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Simulation of Propagation of Radioemission of High Energy Cascade Developed in Lunar Ground and Its Transfer Through Regolith-Vacuum Border

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Problem of generation and propagation of radioemission from cascades initiated in lunar ground by high energy particles including the process of radiowave passage through regolith-vacuum boundary is considered in 4 dimensions using a finite difference scheme. The calculation results for different shower and media interface configurations make it possible to estimate radioemission intensity and transition coefficient which are important for experiment design.

1. Introduction

It is common knowledge that one of the instruments for super high energy cosmic ray study is the detection of radioemission from hadronic and electromagnetic cascades developing in different media, which was not developed to the full extent of its power for a variety of reasons. In 1961 the founder of the method of cosmic ray detection G.A.Askaryan among other things suggested to search for radio signals from particle cascades developing in lunar ground using antennae placed on the surface of the Moon [1]. Later on a series of experiments was carried out aiming at the detection of such radioemission with the help of radiotelescopes without any considerable results.

Recently LORD (Lunar Orbital Radio Detector) experimental project was proposed and started its development [2]. According to the project, an array of antennae of decimeter wavelength band is installed on board of a satellite orbiting the Moon with orbit altitude 100-1000 km. Antennae search the lunar surface within line-of-sight range and detect short radiopulses of nanosecond duration. Such pulses could originate from hadronic and electromagnetic cascades initiated by super high energy cosmic ray nuclei and neutrinos in near-surface layer of lunar ground. The authors started a prefatory computer simulation of LORD experiment.

2. Calculation method and results

Experimental conditions for the detection of radiofield of the cascades developing in the lunar ground are such that the radioemission is generated in one medium (lunar regolith) then transferred to and finally detected in another one (vacuum). The situation is additionally complicated by the fact that this radioemission is absorbed by regolith and thus it is only possible to detect radiopulses coming from a thin near-surface layer of lunar ground. Simple methods for radioemission simulation, using geometrical approach, are not valid in our case as they are based on an assumption that the medium is boundless and the observer is distant (the distance to the observer is much greater than the wavelength). The fine points of radiation transfer through the media border should be taken into account. Problem stated in such a way suggests one to find a solution $A(t,x,y,z)$ of 3-dimentional wave equation for vector-potential:

$$\frac{1}{v^2}\frac{\partial^2 A}{\partial t^2} = \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + \frac{\partial^2 A}{\partial z^2} + f(t,x,y,z)$$

in $(0,X)\times(0,Y)\times(0,Z)\times(0,T)$ domain including two homogeneous media with a certain interface and homogeneous boundary conditions:

$$A(t,0,y,z) = A(t,X,y,z) = A(t,x,0,z) = A(t,x,Y,z) =$$
$$= A(t,x,y,0) = A(t,x,y,Z) = 0$$

initial conditions:

$$A(0,x,y,z) = A_t(0,x,y,z) = 0$$

and different source functions $f(t,x,y,z)$.

While selecting a difference method the multidimensionality of the problem, necessity to consider different step sizes for different dimensions and a variety of source functions were taken into account. Finally an unconditionally stable scheme was selected with $\sigma = 1/4$ [3]:

$$\left[E - \frac{v^2\tau^2}{4}(\Lambda_x + \Lambda_y + \Lambda_z)\right] A^{m+1}_{i,j,k} =$$
$$= 2\left[E + \frac{v^2\tau^2}{4}(\Lambda_x + \Lambda_y + \Lambda_z)\right] A^{m}_{i,j,k} -$$
$$- \left[E - \frac{v^2\tau^2}{4}(\Lambda_x + \Lambda_y + \Lambda_z)\right] A^{m-1}_{i,j,k} + v^2\tau^2 f^{m}_{i,j,k}, \tag{1}$$
$$\Lambda_x = \frac{1}{h_x^2}(A_{i-1} - 2A_i + A_{i+1}),$$
$$\Lambda_y = \frac{1}{h_y^2}(A_{j-1} - 2A_j + A_{j+1}),$$
$$\Lambda_z = \frac{1}{h_z^2}(A_{k-1} - 2A_k + A_{k+1}),$$

here i,j,k,m - indices in x,y,z,t, τ – step size in t, v - wave propagation velocity, h_x,h_y,h_z - steps sizes in x,y,z, E – unit matrix. The scheme unconditionally converges with the speed of $O(\tau^2 + h_x^2 + h_y^2 + h_z^2)$.

In order to obtain an economical scheme the original one (1) was factorized. For the purpose the right-hand operator of (1) was substituted by

$$C = C_1 C_2 C_3,$$

$$C_1 = E - \frac{v^2\tau^2}{4}\Lambda_x, \quad C_2 = E - \frac{v^2\tau^2}{4}\Lambda_y, \quad C_3 = E - \frac{v^2\tau^2}{4}\Lambda_z.$$

As a result the scheme (1) takes the form

$$C_1 C_2 C_3 A^{m+1}_{i,j,k} = d^{m}_{i,j,k}, \tag{2}$$

here $d^{m}_{i,j,k}$ is the right-hand part of (1). The solution of (2) is equivalent to the successive solution of the three systems of equations:

$$C_1 p^{m+1}_{i,j,k} = d^{m}_{i,j,k}, \tag{3}$$
$$C_2 q^{m+1}_{i,j,k} = p^{m+1}_{i,j,k}, \tag{4}$$
$$C_3 A^{m+1}_{i,j,k} = q^{m+1}_{i,j,k}. \tag{5}$$

The final scheme (3-5) is unconditionally stable and economical. The factorization does not change the speed of convergence and the final scheme has the same speed $O\left(\tau^2 + h_x^2 + h_y^2 + h_z^2\right)$.

A program implementing the scheme (3-5) makes it possible to specify the number of partition knots and step size for any of the four coordinate separately and set any initial and boundary conditions and source function. Computation time for a 50^4 grid solution amounts to a few minutes with Athlon 1700.

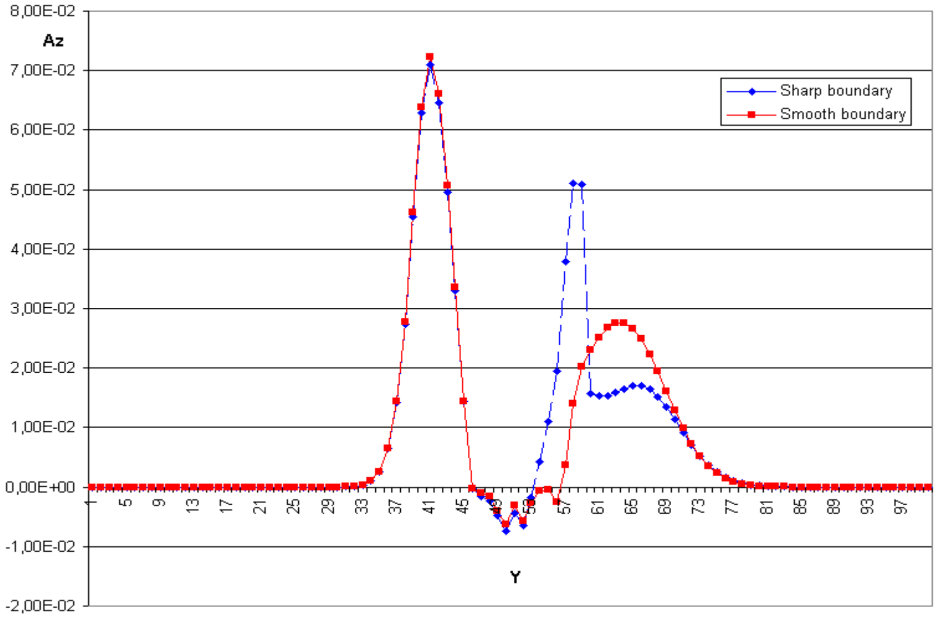

Figure 1. $\boldsymbol{A}_z$ component of vector-potential section at t = 40, x = 50, z = 72. Two cases of regolith-vacuum interface are shown: sharp one (abrupt change of refraction index) and continuous one (refraction index changes linearly within the domain of 4 steps).

The developed program can consider the cases with discontinuous change of refractive index (when it changes abruptly from knot to knot) as well as the cases with smooth border when refractive index varies continuously according to a given law. Besides we got a version for consideration of a random interface case (abrupt change of refractive index occurring at a random point in the vicinity of conventional border).

Figure 1 compares the solutions in two cases of continuous and sharp media interface for $100 \times 100 \times 100 \times 100$ grid (step size in space is 0.3 m and step size in time is 1 ns) at 40^{th} step in time. Onwards the coordinates are given in steps. The source function used was a disk-shaped charged volume moving in parallel to the interface along the z axis (which makes only $\boldsymbol{A}_z$ component of vector-potential differ from zero) at x = 50, y = 50 (the interface is set in y = 60 plane) over 20 steps in time with the speed of light in vacuum c. The velocity of wave propagation was assumed to be c/n in regolith (here n=1.8 is refractive index value in regolith) and c in vacuum.

The considered direction of source movement (in parallel to the interface) is the simplest in calculation but is marginal for Cherenkov emitter because the radiation front strikes upon the interface at an angle of total internal reflection. As a result the passed radiation lacks pronounced directivity.

To study the effects of radiation transfer through the interface in more detail without perplexing the calculations the moving source was substituted by a static source array of 6×6 coherent harmonic oscillators. Such a scheme yields a plane wave moving in the direction perpendicular to the array surface with a pronounced maximum. In case of normal incidence upon the interface the transition coefficient amounts to 0.31. Figure 2 shows A_z profiles at different instants for this case. For the case of oblique incidence at 18° off the normal the passed wave shows the refraction angle of 33° which is in accordance to the geometrical limit; transition coefficient value is 0.21.

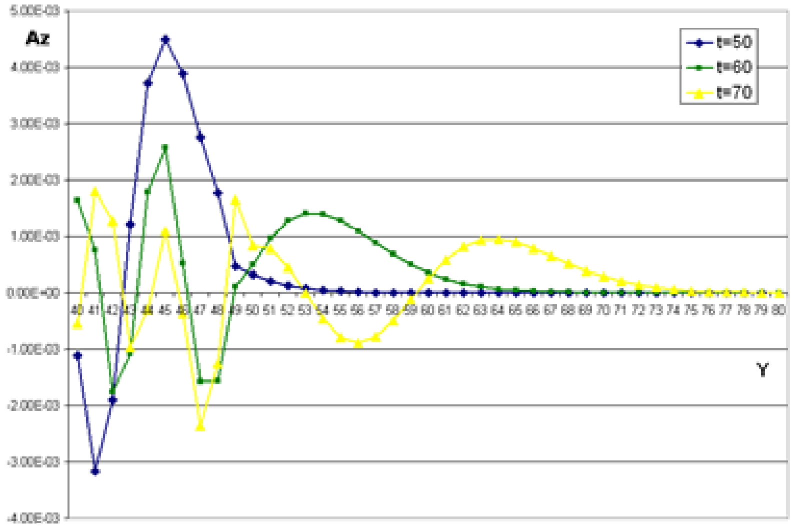

Figure 2. A_z component of vector-potential profiles for $x = 50$, $z = 33$ line (radiation maximum) for the normal incidence case at different instants (50, 60, 70). The source is an array of harmonic oscillators. Media interface is $y = 50$ plane.

3. Conclusions

A finite difference scheme is used to study the process of generation and propagation of radioemission from cascades initiated in lunar ground and its passage through regolith-vacuum interface. First results show the scheme really works and make it possible to estimate the transition coefficient.

References

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