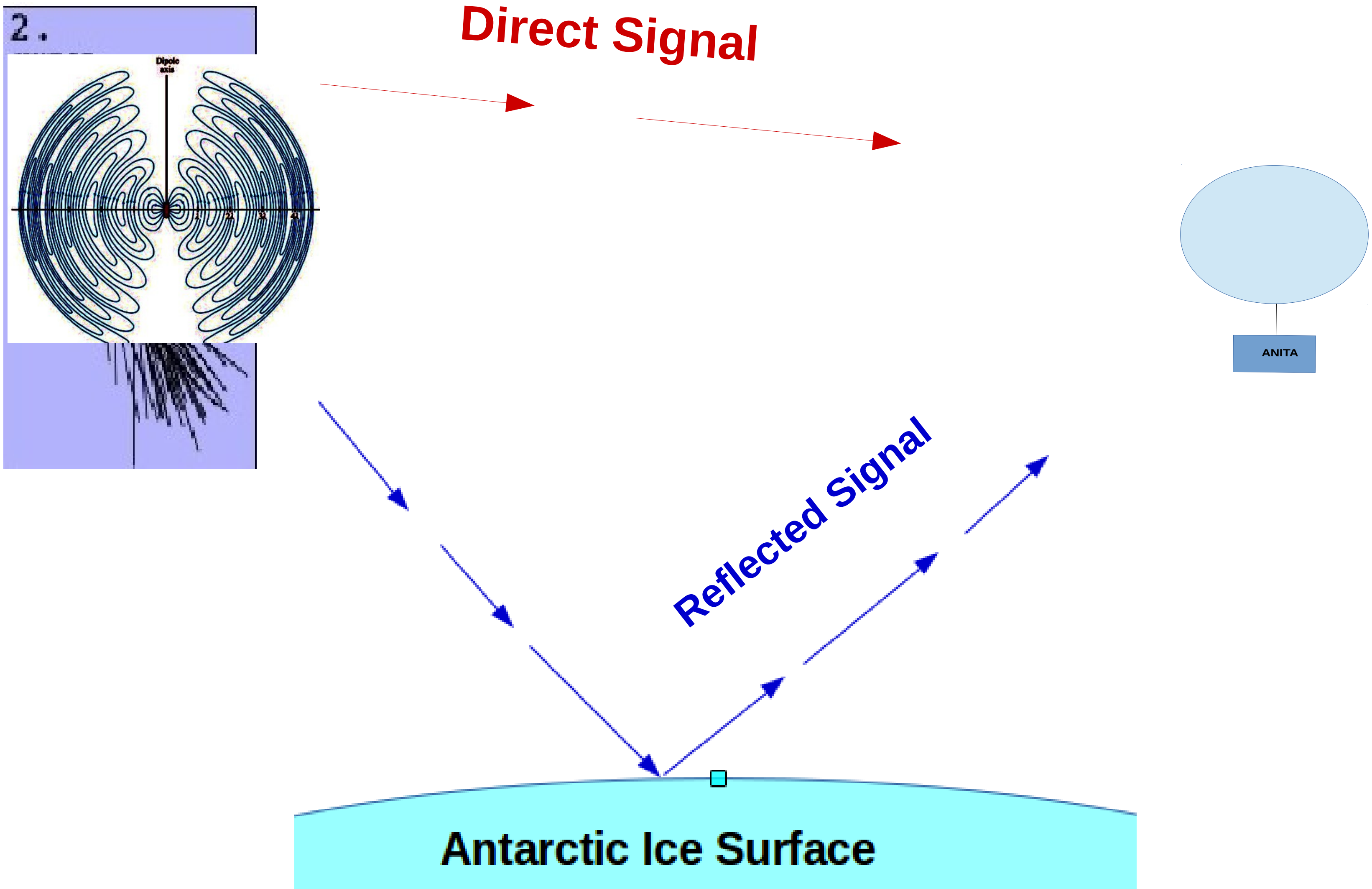
- **Extension of this formalism for in-ice (such as RADAR, RNO-G) or under water neutrino detection**

# Development of Complete Theoretical Framework for NASA sponsored ANITA experiment

# Decomposition of Spherical Waves into plane waves: Weyl Formalism (Year 1919)

## A dipole radiator on the z axis

- Extensive Air Shower (EAS)
- Geosynchroton radiation (200- 650) MHz



Direct Signal

ANITA

Reflected Signal

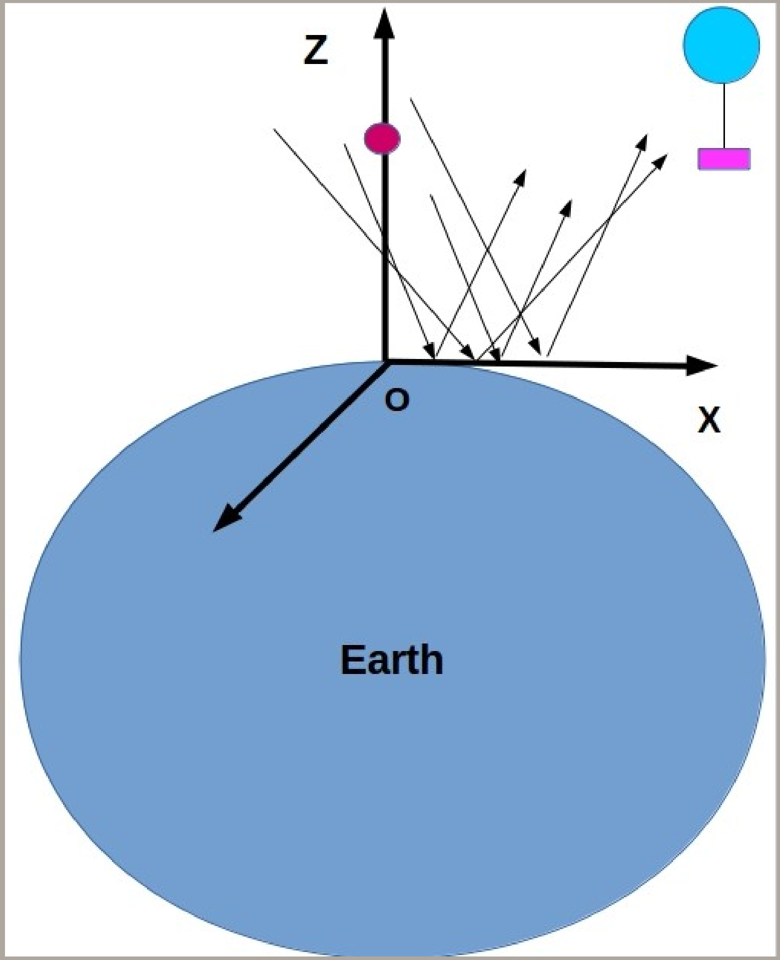
Antarctic Ice Surface

# Start with the simplest case

## Assume Earth Surface is FLAT

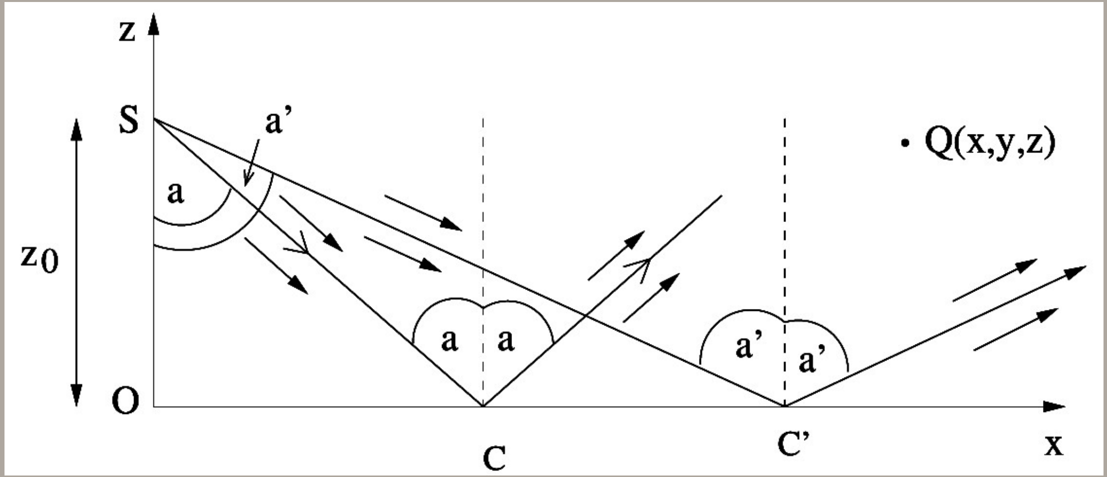
**Flat +Smooth**

**Flat +Rough**



# Decomposition of Spherical Waves into plane waves: Weyl Formalism

**Start with a Hertz dipole at (0,0,$z_0$)**

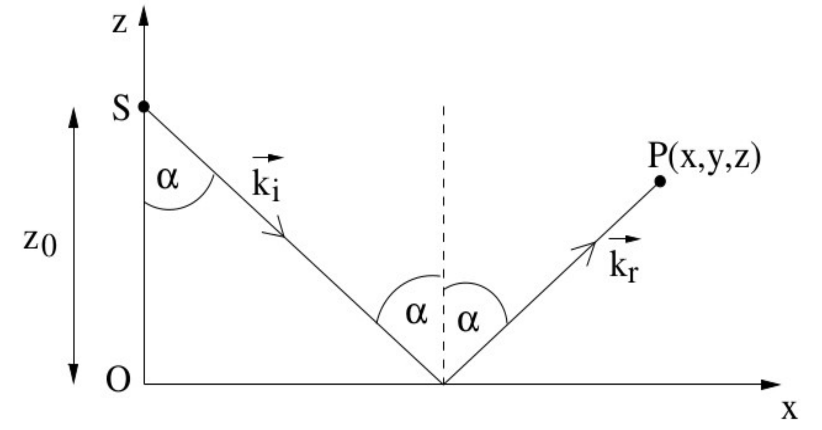


**Hertz Potential (In Far Field r>> λ)**

$$\Pi_y(x,y,z) = \frac{e^{ikR}}{4\pi\epsilon R} + F_1(x,y,z)$$

**Primary field** **Due to reflection**

$$\frac{e^{ikR}}{R} = \frac{ik}{2\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty} e^{ik[x\sin\alpha\cos\beta + y\sin\alpha\sin\beta + (z_0 - z)\cos\alpha]}\sin\alpha\, d\alpha\, d\beta$$



$$\vec{k}_I = k(\sin\alpha\cos\beta\hat{x} + \sin\alpha\sin\beta\hat{y} - \cos\alpha\hat{z})$$

$$\vec{k}_t = k_1[\sin\alpha_t\cos\beta_t\hat{x} + \sin\alpha_t\sin\beta_t\hat{y} - \cos\alpha_t\hat{z}]$$

S. Prohira, A. Novikov, **P. Dasgupta**, P. Jain et al. **Phys. Rev. D 98, 042004**

# Compute the Incident Field associated with each plane wave

$$
\begin{aligned}
\vec{E} &= \vec{\nabla}(\vec{\nabla}\cdot\vec{\Pi}) + k^2\vec{\Pi} \\
\vec{H} &= \frac{k^2}{i\omega\mu}(\vec{\nabla}\times\vec{\Pi})
\end{aligned}
$$

**Electric and Magnetic field associated with each incident plane wave**

$$
\begin{aligned}
\vec{E}_{\mathrm{inc}} &= \frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}[-\sin^2\alpha\cos\beta\sin\beta\hat{x} \\
&\quad + (1-\sin^2\alpha\sin^2\beta)\hat{y} + (\sin\alpha\sin\beta\cos\alpha)\hat{z}] \\
\vec{H}_{\mathrm{inc}} &= \frac{ik^2\omega}{8\pi^2}\tilde{\Pi}[\cos\alpha\hat{x} + (\cos\beta\sin\alpha)\hat{z}].
\end{aligned}
$$

**Decompose into s and p components**

$$\vec{E}_{inc} = \vec{E}^{s}_{inc} + \vec{E}^{p}_{inc}$$

$$\vec{H}_{inc} = \vec{H}^{s}_{inc} + \vec{H}^{p}_{inc}$$

# Reflection and Transmission: Flat Surface

- **Reflected Field components** $E^s_{ref}$ , $E^p_{ref}$ , $H^s_{ref}$ , $H^p_{ref}$
- **Transmitted Field Components** $E^s_{trans}$ , $E^p_{trans}$ , $H^s_{trans}$ , $H^p_{trans}$

$$E_{ref} = E^s_{ref} + E^p_{ref}$$

$$E_{trans} = E^s_{trans} + E^p_{trans}$$

$$H_{ref} = H^s_{ref} + H^p_{ref}$$

$$H_{trans} = H^s_{trans} + H^p_{trans}$$

**Impose boundary conditions at z=0**

$$f_r^s = \frac{k \cos\alpha - k_1 \cos\alpha_t}{k \cos\alpha + k_1 \cos\alpha_t}$$

$$f_r^p = \frac{k_1 \cos\alpha - k \cos\alpha_t}{k_1 \cos\alpha + k \cos\alpha_t}$$

$$f_t^s = \left(\frac{k}{k_1}\right)^2 \frac{2k_1 \cos\alpha}{k_1 \cos\alpha_t + k \cos\alpha}$$

$$f_t^p = \left(\frac{k}{k_1}\right)^2 \left(\frac{1}{\cos\alpha_t}\right) \frac{2k_1 \cos^2\alpha}{k_1 \cos\alpha + k \cos\alpha_t}$$

# Transmitted Field: Flat Reflecting Surface

$$E_{(trans),y} = \frac{ik_1^3}{8\epsilon_1\pi^2}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty}\tilde{\Pi}_t(f_t^s\cos^2\beta_t + f_t^p\cos^2\alpha_t\sin^2\beta_t)\sin\alpha\, d\alpha\, d\beta$$

**Transmitted Electric fieid component perpendicular to the Plane of incidence (H- Pol)**

# Reflected Field (y component) for H-Pol : Flat Refleting Surface

$$E_{(ref),y} = \frac{ik^3}{8\epsilon\pi^2}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty}\tilde{\Pi}_{ref}(f_r^s\cos^2\beta - f_r^p\cos^2\alpha\sin^2\beta)\sin\alpha\, d\alpha\, d\beta$$

**Electric fieid component perpendicular to Plane of incidence (H- Pol)**

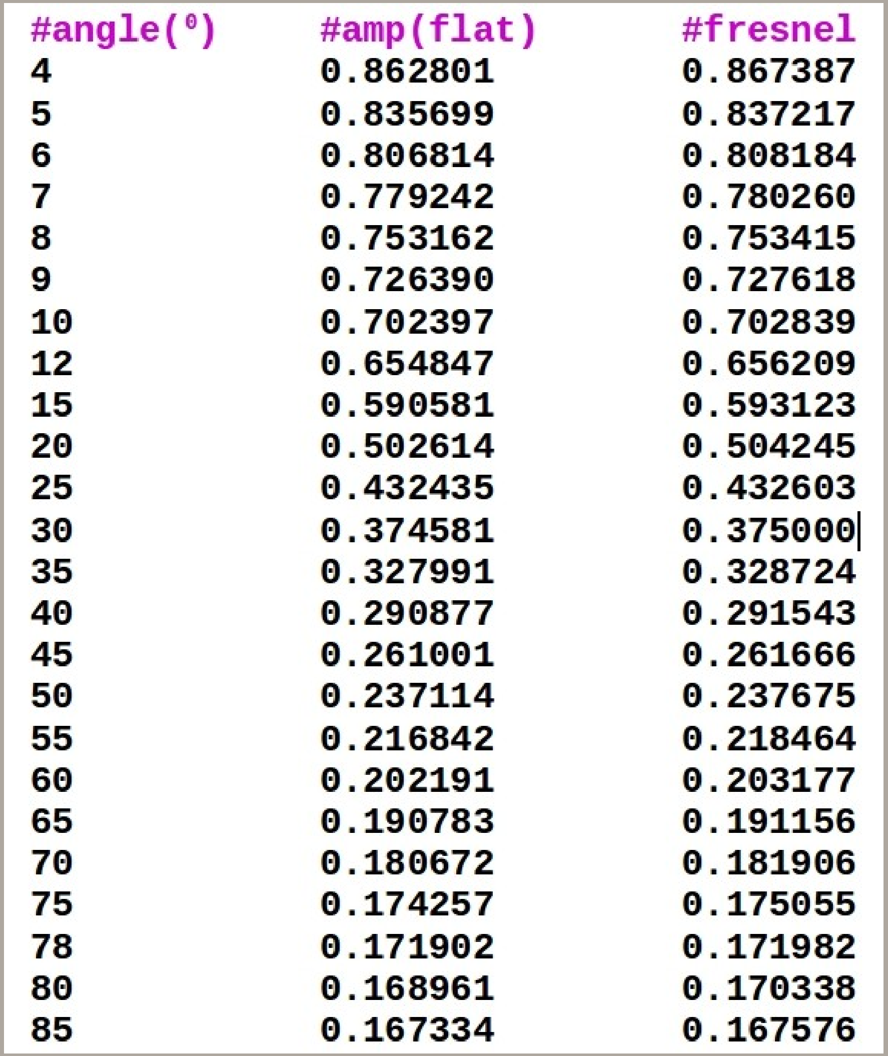
**Compute this Integral for different Elevation Angles in the Frequeny range (200-650) MHz**

**Also change R.I of ice from 1.25 to 1.75**

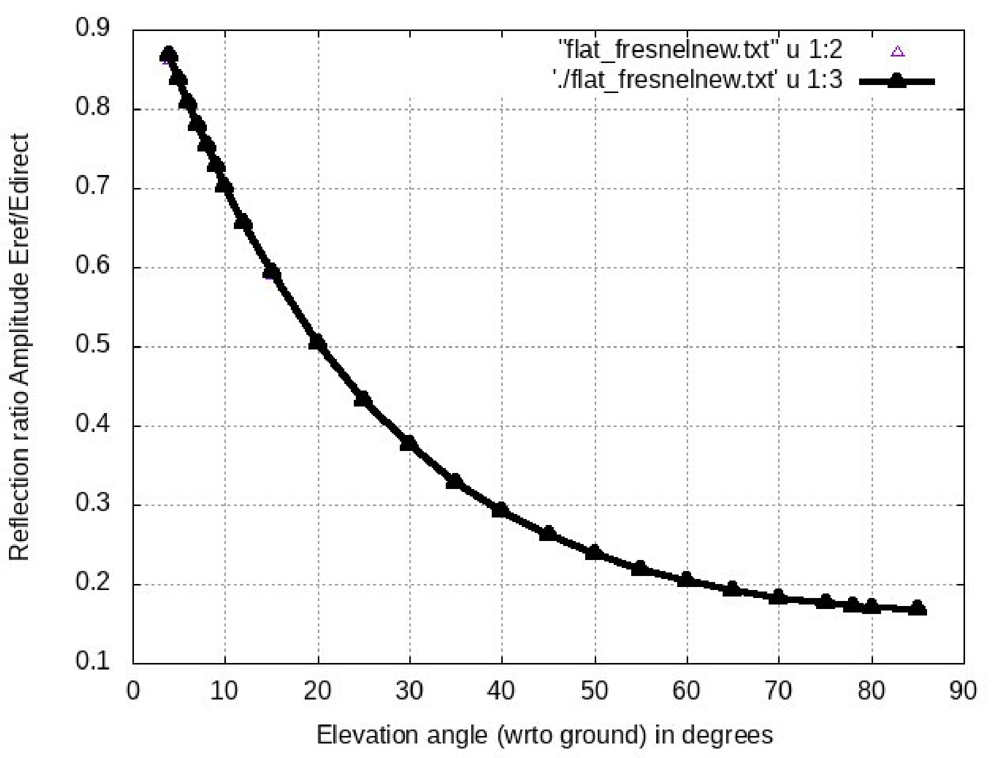
**Compare the simulated field Ref/Direct amplitude with Fresnel Coeffcients**

# H-Pol (reflected/direct) amplitude Ratio: Flat Surface calculation using our theoretical framework

$$E_{(ref),y} = \frac{ik^3}{8\epsilon\pi^2}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty}\tilde{\Pi}_{ref}(f_r^s\cos^2\beta - f_r^p\cos^2\alpha\sin^2\beta)\sin\alpha d\alpha d\beta$$



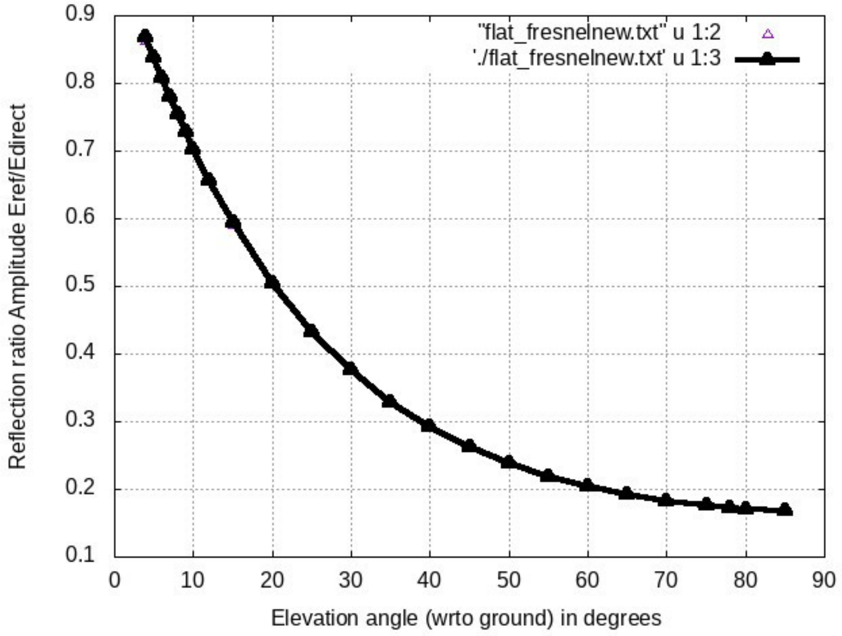
| #angle(°) | #amp(flat) | #fresnel |
|---|---|---|
| 4 | 0.862801 | 0.867387 |
| 5 | 0.835699 | 0.837217 |
| 6 | 0.806814 | 0.808184 |
| 7 | 0.779242 | 0.780260 |
| 8 | 0.753162 | 0.753415 |
| 9 | 0.726390 | 0.727618 |
| 10 | 0.702397 | 0.702839 |
| 12 | 0.654847 | 0.656209 |
| 15 | 0.590581 | 0.593123 |
| 20 | 0.502614 | 0.504245 |
| 25 | 0.432435 | 0.432603 |
| 30 | 0.374581 | 0.375000 |
| 35 | 0.327991 | 0.328724 |
| 40 | 0.290877 | 0.291543 |
| 45 | 0.261001 | 0.261666 |
| 50 | 0.237114 | 0.237675 |
| 55 | 0.216842 | 0.218464 |
| 60 | 0.202191 | 0.203177 |
| 65 | 0.190783 | 0.191156 |
| 70 | 0.180672 | 0.181906 |
| 75 | 0.174257 | 0.175055 |
| 78 | 0.171902 | 0.171982 |
| 80 | 0.168961 | 0.170338 |
| 85 | 0.167334 | 0.167576 |



**S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. PHYS. REV. D 98, 042004 (2018)**

# This framework works perfectly for a flat diectric medium

## Our result matches with Fresnel Reflection and Transmission coefficients

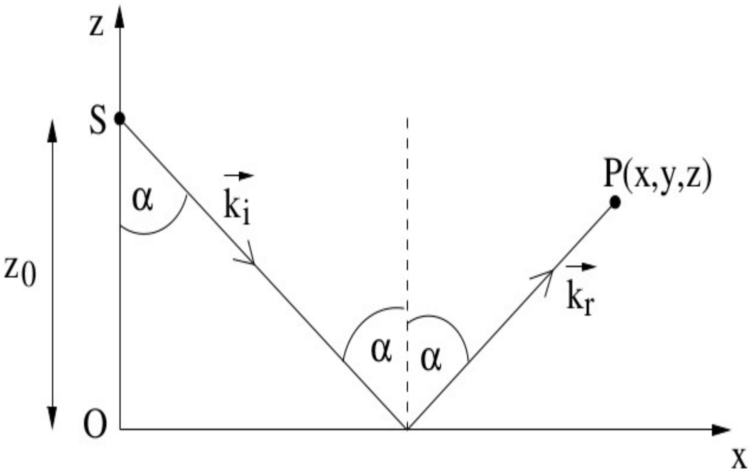


**Now the realistic case of Spherical +Uneven Earth Surface**

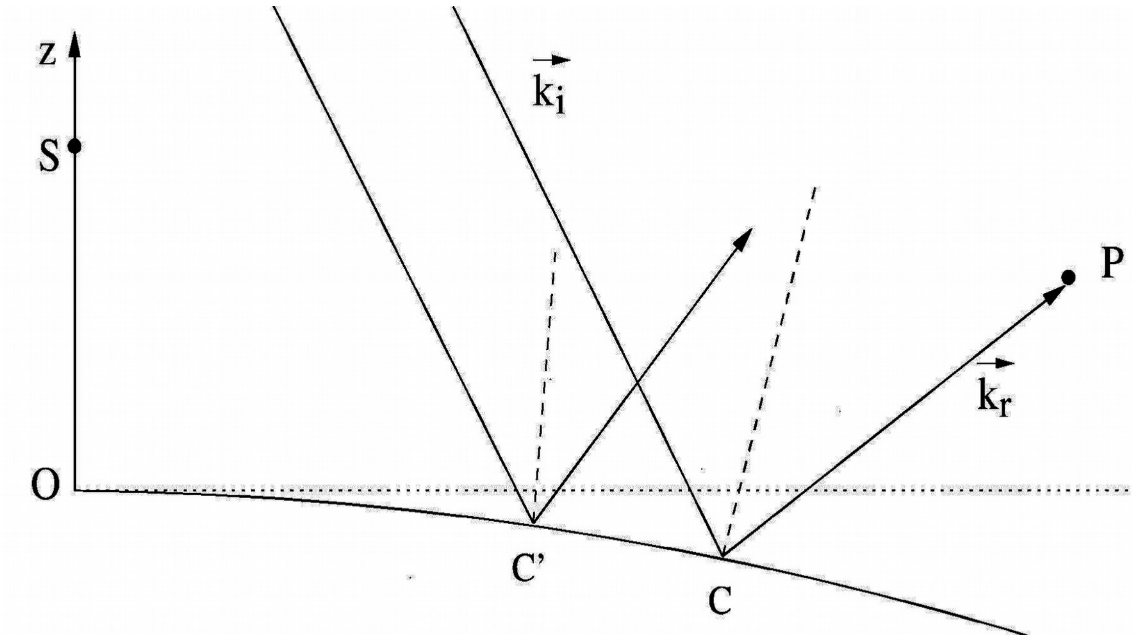
**Complexity starts from here**

# A Rigorous Formalism to study the Radio Signals Reflecting off a Spherical Surface

**Flat Earth Surface**

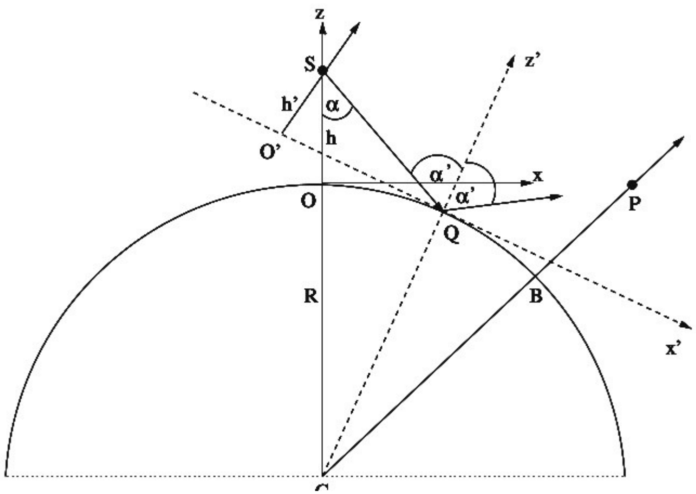


**Spherical Earth Surface**



- We extend our Formalism for a Spherical Reflecting Surface
- We do not make any approximation
- Surface topography data for Roughness Model

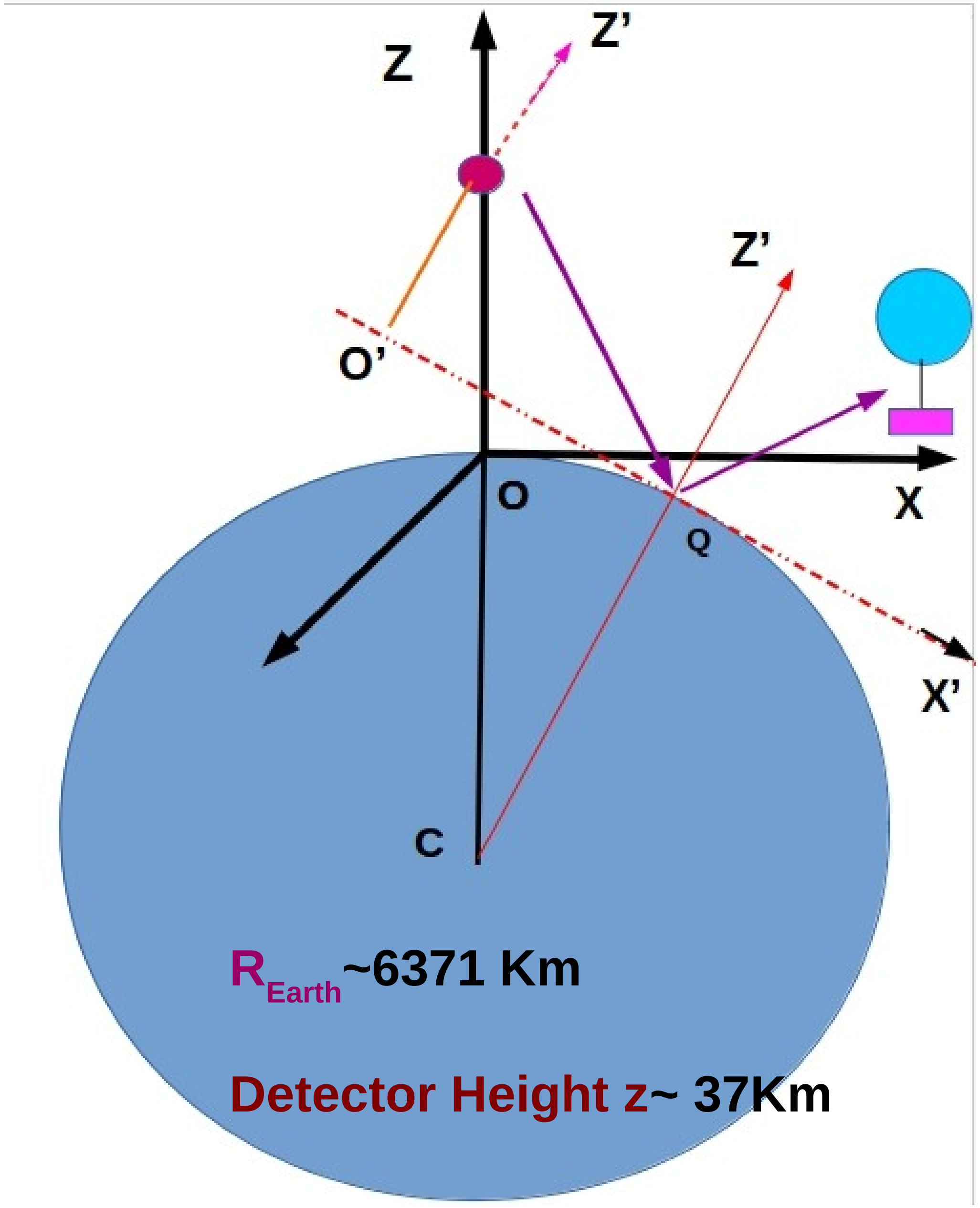
S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. Phys. Rev. D 98, 042004



**For each plane wave with angle alpha and beta we need to find the rotation matrix to transform the coordinate sytem from x-y-z to x’-y’-z’**

$$Rot = \begin{pmatrix} \cos(\alpha' - \alpha)\cos\beta & \cos(\alpha' - \alpha)\sin\beta & -\sin(\alpha' - \alpha) \\ -\sin\beta & \cos\beta & 0 \\ \sin(\alpha' - \alpha)\cos\beta & \sin(\alpha' - \alpha)\sin\beta & \cos(\alpha' - \alpha) \end{pmatrix}$$

**We then translate the coordinate system to change o to o’**



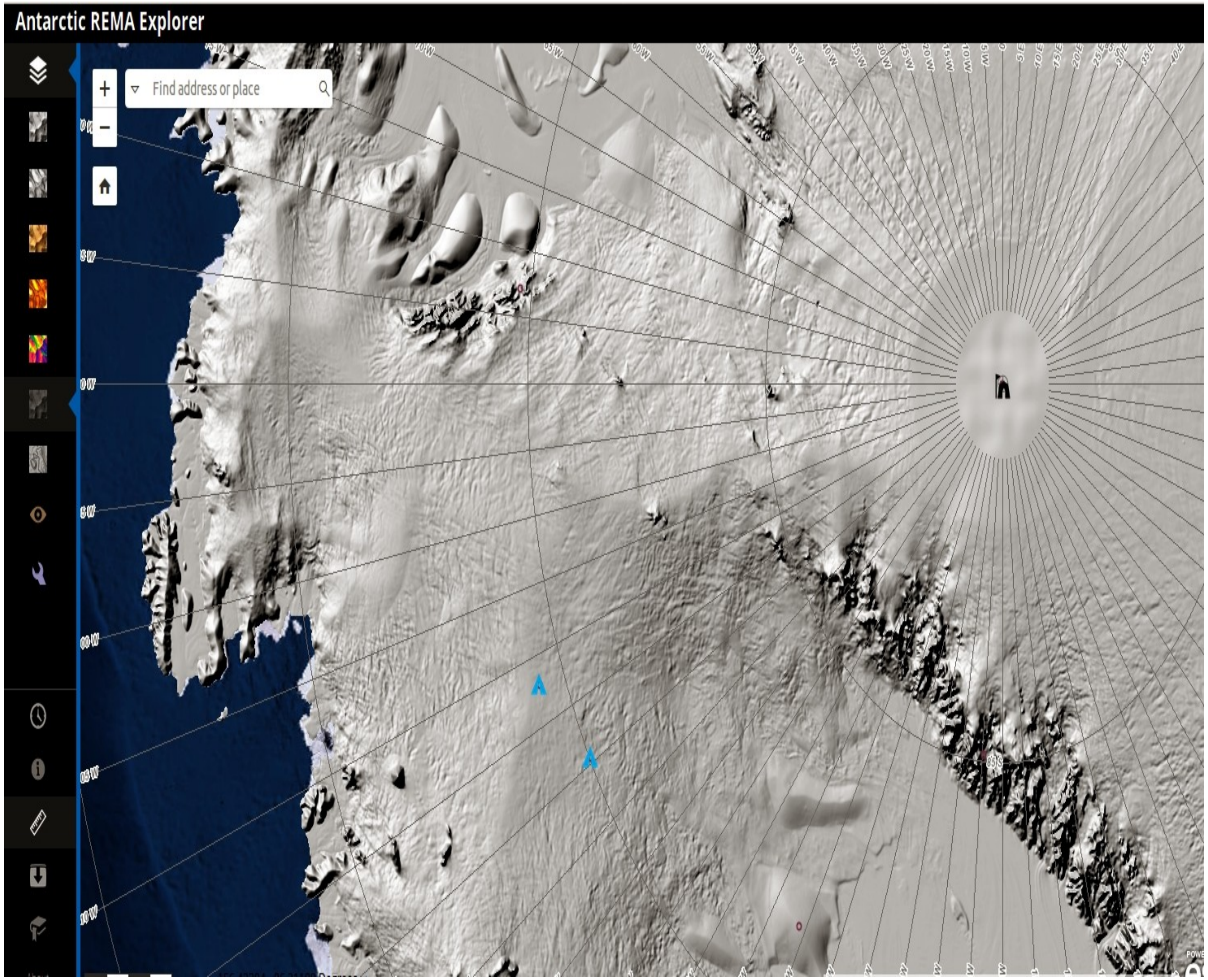
**$R_{Earth}$~6371 Km**

**Detector Height z~ 37Km**

**S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. Phys. Rev. D 98, 042004**

# Antarctic Surface Topography from The Reference Elevation Model of Antarctica (REMA)

**We receive this data from National Geospatial-Intelligence Agency (NGA), USA**



# Antarctic Surface

# Reflection and Transmission: Spherical Surface

- **Reflected Field components** $E'^{(s)}_{ref}$ $E'^{(p)}_{ref}$ & $H'^{(s)}_{ref}$ $H'^{(p)}_{ref}$

- **Transmitted Field Components** $E'^{(s)}_{trans}$ , $E'^{(p)}_{trans}$ & $H'^{(s)}_{trans}$, $H'^{(p)}_{trans}$

$$E'_{ref} = E'^{(s)}_{ref} + E'^{(p)}_{ref}$$

$$E'_{trans} = E'^{(s)}_{trans} + E'^{(p)}_{trans}$$

$$H'_{ref} = H'^{(s)}_{ref} + H'^{(p)}_{ref}$$

$$H'_{trans} = H'^{(s)}_{trans} + H'^{(p)}_{trans}$$

**Impose boundary conditions at $z' = 0$**

$$f_r'^s = \frac{k\cos\alpha' - k_1\cos\alpha'_t}{k\cos\alpha' + k_1\cos\alpha'_t},$$

$$f_t'^s = \left(\frac{k}{k_1}\right)^2 \frac{2k_1\cos\alpha'}{k\cos\alpha' + k_1\cos\alpha'_t}.$$

$$f_r'^p = \frac{k_1\cos\alpha' - k\cos\alpha'_t}{k_1\cos\alpha' + k\cos\alpha'_t}$$

$$f_t'^p = \left(\frac{k}{k_1}\right)^2 \left(\frac{1}{\cos\alpha_t}\right) \frac{2k_1\cos\alpha\cos\alpha'}{k_1\cos\alpha' + k\cos\alpha'_t}.$$

# Antarctic Surface Roughness Model by Peter Gorham

**Gorham's Roughness Model is an average roughness model**

**We started with simple model to compute reflected fields**

**L is the radius we compute around the specular angle theta$_z$**

**For $L_0$ = 150 m, Sigma$_h$(L) = 0.041m**

**H = Hurst Parameter = 0.65**

$$\sigma_h(L) = \sigma_h(L_0)\left(\frac{L}{L_0}\right)^H$$

$$F(k,\rho,\theta) = \exp[-2k^2\sigma_h(\rho_\perp)^2\cos^2\theta_z]$$

**k (wave number) is dependent on the Frequency of Incoming wave**

# After Computing Electric and Magnetic fields in x'-y'z'

# We transform back to the original (x-y-z) coordinate system by inverse rotation

Compare with Experimental Data

$$\vec{E}_{ref} = \mathrm{Rot}^{-1} . \vec{E'}_{ref}$$

&

$$\vec{H}_{ref} = \mathrm{Rot}^{-1} . \vec{H'}_{ref}$$

# Reflected fields for Spherical + Rough Reflecting Surface

$$\exp\left(i[\vec{k}'_{\rm inc}\cdot(\vec{r}'_s-\vec{h}')+\vec{k}'_{\rm ref}\cdot(\vec{r}'-\vec{r}'_s)]\right)$$

$$E_{\rm ref,y}=\frac{1}{2}\frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}_{S,r}F(k,\rho,\theta)[f'^s_r(1+\cos 2\beta)$$
$$-f'^p_r\cos\alpha\cos(2\alpha'-\alpha)(1-\cos 2\beta)]$$

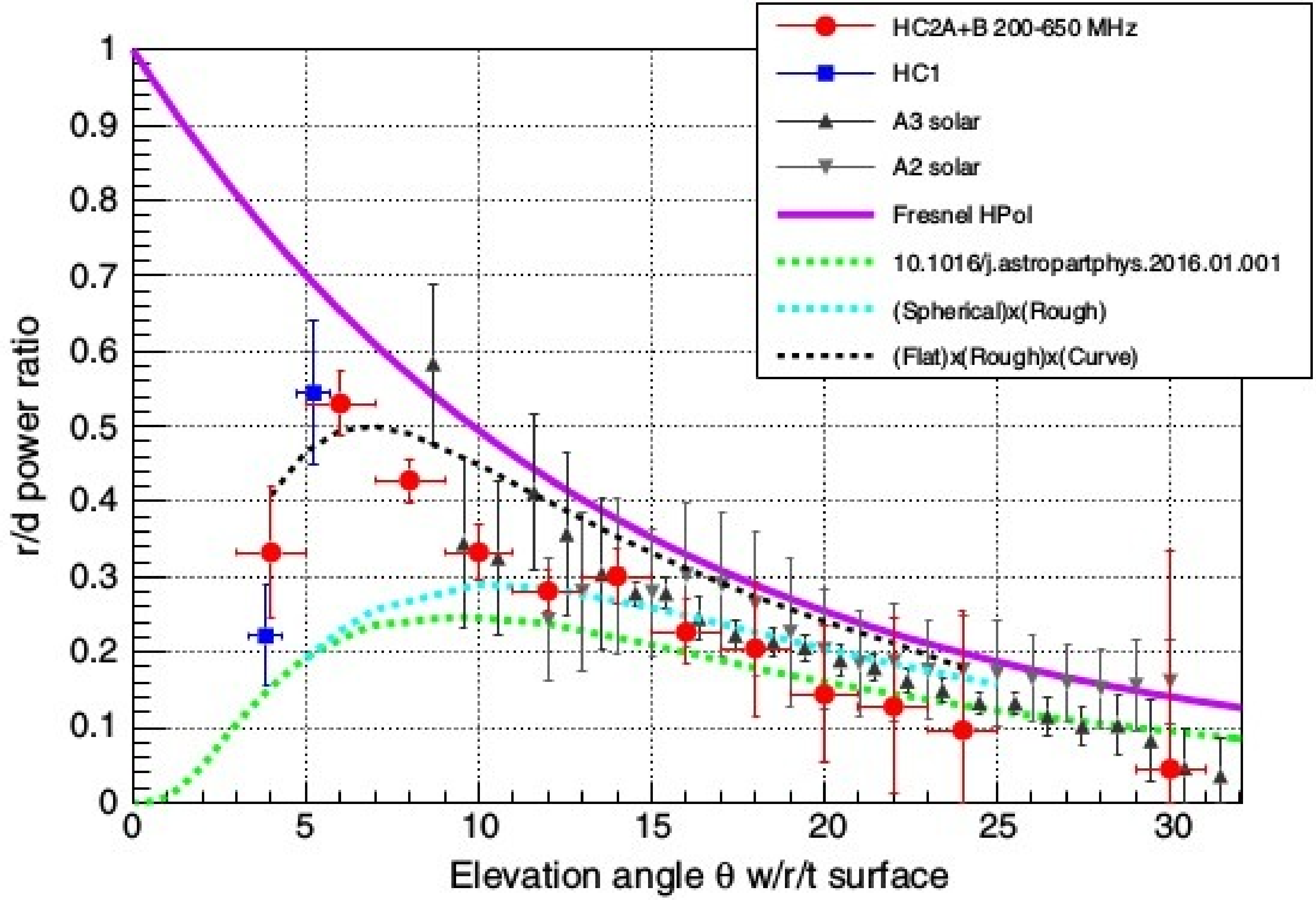
**Integrating over dΩ gives Total $E_{\rm ref}$ (H-Pol)**

**Take Ratio with the amplitude of Direct pulse propagated from Dipole to Detector**

**Compare this amplitude ratio r/d with the HiCal Experimental data**

**S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. PHYS. REV. D 98, 042004 (2018)**

# r/d power ratio compared with HiCal data



**S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. PHYS. REV. D 98, 042004 (2018)**

# Testing our Framework

- We Compute Reflected H-Pol Fields and compared with HiCal-2 Data

- This Formalism works very well for elevation angle >10$^0$

- For elevation angle < 10$^0$ are off from HiCal-2 data

- Results shown in August 2018 in Physical Review D. Volume 98, 042004

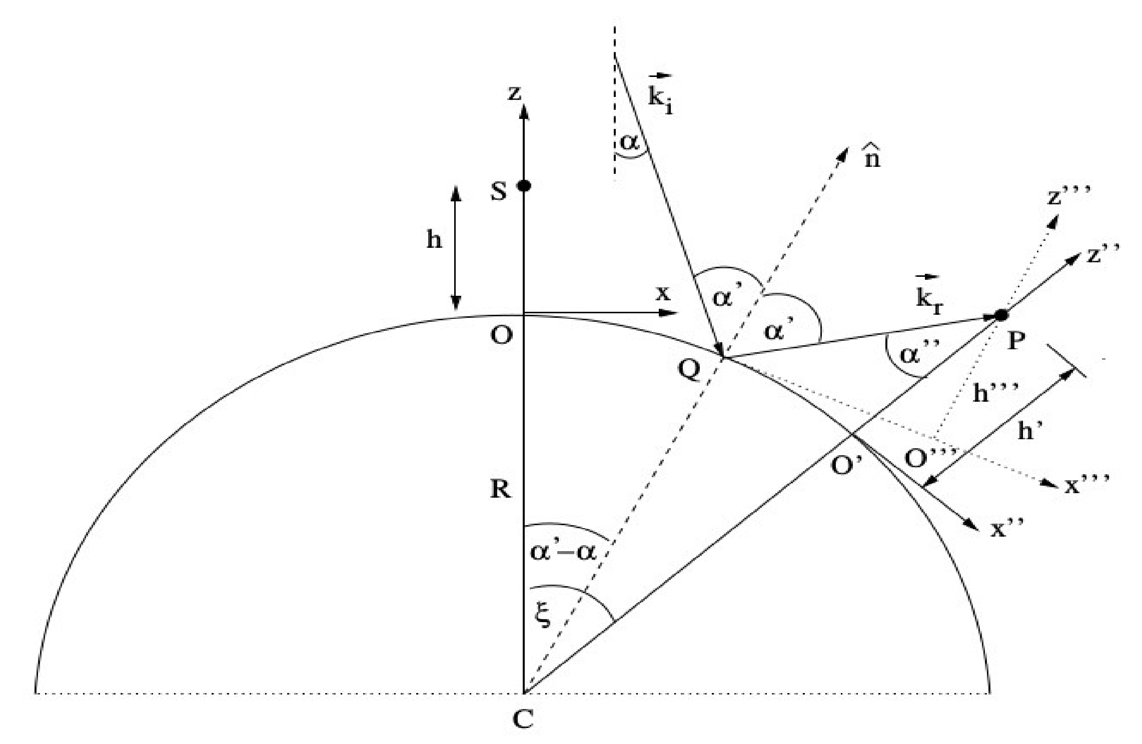
- Refinement of the Framework is necessary to apply this model for all elevation angles applicable to ANITA payload”

# Refinement of our theory

- **Next, we developed a formalism called “Local Plane Wave Approximation” which is a modified version of our theory developed in Physical Review D, volume 98, 042004**

- **This theoretical development is currently under review in Astroparticle Physics Journal (arXiv:1811.00900v2)**

# Refinement of Framework : “Local Plane Wave Approximation”



$$Rot_1 = \begin{pmatrix} \cos\xi\cos\tilde{\beta} & \sin\tilde{\beta} & -\sin\xi\cos\tilde{\beta} \\ -\cos\xi\sin\tilde{\beta} & \cos\tilde{\beta} & \sin\xi\sin\tilde{\beta} \\ \sin\xi & 0 & \cos\xi \end{pmatrix}$$

**By Rotatiing the coordinate system and subsequent translation we make sure k'''$_{inc}$ , k'''$_{ref}$ & local normal lie in the same plane**

$$\begin{aligned}\vec{E}_i''' &= R_{y'}(\psi)\vec{E}_i' \\ &= \frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}_{S,i}[(\sin\tilde{\beta}\cos^2\tilde{\alpha}\cos\psi + \sin\alpha\cos\tilde{\alpha}\sin\beta\sin\psi)\hat{x}''' + \cos\tilde{\beta}\hat{y}''' \\ &+ (\sin\alpha\cos\tilde{\alpha}\sin\beta\cos\psi - \cos^2\tilde{\alpha}\sin\tilde{\beta}\sin\psi)\hat{z}''']\end{aligned}$$

$$\begin{aligned}\vec{H}_i''' &= R_{y'}(\psi)\vec{H}_i' \\ &= \frac{ik^2\omega}{8\pi^2}\tilde{\Pi}_{S,i}[\cos\tilde{\beta}\cos(\tilde{\alpha}-\psi)\hat{x}''' - \cos\tilde{\alpha}\sin\tilde{\beta}\hat{y}''' \\ &+ \cos\tilde{\beta}\sin(\tilde{\alpha}-\psi)\hat{z}''']\end{aligned}$$

**P. Dasgupta and P Jain arXiv:1811.00900, April 2020**

# Reflection and Transmission: Spherical Surface with Local Plane Wave Analysis

- Reflected Field components $E'''^{(s)}_{ref}$ $E'''^{(p)}_{ref}$ & $H'''^{(s)}_{ref}$ $H'''^{(p)}_{ref}$

- Transmitted Field components $E'''^{(s)}_{trans}$ , $E'''^{(p)}_{trans}$ & $H'''^{(s)}_{trans}$, $H'''^{(p)}_{trans}$

$$E'''_{ref} = E'''^{(s)}_{ref} + E'''^{(p)}_{ref}$$

$$E'''_{trans} = E'''^{(s)}_{trans} + E'''^{(p)}_{trans}$$

$$H'''_{ref} = H'''^{(s)}_{ref} + H'''^{(p)}_{ref}$$

$$H'''_{trans} = H'''^{(s)}_{trans} + H'''^{(p)}_{trans}$$

Impose boundary conditions at z=0

$$f_r'^{(s)} = \frac{k\cos(\tilde{\alpha}-\psi) - k_1\cos(\tilde{\alpha}_t-\psi)}{k\cos(\tilde{\alpha}-\psi) + k_1\cos(\tilde{\alpha}_t-\psi)},$$

$$f_t'^{(s)} = \left(\frac{k}{k_1}\right)^2 \frac{2k_1\cos(\tilde{\alpha}-\psi)}{k\cos(\tilde{\alpha}-\psi) + k_1\cos(\tilde{\alpha}_t-\psi)}$$

$$f_r'^{(p)} = \frac{k_1\cos(\tilde{\alpha}-\psi) - k\cos(\tilde{\alpha}_t-\psi)}{k_1\cos(\tilde{\alpha}-\psi) + k\cos(\tilde{\alpha}_t-\psi)},$$

$$f_t'^{(p)} = \left(\frac{k}{k_1}\right)^2 \left(\frac{1}{\cos\tilde{\alpha}_t}\right) \frac{2k_1\cos(\tilde{\alpha}-\psi)\cos\tilde{\alpha}}{k_1\cos(\tilde{\alpha}-\psi) + k\cos(\tilde{\alpha}_t-\psi)}$$

# Local Plane Wave Approximation: Electric and Magnetic Field (HPol &VPol)

**Peter Gorham's roughness model**

$$F(k,\rho,\theta) = \exp[-2k^2\sigma_h(\rho_\perp)^2\cos^2\theta_z]$$

$$\sigma_h(L) = \sigma_h(L_0)\left(\frac{L}{L_0}\right)^H$$

**Reflected fields for a Spherical + Rough Reflecting Surface**

$$E_{r,y} = \frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}_{S,r}\left[f_r'^{(s)}\cos^2\tilde{\beta} - f_r'^{(p)}\cos\tilde{\alpha}\cos(\tilde{\alpha}-2\psi)\sin^2\tilde{\beta}\right]$$

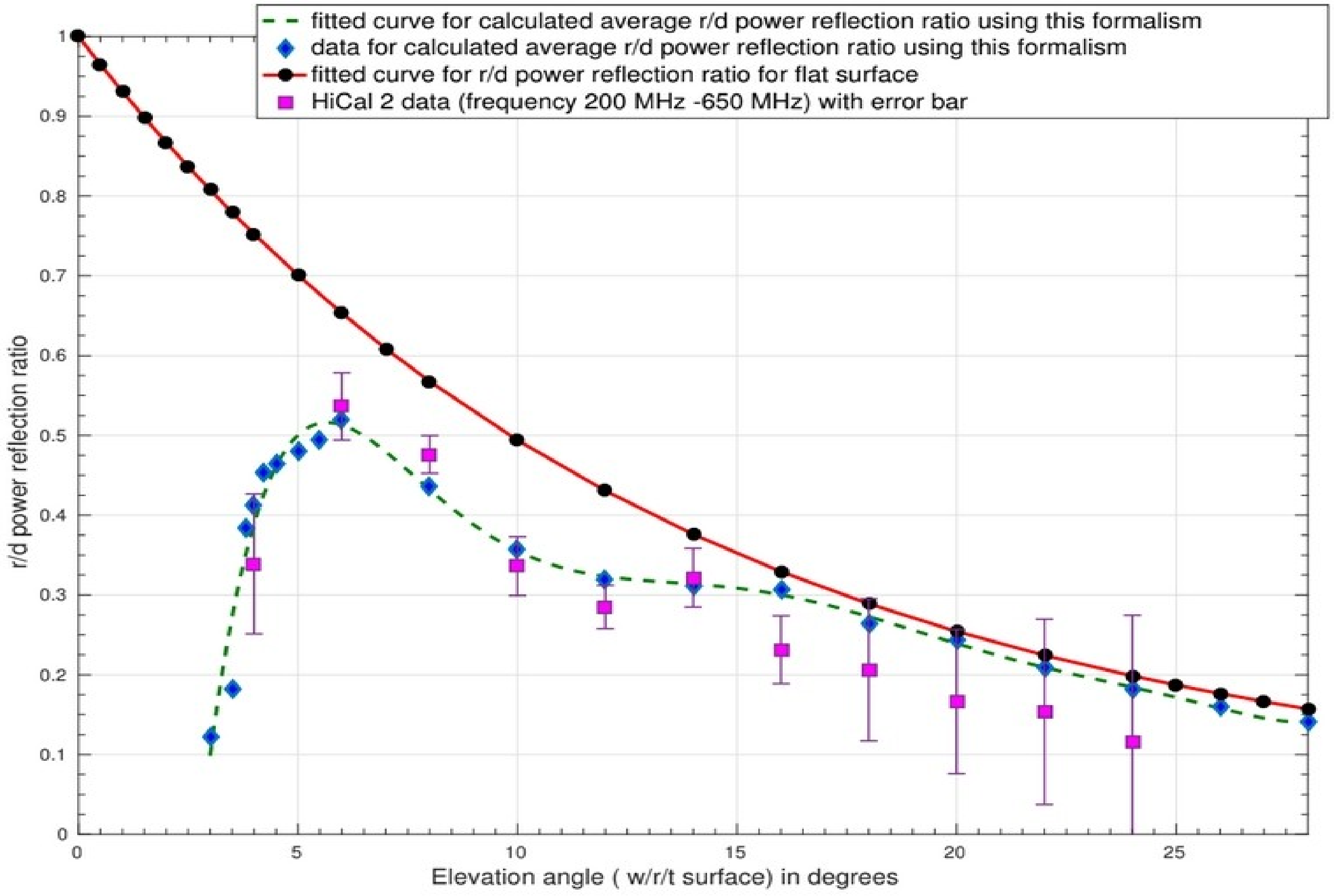
$$E_{(r,total),y} = \int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty} F_{rough}E_{r,y}\sin\alpha\, d\alpha\, d\beta.$$

**Take Ratio with the amplitude of Direct pulse propagated from Dipole to Detector**

**Compare this amplitude ratio r/d with the HiCal Experimental data**

P. Dasgupta and P Jain arXiv:1811.00900, November 2018

# r/d power ratio for a spherical-rough surface: Local Plane Wave Approximation



**P. Dasgupta and P Jain (Under Review: Astroparticle Physics Journal), arXiv:1811.00900v2**

# Using First Principle Calculation

**We developed**

**“First Complete Theoretical Framework” for ANITA**

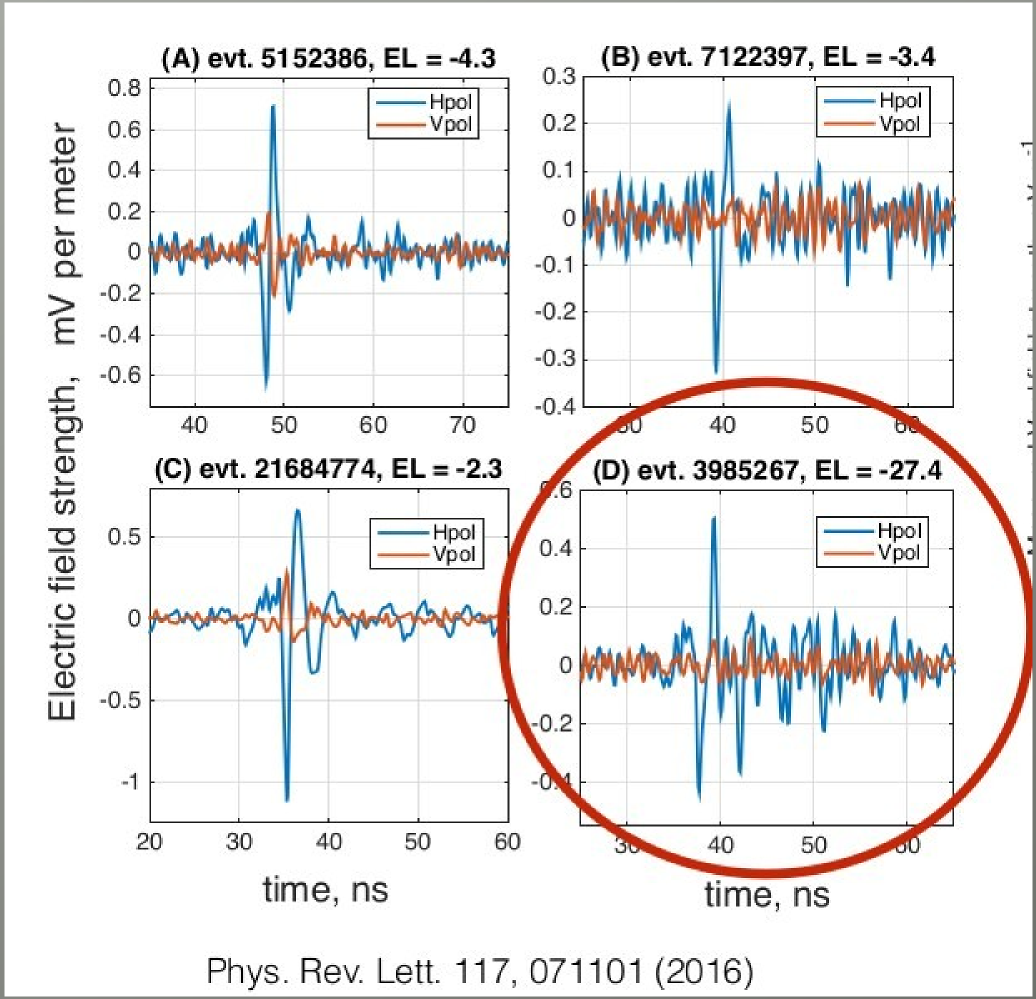
**&**

**its successor neutrino detection experiments**

# “Anomalous Events” Detected by ANITA

# ANITA Anomalous Events

**Two Unusual steeply pointed up-going air showers with E ~ EeV scale**



Phys. Rev. Lett. 117, 071101 (2016)

**Dominantly H-Pol**

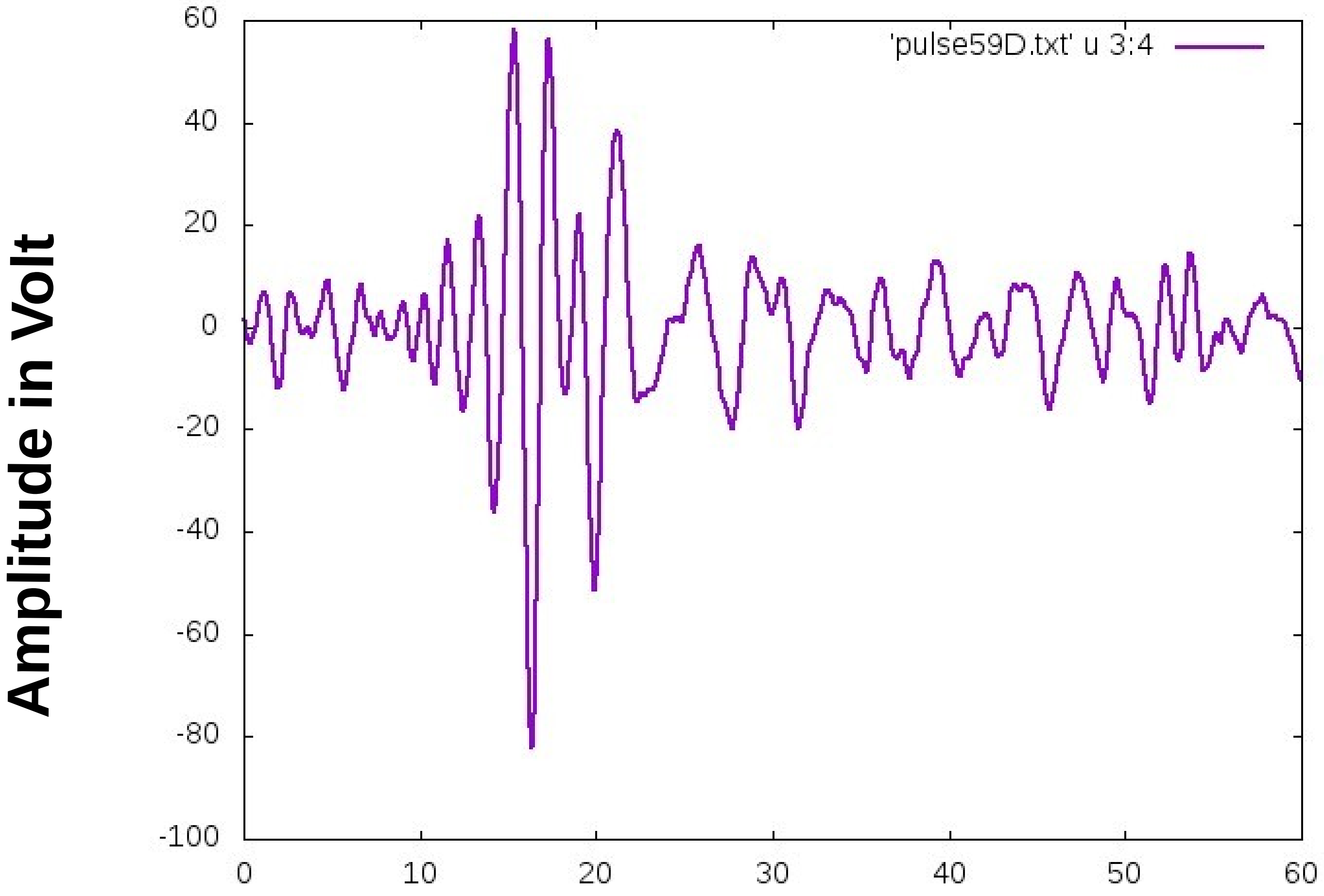
**No Phase Inversion !**

**Tau-neutrino interaction in ice?**

# Our Formalism Explain these anomalous events??

**Next we try to unfold this mystery**

# HiCal Pulse



Amplitude in Volt

Time in ns

# Generalizing Framework for Electromagnetic Pulses (Applicable to ANITA events)

- monochromatic spherical electromagnetic waves.
- Reflection from ice as a function of frequency, angle of reflection.

**We need to consider Electromagnetic pulses to study the ANITA signals**

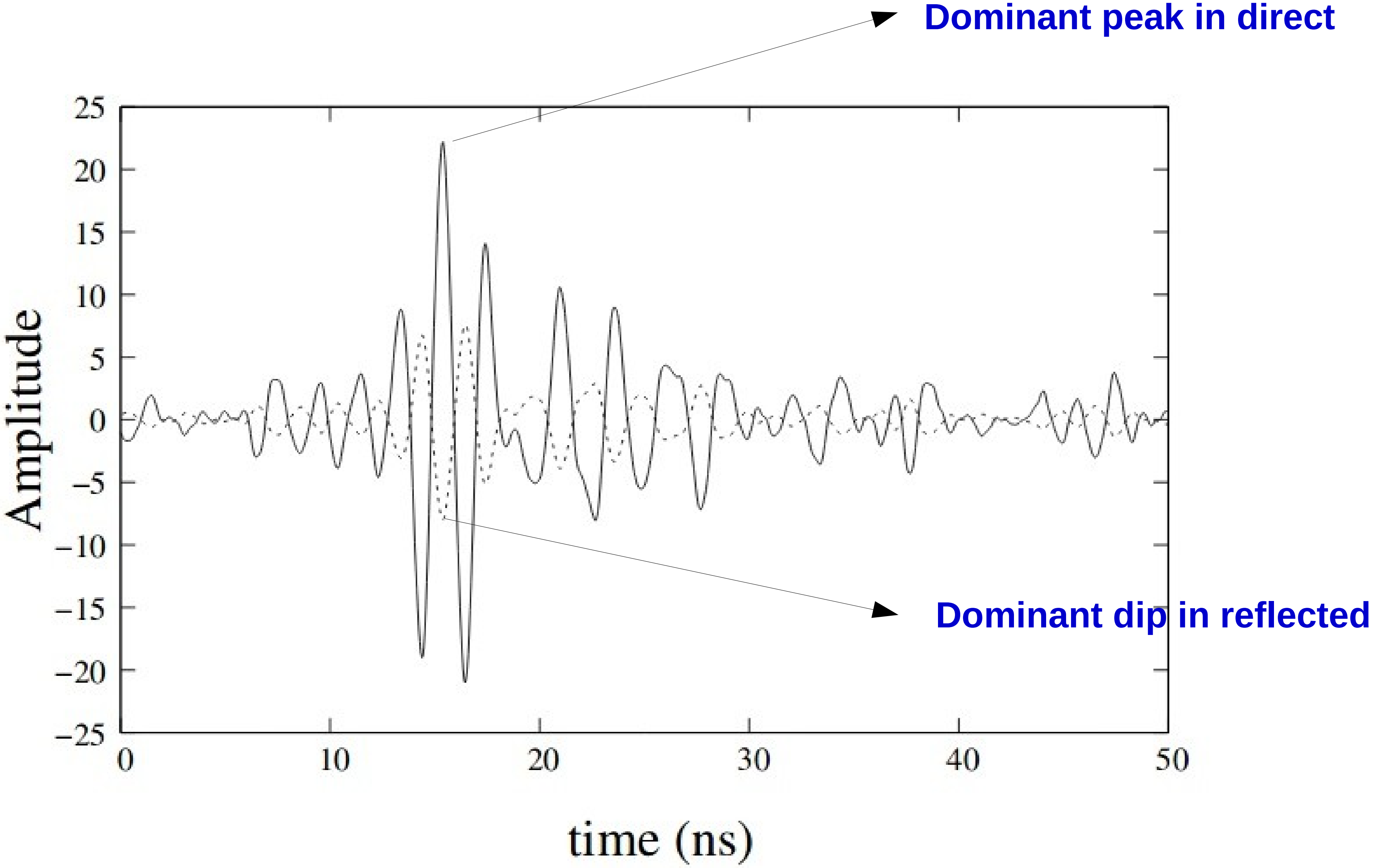
$$\tilde{F}(n) = \sum_{p=0}^{N-1} f(p) e^{i\frac{2\pi n}{N}p}$$

$$E'_{ref,y} = \int_0^{\frac{\pi}{2}-i\infty} \int_0^{2\pi} \int_\omega \frac{ik}{2\pi} \tilde{\Pi}_{S,r} F_{rough}(\omega,\alpha,\beta,\theta_z)\eta(\alpha,\beta,\omega)(\tilde{F}(\omega)e^{-i\omega(t+t_0)})d\omega d\Omega\,.$$

**Superposition of dipole radiation of different frequencies**

**Incorporating our formalism to compute Direct and Reflected pulse profile (using HiCal 2 pulses)**

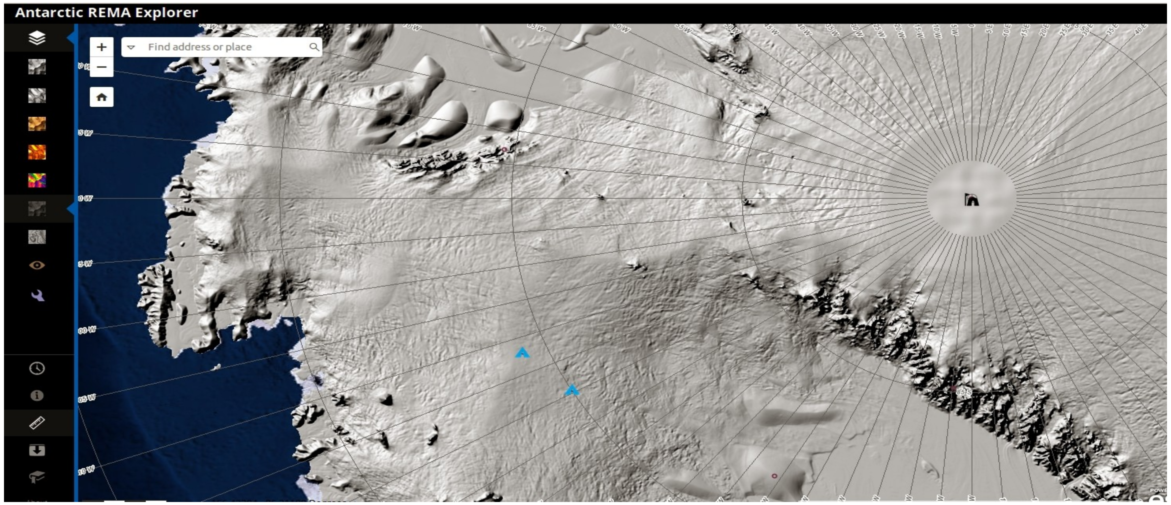
# Polarity of Reflected signals



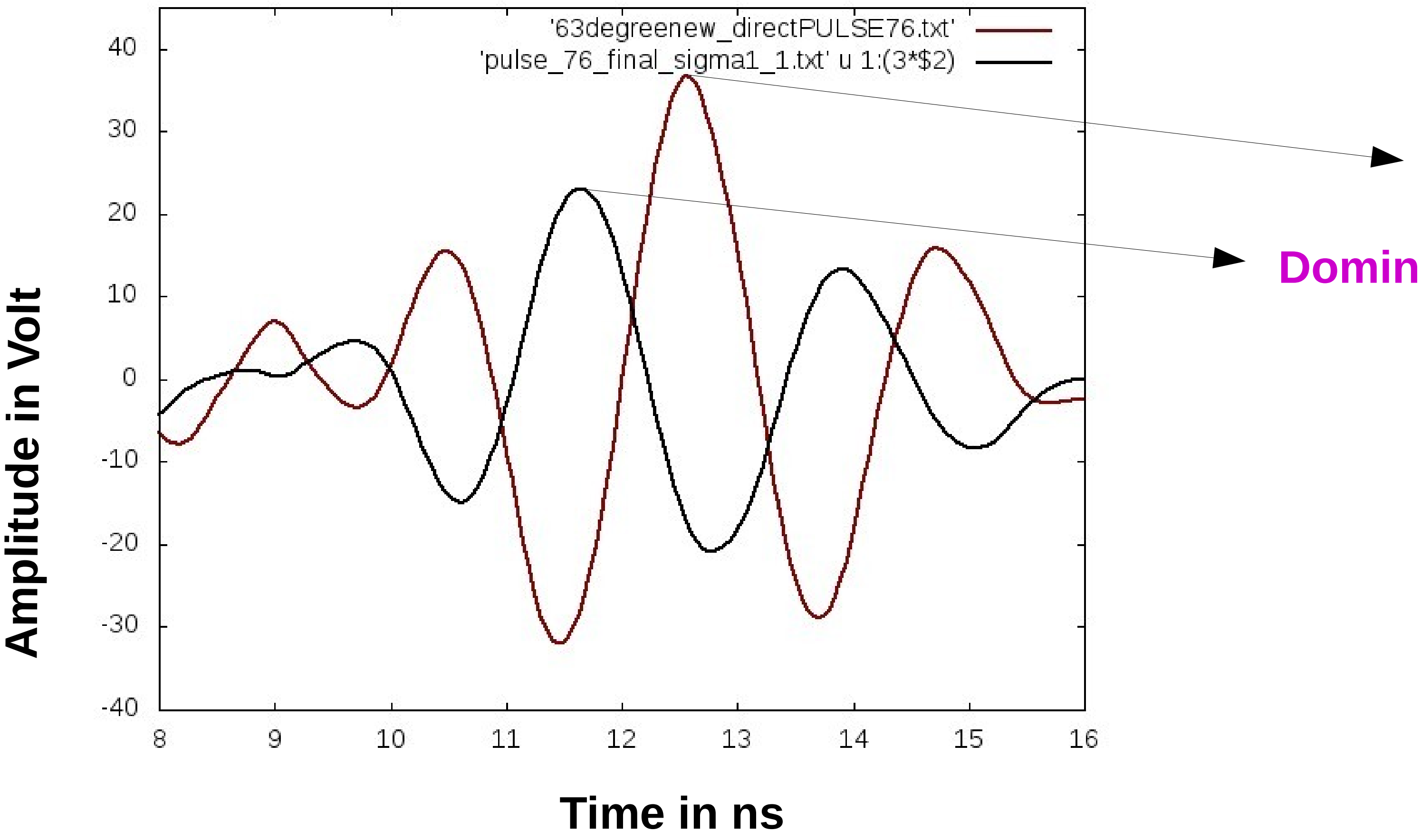
**P. Dasgupta, P. Jain arXiv: 1811.00900**

# New Roughness Models

- Antarctic topographic data one side is quite smooth but the other side has lots of variation in altitude.
- In order to account for this we allowed our incident angle to vary over a range of about 3 Km by about 1 degree.
- We also simply increase the curvature. This will model a hill like structure in the region of mystery events



# Non-Inversion of phase using new roughness model

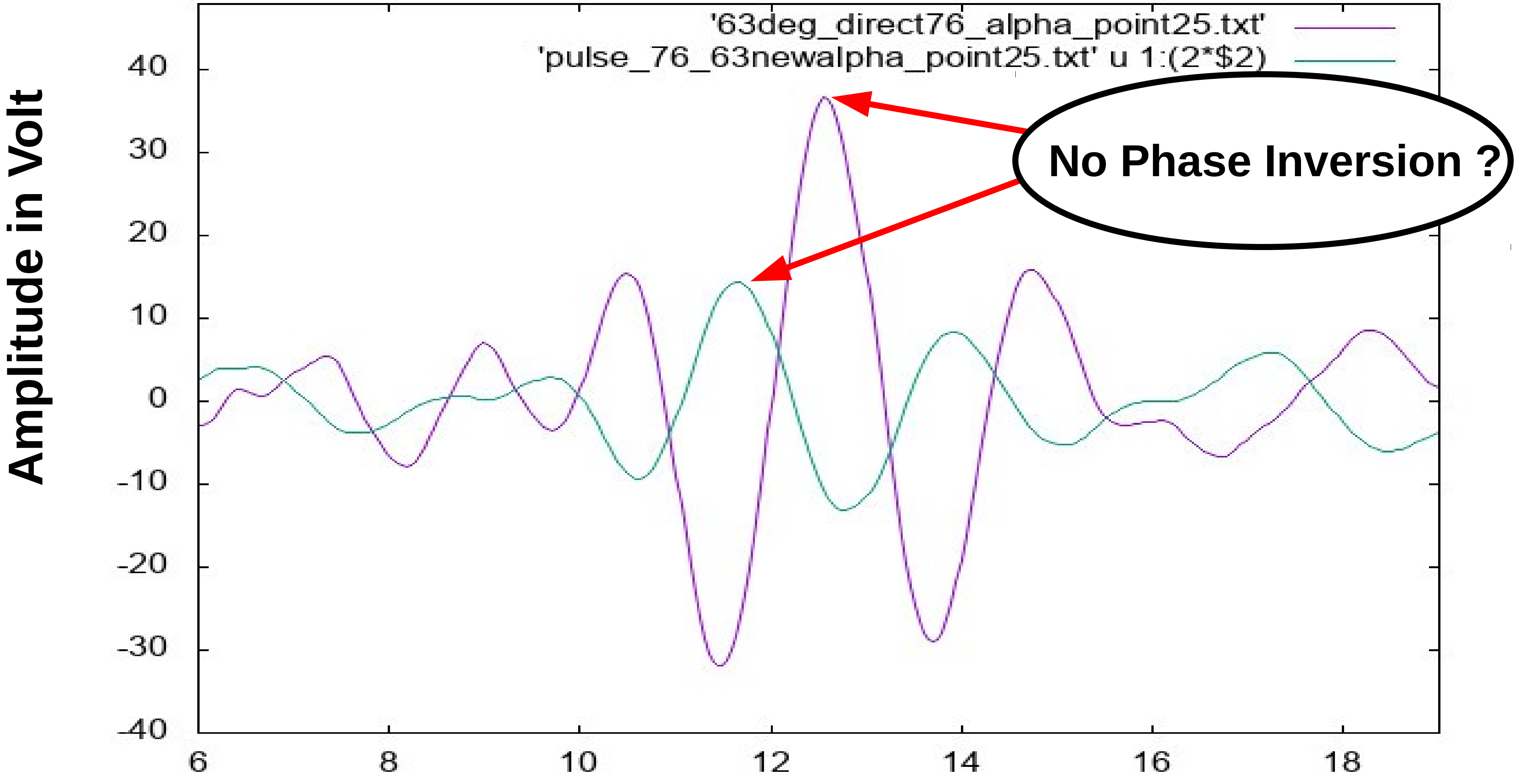


**Dominant peak**

**Dominant peak**

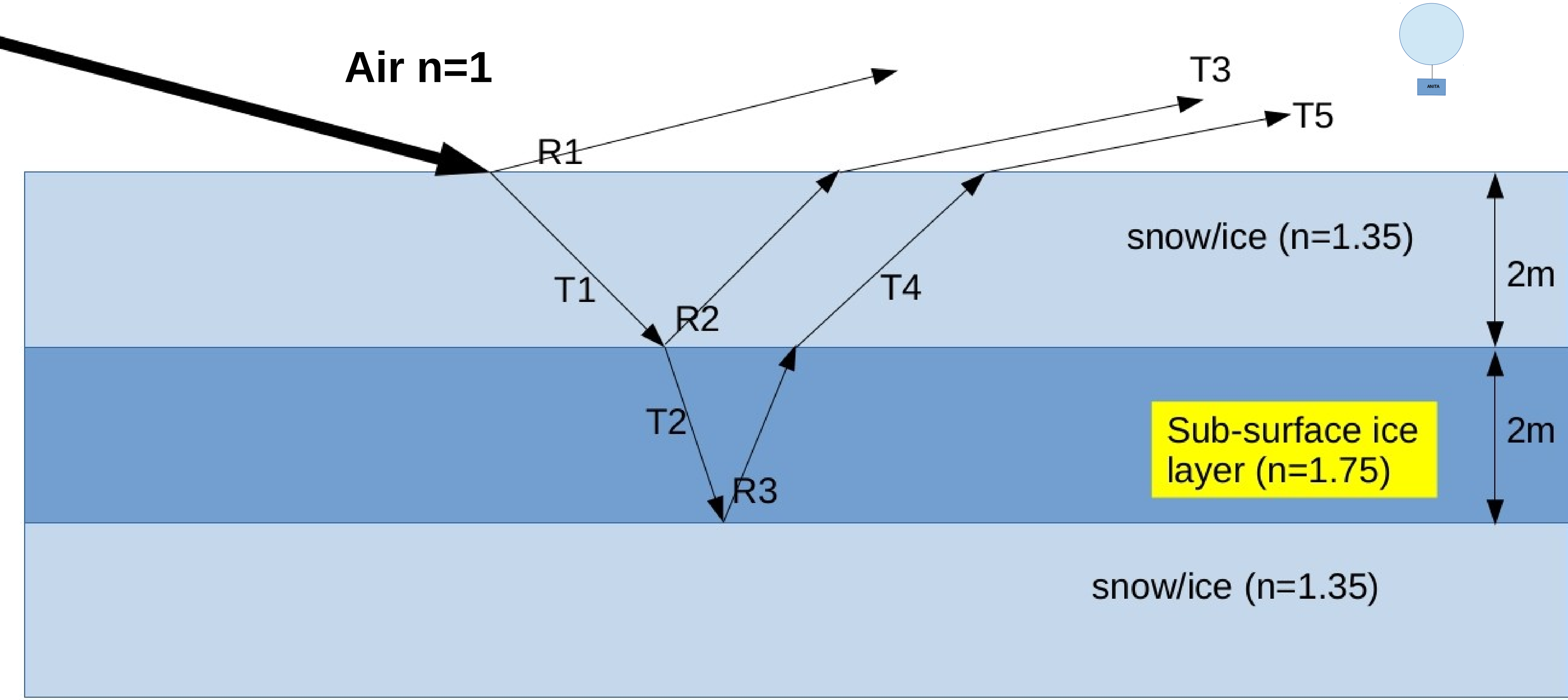
**We see non-inversion of phase in simulated reflected pulses**

# Possible explanation for ANITA mystery events ?



No Phase Inversion ?

# Sub-Surface Reflection: Another Possible Explanation for Mystery Event



**I am at the finishing stage of this work with Prof. Dave Besson, PI of HiCal Expt**

**(work in progress)**

**Pic Courtesy: Dave Z Besson**

# Conclusion

**We developed complete theoretical framework for UHECR induced radio detection at Balloon payload for a spherical, rough reflecting surface.**

**Future ground based and Balloon-borne Cosmic Ray detection experiments can use our formalism.**

**Incorporation of actual Antarctic surface topographical data in the ANITA Monte Carlo (icemc)**

**Explanation for ANITA mystery events ? We show that surface topography can cause additional phase inversion in pulses.**

**Our framework can be implemented for the in ice propagation of the radio signals applicable to RADAR, RNO-G project**

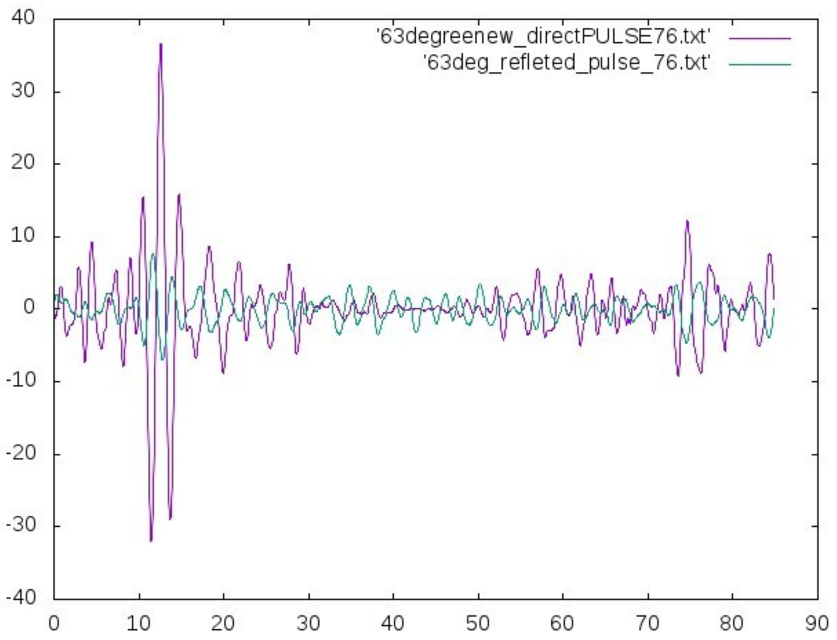
# Thank You

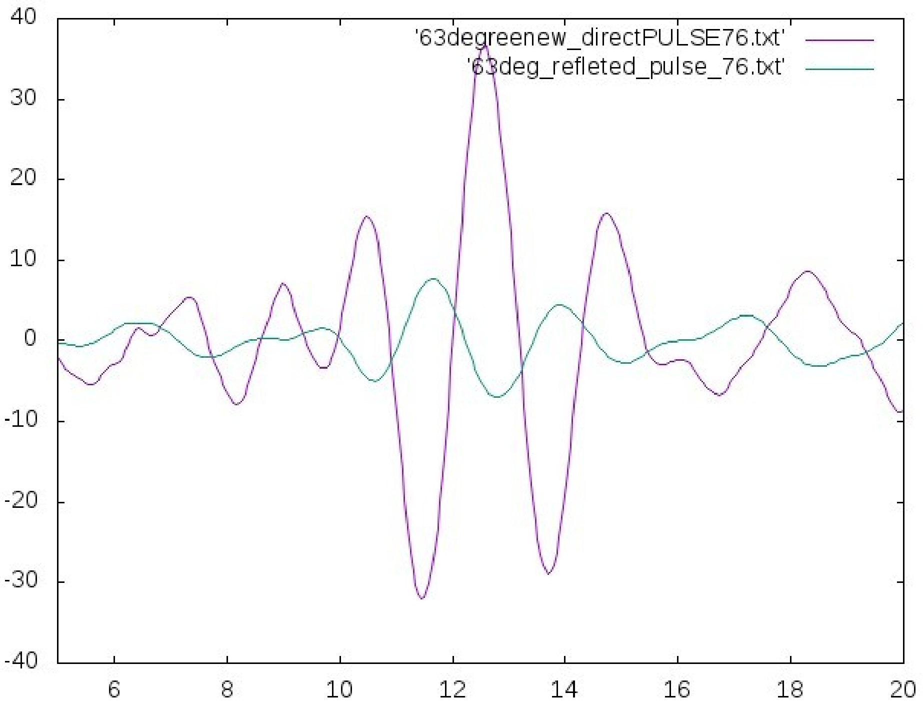
# BACK UP

# Recent results with random surface roughness

- Random surface roughness profile

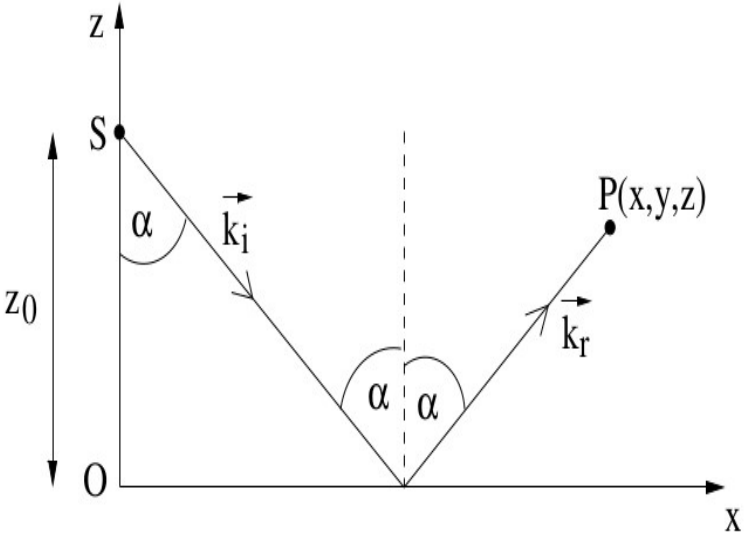
- No polarity Inversion !!



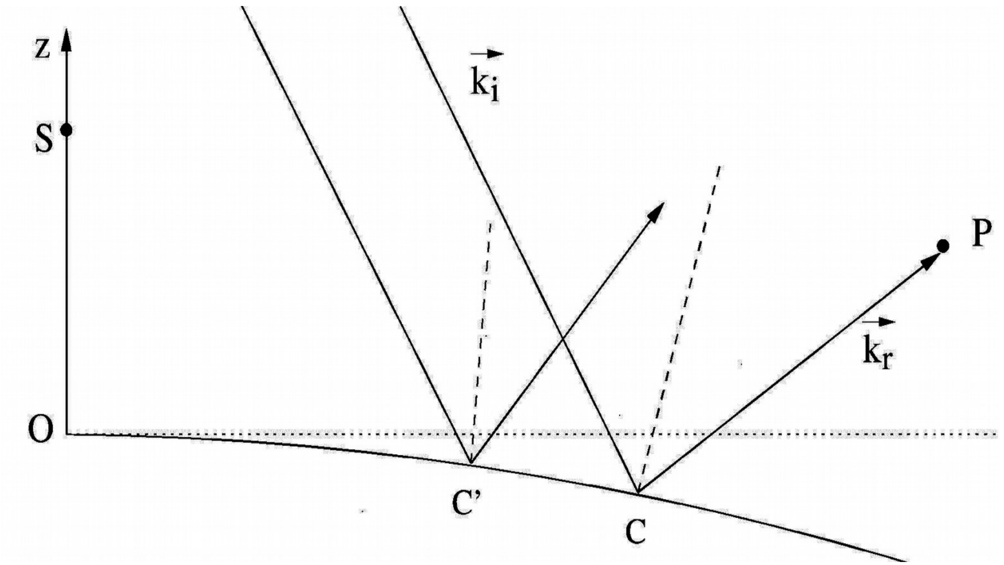


# A Rigorous Framework for ANITA-HiCal

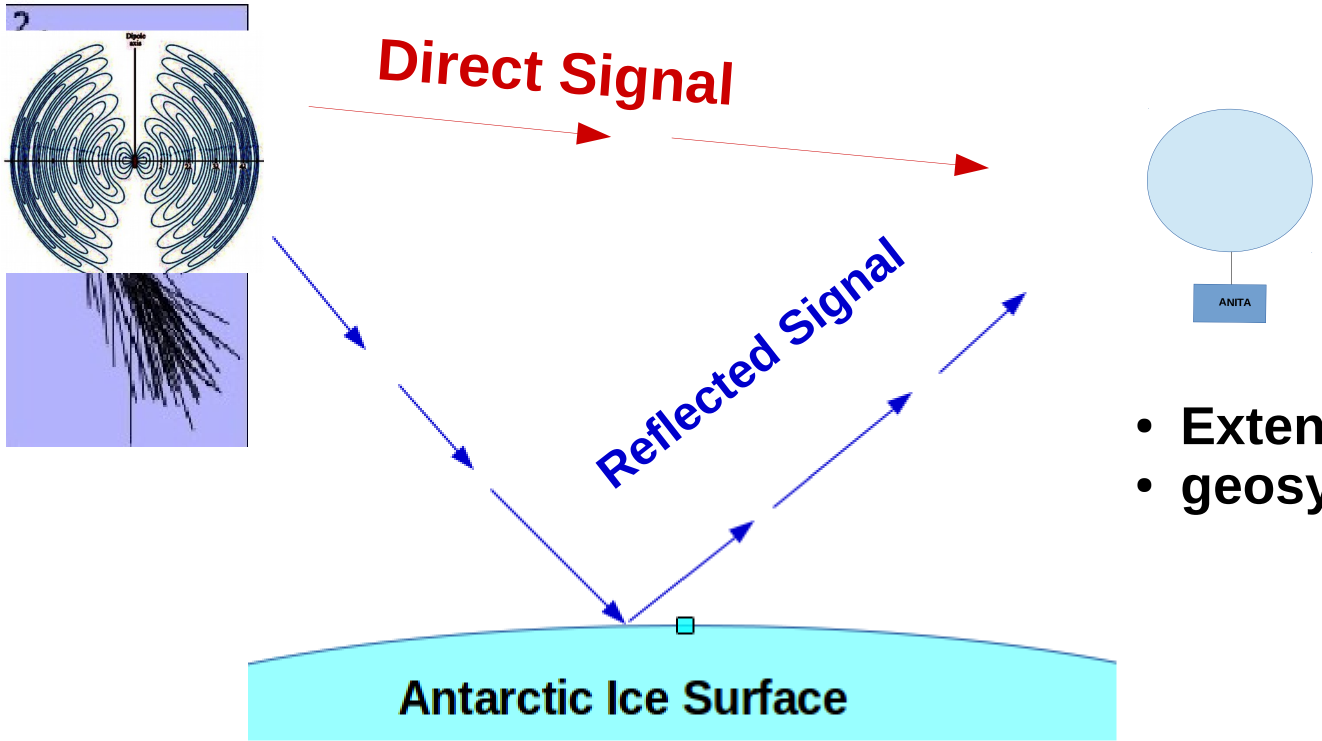
## Reflection off a Flat Surface



## Reflection off a Spherical Surface



- A dipole radiator on the z axis



- **Extensive Air Shower (EAS)**
- **geosynchroton radiation**

**Our formalism might be able to unfold the mystery of ANITA anomalous events.**

**We will submit these new results soon.**

# Future Scope in UHE Neutrino Study

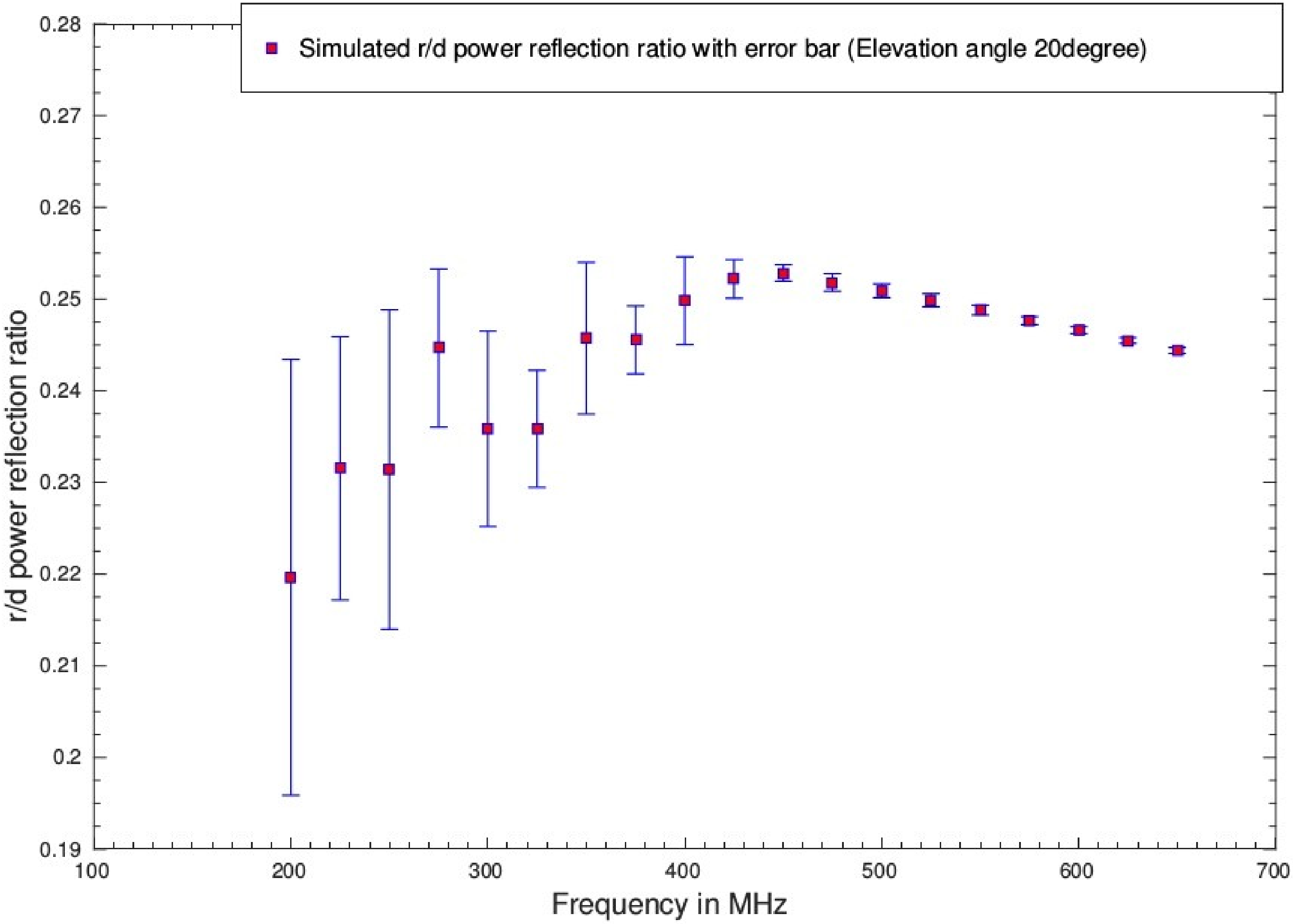
**Huge ANITA Data to be analysed**

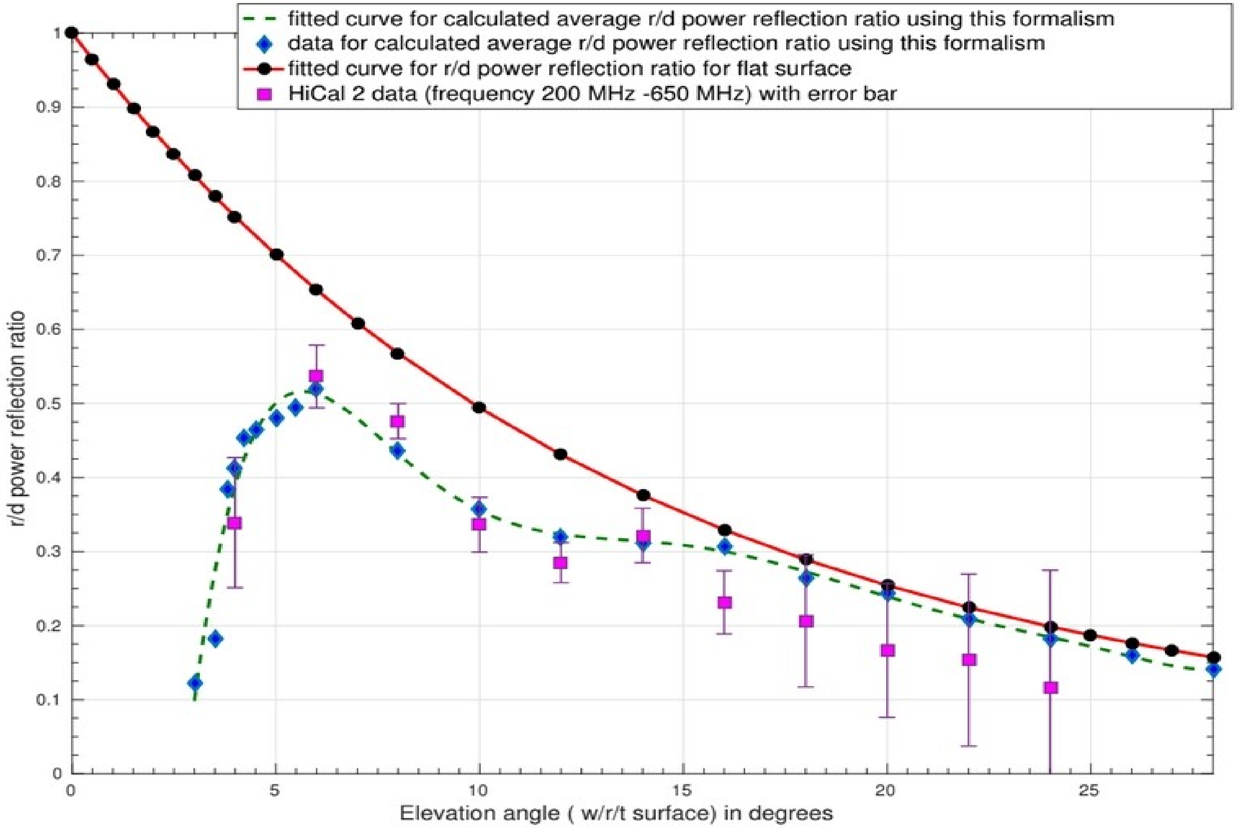
**Cosmic Ray and Tau neutrino analysis**

**Unfolding Mystery events & the Sources**

**ANITA 5 Proposal !! ARA, ARIANA Experiment !**

# Frequency dependence of r/d power ratio





**P. Dasgupta and P Jain arXiv:1811.00900, November 2018**

## For a Flat Surface

**Reflected Field /Direct Field**

**Fresnel coefficients**

## Reflecting Surface is Curved

**Reflection of Spherical waves from Spherical-Rough surface**

**We also studied the case of non-uniform Roughness**

# Fourier-Bessel Integral: Expansion of Spherical Wave into plane waves

$$h_0^{(1)}(kR) = \frac{e^{ikR}}{ikR} = \int_{i\infty}^{1} e^{ikR\eta}\,d\eta.$$

Using $k.R= k R \cos \gamma$

$$\frac{e^{ikR}}{ikR} = \int_0^{\frac{\pi}{2}-i\infty} e^{ikR\cos\gamma}\sin\gamma\,d\gamma$$

**Since value of the integral is invarient to a rotation of the reference axes, Hence we get the desired Weyl representation of Spherical Waves into plane waves**

$$\frac{e^{ikR}}{R} = \frac{ik}{2\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty} e^{ikR\cos\gamma}\sin\alpha\,d\alpha\,d\beta.$$

# Why to study Ultra High Energy Neutrinos ??

- Ideal Astronomical Messengers
- Uncharged, not affected by $B_{earth}$
- New information on UHE (> $10^{19}$ eV) CR
- GZK effect : CR interaction with $Y_{CMB}$ produce neutrinos.
- UHE neutrino Sources !!

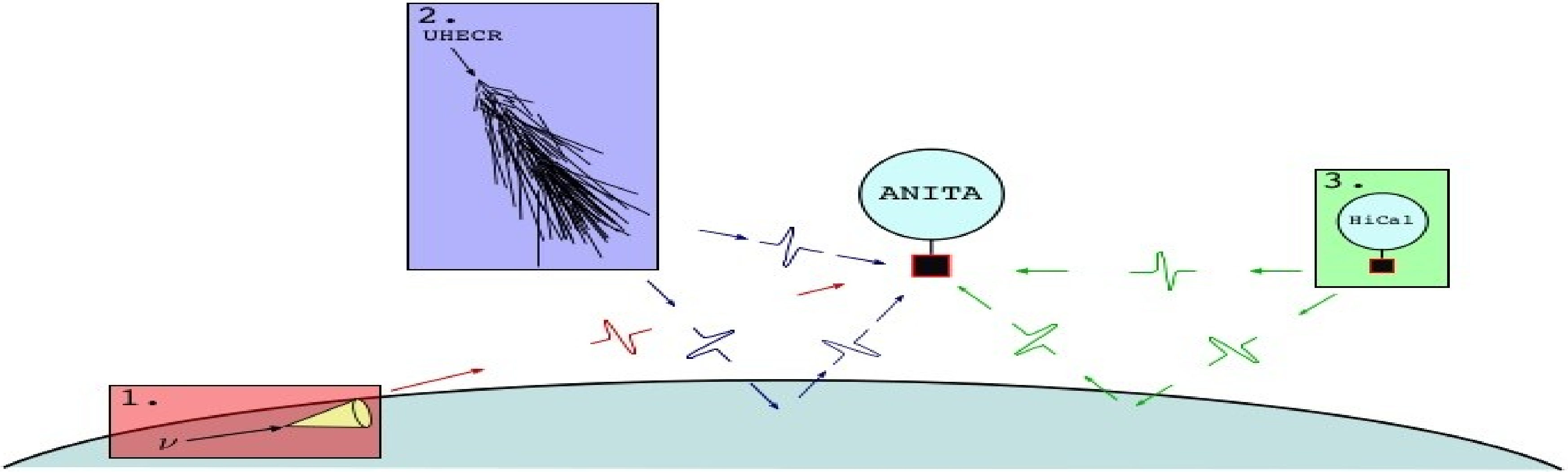
$$p_{CR}^{+} + \gamma_{CMB} \rightarrow \Delta^{*} \rightarrow n + \pi^{+}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

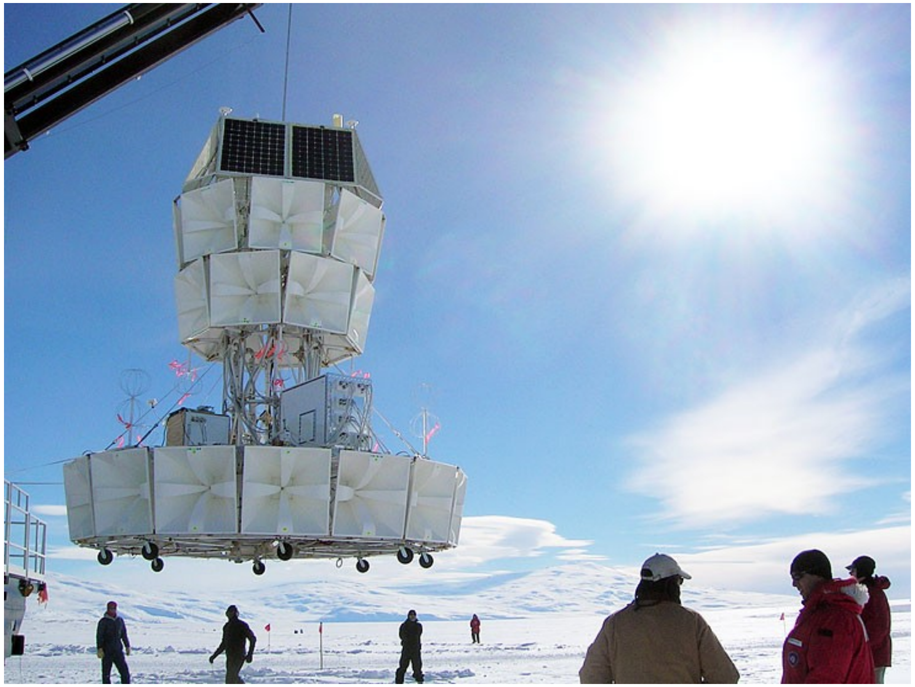
# ANITA and HiCal Working Principle

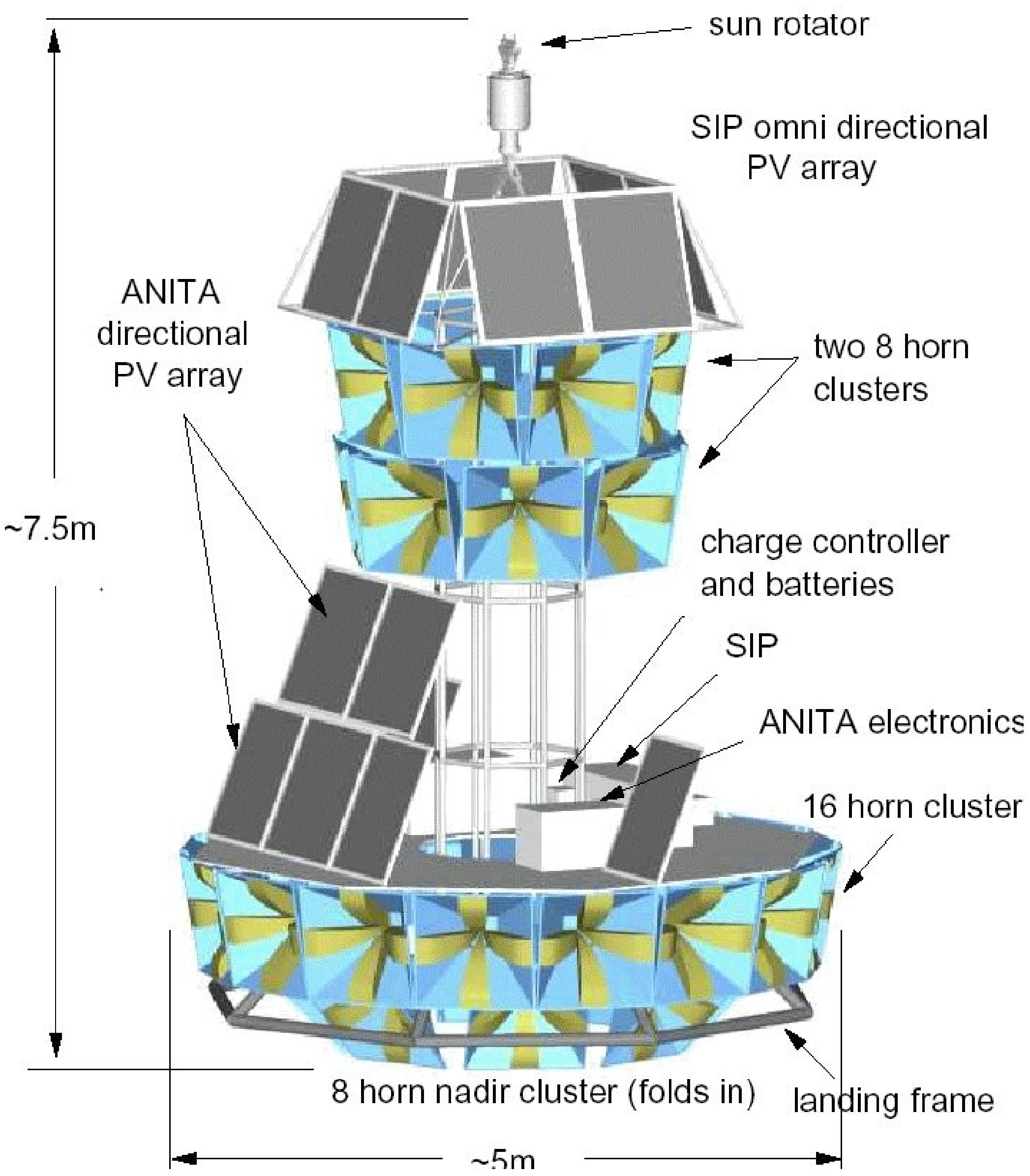
- **Antarctic Impulsive Transient Antenna is a balloon-borne RF (200-650) MHz Receiver Array.**
- **High Altitude Calibration (HiCal) is a Balloon-Borne RF Transmitter, in concert with the ANITA RF receiver array.**
- **ANITA-HiCal Measures Antarctic Surface Reflectivity in RF regime.**
- **Main Goal of ANITA is to detect Highest Energy Particles via the Radio signals produced by the UHECR interacrion with Earth's atmosphere.**
- **Down Coming Charged Particles produce Mainly H-Pol radiation.**



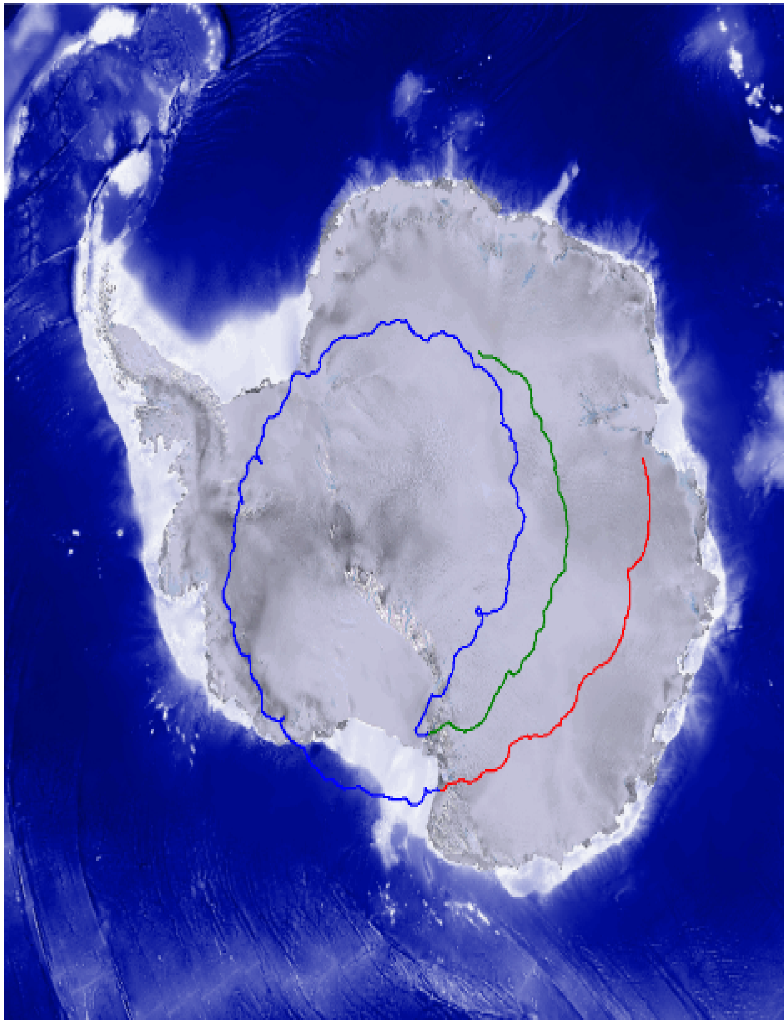
**P. W. Gorham et al. arXiv:1710.11175**

# ANITA Detector



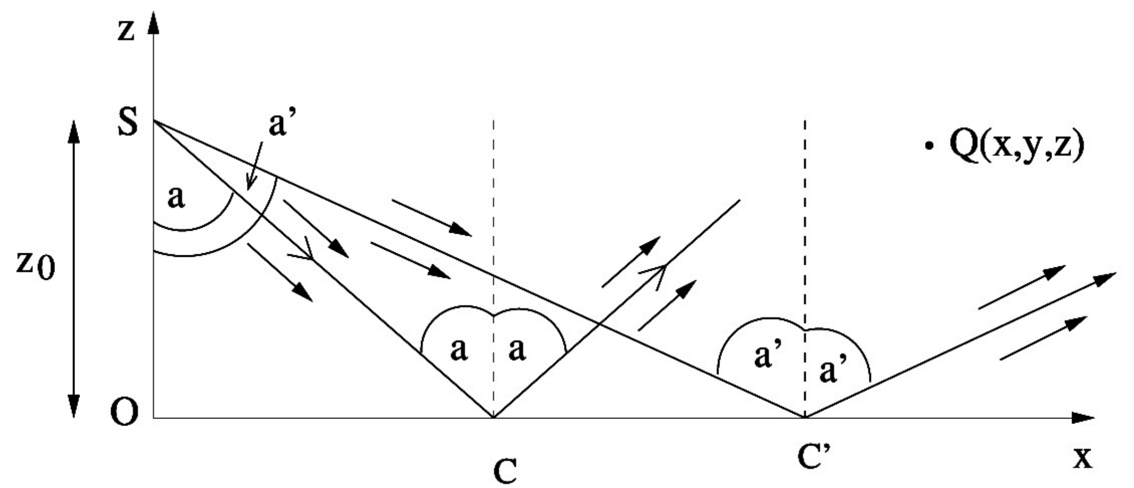


28-32 days at float



**He balloon flying at a height 37Km above Antarctica, carries array of radio antennas to detect radio signals from Cosmic Neutrinos/UHECRs**

# Weyl Formalism : Decomposition of Spherical Waves into Plane Waves



Start with a Hertz dipole at (0,0,$z_0$)

Hertz Potential (In Far Field r>> λ)

$$\Pi_y(x,y,z) = \frac{e^{ikR}}{4\pi\epsilon R} + F_1(x,y,z)$$

**Primary field**

**Due to reflection**

$$\vec{k}_I = k(\sin\alpha\cos\beta\hat{x} + \sin\alpha\sin\beta\hat{y} - \cos\alpha\hat{z}\,)$$

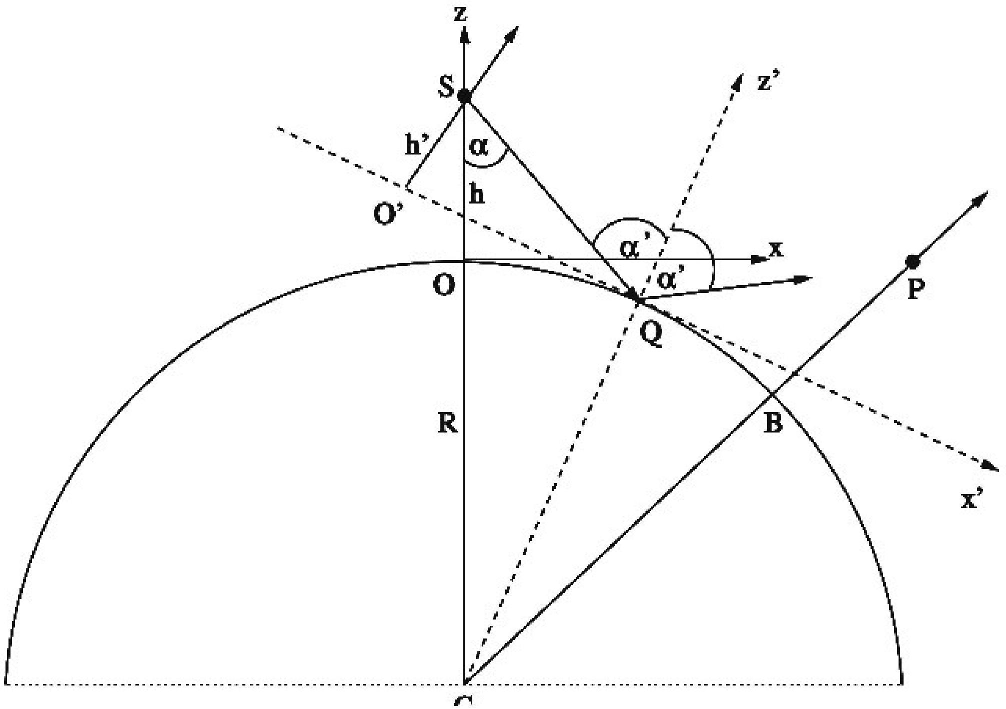
**Incident wave vector k(α,β)**

$$\vec{k}_t = k_1[\sin\alpha_t\cos\beta_t\hat{x} + \sin\alpha_t\sin\beta_t\hat{y} - \cos\alpha_t\hat{z}]$$

**Transmitted wave vector k($\alpha_t$,$\beta_t$)**

* Weyl Formalism (H. Weyl, Ann. Physik, 60,481,1919)
Stratton(1941), Born &Wolf (1980)

# Spherical Earth Surface: Reflection and Refraction of radio signals



$R_{Earth}$~6371 Km

Detector Height $z_0$~ 37Km

$$Rot = \begin{pmatrix} \cos(\alpha' - \alpha)\cos\beta & \cos(\alpha' - \alpha)\sin\beta & -\sin(\alpha' - \alpha) \\ -\sin\beta & \cos\beta & 0 \\ \sin(\alpha' - \alpha)\cos\beta & \sin(\alpha' - \alpha)\sin\beta & \cos(\alpha' - \alpha) \end{pmatrix}$$

S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al. Phys. Rev. D 98, 042004

# Include Non Uniform Roughness Parameter

**Previously we incorporated Roughness Factor that assumed a circular region around the specular point**

$$F(k,\rho,\theta) = \exp[-2k^2\sigma_h(\rho_\perp)^2\cos^2\theta_z] \qquad \sigma_h(L) = \sigma_h(L_0)\left(\frac{L}{L_0}\right)^H$$

**where, sigma($L_0$)= 0.041, $L_0$= 150 m, H= Hurst Parameter=0.65,**

$X^2 + Y^2 = L^2$ ← **Circular**

**Now, I use an elliptical region around the specular pt $X^2 + (aY)^2 = L^2$**

**with a<1**

**We compute reflected pulses using this assymetric roughness parameter “a”**

**choosing a=0.1, 0.25, 0.5 and a=1 (which is the symmetric case, as given by Peter Gorham's model)**

**0.041< =sigma($L_0$)<=0.071 and $L_0$ changed accordingly between 150m to 80 m**

**RESULTS with different assymetric factors “a”, and slightly changed sigma($L_0$), and $L_0$ values are obtained.**