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ANITA: Radio Detection of Ultra High Energy Cosmic Rays and Neutrinos

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We briefly review the detection of cosmic rays and ultra high energy neutrinos using ANITA detector. We describe a rigourous formalism to handle reflection of electromagnetic waves and pulses from spherical surface. The source is assumed to be a dipole radiator which emits over a frequency interval 200-650 MHz. The reflection is handled by using a local plane wave approximation in which the reflected wave for each incident plane wave is assumed to be locally a plane wave. The results for the power reflection ratio are found to be in good agreement with the HiCal experimental data. For simple models of surface roughness we find that the reflected pulse shows the expected phase inversion relative to the incident pulse.

KEYWORDS: ultra high energy cosmic rays, neutrinos, radio waves, . . .

1. Introduction

Antarctic Impulsive Transient Antenna (ANITA) is a balloon based observatory desiged to detect ultra high energy neutrinos and cosmic rays through observation of radio pulses. A cosmic ray generates an extensive air shower after collision with an atmospheric nucleus. Charged particles produced in this shower produce a radio pulse due to propagation in the Earth's magnetic field. This pulse may be detected directly or after reflection from the Antarctica ice surface by the detector. An ultra high energy neutrino can also generate such a pulse if its direction of propagation is close to horizontal. Furthermore a cosmic neutrino can interact with ice and produce a radio pulse by the Askaryan effect. This pulse can be detected inside ice or after emerging out into the atmosphere. By detecting such radio pulses, the ANITA detector can deduce the properties, such as, the energy and the angle of incidence of the primary cosmic ray particle.

The radio pulse arising due to geo-synchrotron emission is dominated by H-polarization, i.e. the polarization of the radio wave is parallel to the Earth's surface. The corresponding reflected pulse is also dominated by H-polarization. The signal arising due to Cherenkov emission inside ice, however, primarily has V-polarization. This difference provides an important tool in order to distinguish the origin of these radio pulses. The frequency band of the ANITA detector ranges from 180 to 1200 MHz.

ANITA has so far completed four flights and imposed very stringent limits on the diffuse ultra high energy neutrino flux [1]. It has also observed many cosmic ray events. A very interesting discovery by ANITA is the so called mystery events for which the radio pulse arrives at the steep angle, consistent with reflected signal, but does not show the phase inversion associated with reflection [4].

An important aspect to the observation process is the reflection of radio waves from the ice surface, which is complicated due to the fact that the incident wave is not a plane wave and furthermore one needs to take into account the spherical nature of the Earth's surface and the surface roughness effects. We have developed a rigourous theoretical formalism in order to treat the reflection of electromagnetic waves from the Antarctica surface, assumed to be spherical. We assume that the source S is a dipole radiator, placed at coordinates $(0, 0, z_0)$ such that the dipole vector $\hat{p} = \hat{y}$, as shown in Fig. 1. The observer Q is located at coordinates $(x, 0, z)$. The Hertz potential, including the contribution due to reflection, can be expressed as,

$$\Pi_y(x, y, z) = \frac{e^{ikR}}{4\pi\epsilon R} + F_1(x, y, z) , \tag{1}$$

$\Pi_x = \Pi_z = 0$ and $R = \sqrt{x^2 + y^2 + (z - z_0)^2}$. Here F_1 is the contribution due to reflection.

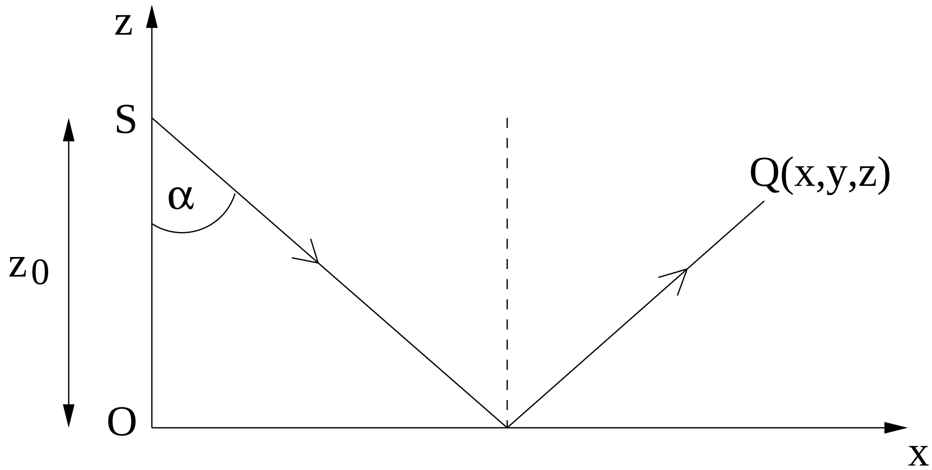

Fig. 1. A dipole source with $\hat{p} = \hat{y}$ is located at S on the z axis and the receiver Q is located in the x-z plane.

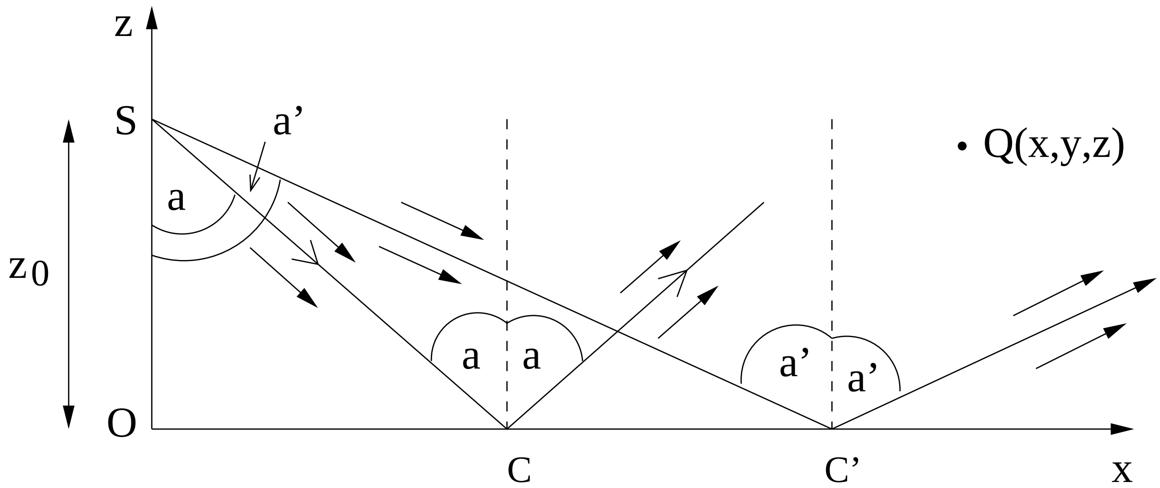

Fig. 2. Here we show the geometry corresponding to reflection from a flat surface with the origin at O. The electromagnetic wave from the dipole at S is decomposed into plane waves each of which undergo reflection from the surface. Here we show wave vectors corresponding to two such plane waves. For each of these plane waves we only show the wave vector emanating from S and C and C' correspond to the points of reflection from the surface. All the reflected waves are added to give the final reflected wave at Q.

2. Reflection of Electromagnetic Waves

The formalism is based on the following decomposition of the Hertz potential, Eq. 1, of dipole radiation:

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

applicable for $0 \leq z \leq z_0$. Here $\pi - \alpha$ is the polar angle and β the azimuthal angle in the spherical polar coordinates. This essentially represents a superposition of plane waves with wave vector

$$\vec{k}_I = k\,(\sin\alpha\cos\beta\hat{x} + \sin\alpha\sin\beta\hat{y} - \cos\alpha\hat{z})\ , \tag{3}$$

The corresponding electric and magnetic fields are given by

$$\begin{aligned}\vec{E} &= \vec{\nabla}(\vec{\nabla}\cdot\vec{\Pi}) + k^2\vec{\Pi}\\ \vec{H} &= \frac{k^2}{i\omega\mu}(\vec{\nabla}\times\vec{\Pi})\end{aligned} \tag{4}$$

The reflected wave from a smooth plane surface can now be determined by using the standard Fresnel formalism for each incident plane wave and adding all the reflected waves. This is illustrated in Fig. 2. The reflected wave corresponding to each incident plane wave is also a plane wave. In Fig. 2 we show two different incident plane waves undergoing reflection at the plane surface. Each plane wave is decomposed into components perpendicular (s) and parallel (p) to the plane of incidence, i.e.,

$$\vec{E} = \vec{E}^s + \vec{E}^p\ , \tag{5}$$

$$\vec{H} = \vec{H}^s + \vec{H}^p\ , \tag{6}$$

and treated independently. Adding contributions for all the plane waves we can determine the reflected H or V polarized wave [2]. We find that the final result for reflection coefficient for the reflection of a dipole radiation from a plane surface exactly matches the standard Fresnel reflection of plane waves.

3. Reflection from Spherical Surface

We next consider reflection of dipole electromagnetic radiation from the Antarctica surface which is assumed to be spherical. We again decompose the incident sperhical wave into plane waves. The final wave is obtained by adding reflected waves corresponding to each plane wave. In the present case, however, the reflected wave for each plane wave is not a plane wave, as illustrated in Fig. 3. In this figure we show an incident plane wave getting reflected at two positions C and C' on the surface. We see that the reflected wave vectors are not parallel and hence will not form a plane wave. However the deviation may not be large if the radius of curvature of the spherical surface is sufficiently large. Explicit calculations show that if the reflected wave for each incident plane wave is approximated as a plane wave, the results agree well with experimental data for large elevation angles but not for small angles [2]. Here the experimental results are obtained by using balloon-borne HiCal radio-frequency transmitter. The elevation angle is the angle of the incident wave with respect to the tangent at the point of specular reflection at the surface. In this calculation the surface roughness is taken into account by using a model as described in [2].

In order to properly treat the reflection from a spherical surface we assume that the reflected wave for each plane wave is locally a plane wave [3]. This means that in the neighbourhood of any point the reflected wave can be treated as a plane wave over a small interval. We term this as local plane wave approximation. For all the incident plane waves we choose the reflection point on the curved surface such that the reflected wave vectors point towards the observation point Q. This is illustrated in Fig. 4.

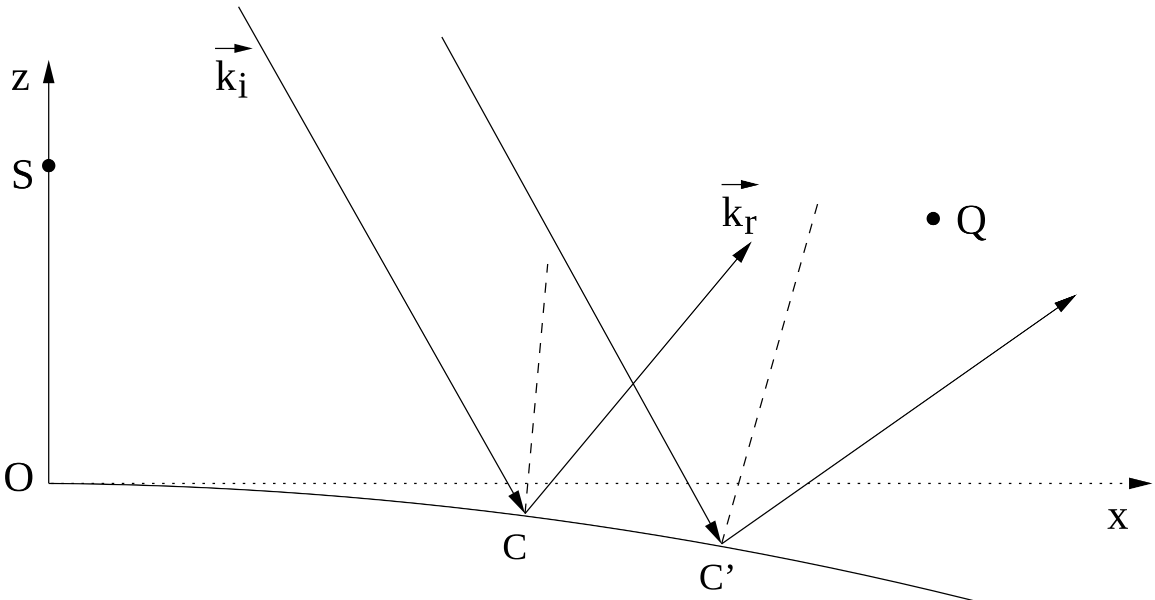

Fig. 3. Here we show the geometry for reflection from a spherical surface. In this case the reflected wave corresponding to an incident plane wave is not a plane wave. Here we show two incident wave vectors for a plane wave. We see the corresponding relfected wave vectors are not parallel and the wave front is not plane.

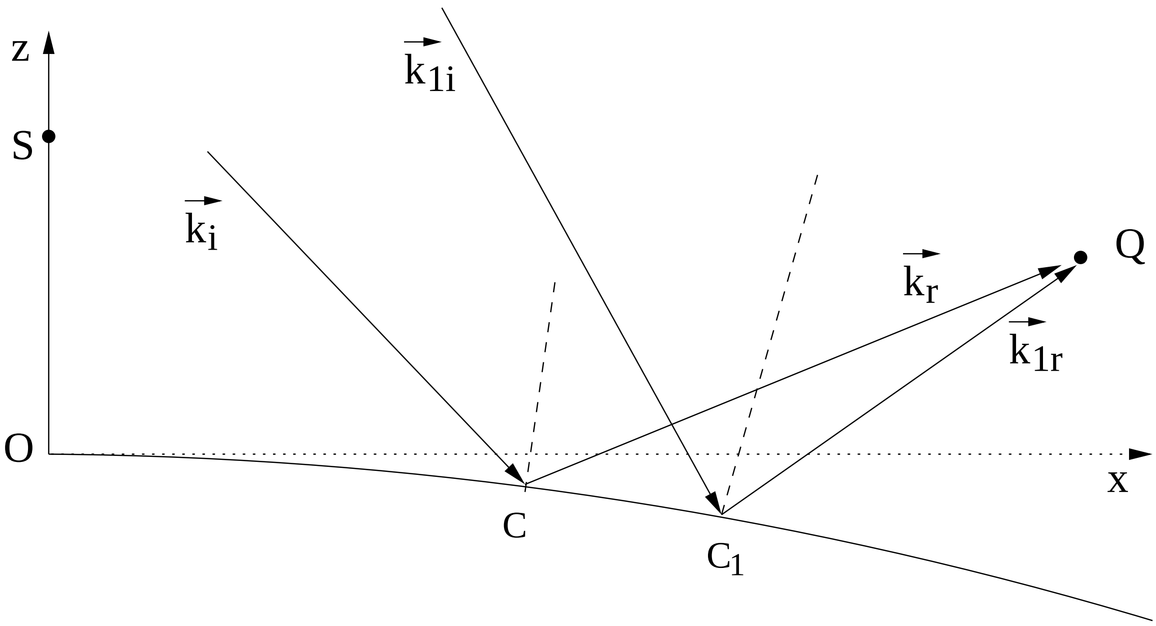

Fig. 4. We treat reflection from a spherical surface by assuming that for each incident plane wave the reflected wave can be approximated to be a plane wave in a small neighbourhood of any point. Hence we consider reflected wave vectors to point directly at the observation point Q and assume that the wave fronts are approximately plane close to Q.

Here we show two incident plane wave vectors and the corresponding reflected wave vectors, which point towards the observation point Q. Note that here we only need to assume that the reflected waves are approximately plane waves in a small neighbourhood of Q. The final results on the reflection coefficient are found to be in good agreement with the HiCal data for all elevation angles [3]. For small elevation angles the observations show a rather dramatic decrease in the power reflection ratio which is well described by the formalism [3].

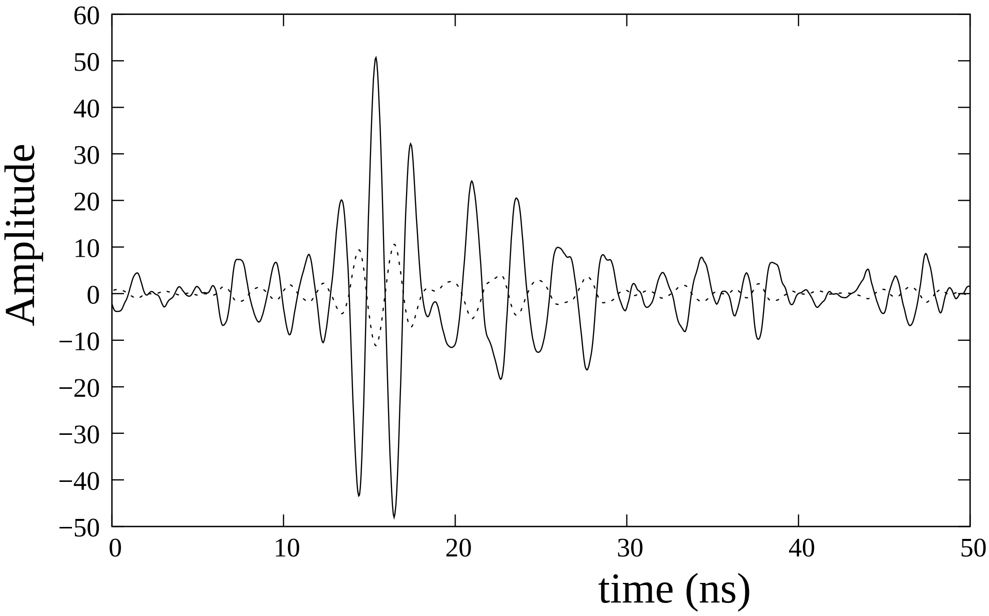

Fig. 5. The direct (solid line) and reflected (dashed line) pulse as a function of time. The reflected pulse shows a phase inversion, as expected. This incident pulse is taken from HiCal emitter. The specular angle of incidence is 63° with respect to the normal to the surface.

4. Reflection of Pulses and Implications for ANITA Mystery Events

For application to ANITA we need to consider electromagnetic pulses. We represent each pulse as a superposition of dipole electromagnetic waves at fixed frequency and treat them by the procedure described earlier. Let the pulse in time domain be represented by $f(p)$. Here $f(p)$ represents one of the polarization components of the pulse. Its Fourier transform is given by

$$\tilde{F}(n) = \sum_{p=0}^{N-1} f(p) e^{i\frac{2\pi n}{N}p} \tag{7}$$

The corresponding direct electric field component at propagation distance r is given by [3]

$$E_d[p,r] = \frac{1}{Nr}\sum_{n=0}^{N-1}[\tilde{F}_{real}[n] + i\tilde{F}_{imag}[n]]e^{-i\frac{2\pi np}{N}} \tag{8}$$

where $\tilde{F}_{real}[n]$ and $\tilde{F}_{imag}[n]$ represent respectively the real and imaginary parts of $\tilde{F}(n)$. In this equation, besides the $1/r$ factor there are additional angle dependent factors which we have not displayed explicitly and may be absorbed in the factors $\tilde{F}_{real}[n]$ and $\tilde{F}_{imag}[n]$. The dipole wave at each frequency is further decomposed into plane waves and after adding all the reflected waves we obtain the final pulse profile [3].

In Fig. 5 we show the reflected pulse for a particular incident pulse using the roughness model given in [3]. We find a phase inversion, as expected. However it is not clear that this will be maintained for all roughness models and different surface profiles. Such a study is important due to the observation of events in ANITA which are observed at a relatively steep angle, consistent with reflected events, but do not show expected phase inversion [4]. It has been speculated that these represent new physics [5–9], perhaps associated with a dark matter candidate decaying inside Earth and producing an upward shower coming out of Earth. Hence it is very important to determine if some standard physics can produce the observed phase in the reflected signal. We have tried some generalization of the roughness models in order to study this possibility. In particular the model used in [3] is symmetric relative to the specular point. We have obtained results assuming an asymmetric model. However we find that such changes do not affect the inversion. We are currently investigating whether some change in topography such as a slow change in slope of the surface can produce the desired effect.

5. Conclusions and Future Work

We have developed a reliable framework to handle reflection of electromagnetic waves from a spherical surface. The source is assumed to be a dipole radiator. We assume a simple model for surface roughness in our analysis. The results are found to be in good agreement with HiCal data and correctly reproduce the sudden decrease in the power reflection ratio at small elevation angles. We have also analyzed reflection of electromagnetic pulses and find the expected phase reversal. This is important in order to find an explanation for the mystery events observed by ANITA. So far we are unable to find a conventional explanation for these events. The formalism can be extended to treat surfaces which may not be exactly spherical. This may be useful for the interpretation of individual events seen in ANITA.

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