The effects of naturally occurring impurities in rock salt

ALINA-MIHAELA BADESCU[1,*] and ALEXANDRA SAFTOIU[2]

[1]University POLITEHNICA of Bucharest, Splaiul Independenţei 313, Sector 6,
Bucharest 060042, Romania
[2]IFIN-Horia Hulubei, Str. Reactorului No. 30, P.O. Box MG-6, Bucharest-Magurele, Romania
*Corresponding author. E-mail: alinabadescu@radio.pub.ro

Abstract. In this paper we investigate the effect that naturally occurring impurities in salt mines have both on effective permittivity of the medium and on radio wave propagation at ∼200 MHz. The effective permittivity is determined based on the dielectric properties of salt and the characteristics of the main impurities. We conclude that at such frequencies the scattering is negligible compared to absorptions. The effect of trapped water in different forms is also evaluated.

Keywords. Effective permittivity; salt mine; radio waves.

PACS Nos 77.22.Ch; 71.55.Eq; 42.25.Fx

1. Introduction

A cosmic neutrino detector images a portion of the Universe using interactions of a nearly massless subatomic particle called neutrino. Neutrinos are weakly interacting particles that cannot be detected directly. Their properties are deduced by analysing their interaction products.

One detection method was proposed by Askaryan [1]. He suggested that if a neutrino interacts within a volume of dielectric, it will produce a broadband electromagnetic (EM) field (including radio frequencies) that can be measured. To compensate for the small interaction probability [2], a huge volume of detecting material is required, which is found in naturally occurring bulk of dielectrics, such as the ice sheets at the poles or natural salt domes. The medium should be transparent to the produced waves to ensure large propagation distances. Thus, salt in salt mines (with a theoretical low dielectric permittivity and high purity) can serve as the detecting medium for radio waves. This was tested at Stanford Linear Accelerator where Milincic detected radio waves from high-energy particles interacting in synthetic rock salt [3].

One of the key problems associated with a neutrino radio detector in salt is the capability to reconstruct the characteristics of cosmic neutrinos that interact in the salt mine

by measuring the radio radiation. The radio waves produced at the interaction point by Askaryan effect [1] travel through salt, and so the propagation medium has a huge impact on measurements and results. Most of the medium's properties can be described using the relative permittivity.

We decided to select an operating frequency of about 200 MHz. Although the Cherenkov generated field has the maximum intensity at a frequency close to a few GHz, we selected this frequency because it is less attenuated at propagation, is less sensible at temperature variations and allows differentiation between incidence angles [4]. As waves propagate in a non-ideal medium before being measured by radio antennas, it is important to have first a good geophysical material description for radio wave propagation. Hapke already remarked that this regime is not well understood [5]. It was suggested that an effective-medium theory should be applied to calculate permittivity.

Although theoretical approaches have been reported by [6,7] and others, models for propagation are rare because the heterogeneity in salt clearly affects radio waves. This was experimentally shown in [8] by measuring the attenuation of a radio signal at 400 and 800 MHz in the 'Unirea' salt dome in Slănic Prahova, Romania. Results showed deviation of a few hundreds of metres from the ideal medium case.

In the following we investigate and quantify the effect that naturally occurring impurities in salt have on radio wave propagation. In §2 the basic dielectric properties of salt are presented and its permittivity is calculated. Section 3 analyses naturally occurring impurities and main heterogeneities in a salt dome. We also analyse other factors such as the presence of water or fissures. The last part summarizes our results.

2. Dielectric properties of salt

Salt is a non-polar ionic dielectric (as are other ionic alkali halide crystals). The crystal structure alternates the positive and negative ions so that the bulk crystal does not have a permanent dipole moment. In the presence of an external field, the negative and positive ions will produce an ionic polarization that together with the electronic one will yield the relative dielectric constant ε_r.

The relative permittivity ε_r is an important factor in wave propagation as it connects the electric displacement field **D** to the electric field intensity **E**. In a linear, homogeneous, isotropic material with 'instantaneous' response to changes in electric field, the relation is

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}, \tag{1}$$

where the vacuum permittivity is $\varepsilon_0 = 8.854 \times 10^{-12}$ Fm^{-1}.

The absorption of electric energy in a dielectric material is the dielectric loss and it can be described in terms of complex permittivity:

$$\varepsilon_r = \Re\{\varepsilon_r\} + i\Im\{\varepsilon_r\}, \tag{2}$$

where the real part is the relative permittivity and the imaginary part is the loss factor. The tangent loss angle is given by

$$\tan\delta = \frac{\Im\{\varepsilon_r\}}{\Re\{\varepsilon_r\}}. \tag{3}$$

The ionic polarizability of NaCl is [9]

$$\alpha_i = \frac{4\pi \varepsilon_0 d_a^3}{0.58 \, (n + 1)},$$
(4)

where d_a is the interatomic separation between the centres of the Na$^+$ and Cl$^-$ atoms and n depends on the number of electrons on the outer shells. Pauling deduced the value of n for a few atoms in [10]. For the salt molecule, in formula (4) the mean value of the ions that form the salt molecule (note that $n_{Cl^+} = 9$ and $n_{Na^-} = 7$) should be used.

When a time-varying field is applied, the complex electronic polarizability is given by

$$\alpha_e = \frac{e^2/m}{\omega_0^2 \left[1 - (\omega/\omega_0)^2\right] + i \, (2b\omega_0/m) \, \omega/\omega_0},$$
(5)

where m is the mass of the ion (first Na and then Cl are considered), e is the electron charge and

$$b = \frac{e^2 \omega_0^2}{12\pi \varepsilon_0 c^3}$$
(6)

is an attenuation constant (c is the speed of light in vacuum). The resonance frequency is $\omega_0 = \sqrt{a/m}$. The constant a is

$$a = \frac{(ze)^2 \, (n + 1)}{4\pi \varepsilon_0 d_a^3}.$$
(7)

Here z is the ion's valence (first Na and then Cl are considered).

For materials with only ionic and electronic polarizabilities, the complex dielectric constant is given by

$$\varepsilon_r = \frac{1 + (1 - \gamma) \, N_V \alpha/\varepsilon_0}{1 - \gamma N_V \alpha/\varepsilon_0},$$
(8)

where the complex polarizability α is the sum of electronic and ionic polarizabilities:

$$\alpha = \alpha_e + \alpha_i.$$
(9)

The constant γ is called the internal field constant and for cubic crystals $\gamma = 1/3$ [11]. In (8) the volume density number is

$$N_V = \frac{\rho_m}{M} N_A,$$
(10)

where M is the molecular weight, N_A is the Avogadro's number and ρ_m is the mass density.

For millimetric and longer wavelengths, the permittivity should be independent of frequency and temperature and equal to its static value. In [12] it is stated that non-polar ionic dielectric materials should have complex permittivities only in the IR and UV frequency ranges. One can verify this statement by applying eqs (4) and (5) at MHz to GHz frequencies. It is found that $\Re \{\alpha_i\} = 4.78 \times 10^{-40}$ Fm^2 and $\Re \{\alpha_e\} = 2.77 \times 10^{-40}$ Fm^2. The imaginary part of the electronic polarizability is very small. The electronic polarizability (for static fields) is in accordance with the value found in [13] for NaCl, which is 2.85×10^{-40} Fm^2. In [13] the case when a variable electric field is applied was not presented.

Using (8)–(10), it is found that the real part of the permittivity for salt is $\Re\{\varepsilon_r\} = 6.2$ and the imaginary part $\Im\{\varepsilon_r\} = 4.69 \times 10^{-32}$. Again, one can show that the frequency dependence is extremely weak up to THz frequencies.

3. The effect of natural impurities

3.1 *Mathematical modelling*

3.1.1 *Effective permittivity.* To find the effect of the medium on propagation of radio waves, one must first determine the real and imaginary parts of permittivity that characterizes it [5].

During the process of diapirism, impurities in salt tend to segregate from the main salt body, and salt becomes purer than the initial bed from which the diapir arises [14]. Yet, the effect of impurities is not negligibly small on radio wave propagation, as demonstrated by experimental measurements of attenuation length of radiowaves amplitudes (that is, the distance where the amplitude of EM field has dropped to $1/e$) [8].

We introduce the notation $X = 2\pi a/\lambda$ (a is the physical dimension of the particle and λ is the wavelength). Typically, for radio waves $X \ll 1$. This is known as the Rayleigh regime. As Hapke remarked in [5], this regime is not well understood. It was suggested that an effective-medium theory should be applied to calculate permittivity.

For a heterogeneous medium, the bulk dielectric constant is represented by a volume-averaged mean dielectric constant of all constituents [5]. If the medium is of permittivity ε_r and contains impurities with ε_{i1} that occupy a volume fraction $\Phi_1 = N_1 4\pi a_1^3/3$ (where N_1 is the number of particles in unit volume and a_1 is the particle radius), then

$$\varepsilon_{r,1} = \varepsilon_r + \frac{3\Phi_1 \varepsilon_r \left[(\varepsilon_{i1} - \varepsilon_r)/(\varepsilon_{i1} + 2\varepsilon_r)\right]}{1 - \Phi_1 \left[(\varepsilon_{i1} - \varepsilon_r)/(\varepsilon_{i1} + 2\varepsilon_r)\right]}. \tag{11}$$

Equation (11) states that the variation in the number density of particles is equivalent to variations in the local dielectric constant.

Impurities in dielectrics affect their bulk electric properties. If located within a solid, the impurities show a concentration gradient in which case a net flux of atoms of impurities will arise as given by Fick's law of diffusion [15]. Combined with Einstein's law of diffusion, the conductivity due to impurities is given by

$$\sigma = \frac{q^2 N f_c A^2}{k_B T} \exp\left(-E/k_B T\right), \tag{12}$$

where f_c is the characteristic resonance frequency of lattice atoms, N is the concentration of ions with charge q and A is the lattice parameter. T is the temperature. The activation energy is $E = 0.86$ eV for NaCl.

The relation between conductivity, frequency, vacuum's permittivity and imaginary part of permittivity is [16]

$$\Im\{\varepsilon_r\} = \frac{\sigma}{2\pi f \varepsilon_0}. \tag{13}$$

3.1.2 *Scattering.* When an incident wave interacts with a particle, a part of its power is absorbed and the direction of wave propagation is changed. The simplest scattering theory assumes that the particle is spherical. This problem was studied by Mie and the results are reproduced in [17]. The solutions depend on the permittivity of the particle with respect to the permittivity of the surrounding medium ε_{rel}, on the radius a of the particle and on the wavelength λ in the surrounding medium.

Let the total incident power density of the wave be J (in W/m^2) that reaches a particle. The affected fraction P_t can be written as the sum of the scattered power P_s and absorbed power P_a:

$$P_t = P_s + P_a.$$

Following the proof in [5], the fraction P_s/J scattered by an impurity particle of radius a (in the Rayleigh regime) is

$$Q_s = \frac{8}{3} X^4 \left| \frac{\varepsilon_{rel} - 1}{\varepsilon_{rel} + 2} \right|^2 \cdot \pi a^2, \tag{14}$$

where

$$\varepsilon_{rel} = \frac{\varepsilon_{particle}}{\varepsilon_{medium}} \quad \text{and} \quad X = \frac{2\pi a}{\lambda}.$$

Although the Mie theory was developed for spherical particles, it also holds for irregularly shaped impurities as long as the particles are small such that $X \ll 1$. If the dimensions of the impurity are not the same in all directions, the particle scatters and absorbs with dipole-like characteristics [17].

For frequencies around 200 MHz, even the largest dimension of heterogeneities in salt (of a few centimeters for conglomerates) are still very small compared to the wavelength. Thus, scattering in the Mie regime should not be a concern for the detector.

3.1.3 *Absorptions.* Another effect associated with impurities (but not only) is absorption [5]. Absorption of electromagnetic radiation is described in the literature by a variety of parameters, including an imaginary component of the dielectric constant (in radio frequency applications).

Mechanisms by which electromagnetic radiation interacts with matter can be classified into four categories: rotational, vibrational, electron excitation and free carrier. The overall effect can be described by the absorption coefficient, proportional to the imaginary part of permittivity:

$$\alpha \approx 4\pi \Im \{\varepsilon_r\} / \lambda,$$

where λ is the propagation wavelength.

3.2 *Primary effect of a single type of impurity*

Impurities in dielectrics affect their bulk electric properties and change the permittivity of the medium, thus propagation of radio waves is not a trivial problem anymore. The higher the number of impurities in the medium, the larger is the departure from ideal propagation case.

We shall first establish the effect of the presence of one impurity type on the relative permittivity of the medium (pure salt) because, as described at the beginning of this

section, the permittivity is a measure of the absorptions and scattering in the medium and it also influences reflections at separation borders.

We considered an impurity characterized by a variable real permittivity ε_p. As one can see in figure 1, the permittivity of the medium ε_r increases with the permittivity of the impurity particles ε_p. The imaginary part of permittivity is not influenced because we considered atoms of impurities with $\Im\{\varepsilon_p\} = 0$.

The dimensions of the impurity influence both the real and imaginary parts of the relative permittivity of the medium (figure 2). The dependence of the imaginary part was noted by many authors [5]. This is because the physical dimension determines the quantity of scattered and absorbed radiation (thus losses). The real part of the permittivity decreases with the increase of size if one considers an impurity with ε_r smaller than that of salt and increases if one considers an impurity with ε_r larger than that of salt.

Another important factor is the concentration of impurities in the medium. The higher the impurity concentration, the larger are the losses (imaginary part). Again, if $\varepsilon_p < \varepsilon_{salt}$ the real part of permittivity decreases, and in the opposite situation, it increases. The same situation occurs for the mass density of impurities.

3.3 *Effect of the naturally occurring impurities in salt*

According to [18], the most common impurities in the Slanic Prahova salt mines are: Al, Ca, Ti, Fe, V, Mn, Cu and Br. Their mass concentration is given in table 1.

After adding contributions from all impurities (given in table 1), using eqs (4)–(13), the bulk dielectric constant is $\varepsilon_r = 7.4747 + i\, 3.31 \cdot 10^{-4}$ (at 187.5 MHz – corresponding to a dipole antenna of 80 cm). One can notice the increase in both imaginary and real parts of permittivity (compared to the ideal case presented at the end of §3, when impurities were not considered).
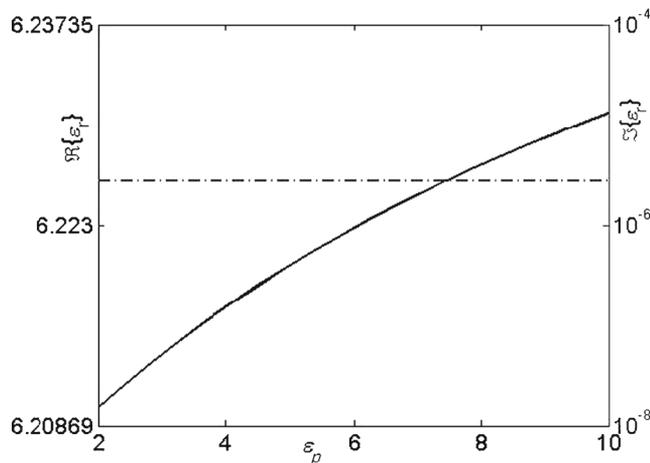
Figure 1. Influence of permittivity of the impurity particles (ε_p) on the permittivity of the medium ε_r. The continuous line corresponds to the real part of permittivity (left vertical axis), while the dash–dotted line corresponds to the imaginary part (right vertical axis).
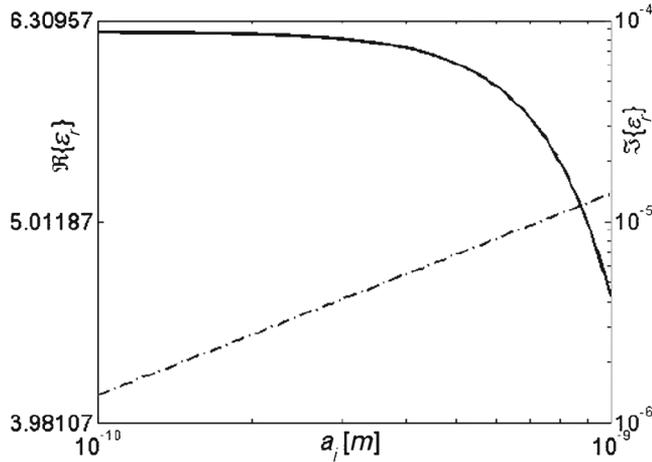
Figure 2. Influence of dimensions of the impurity particles (a_i) on the permittivity of the medium ε_r. The continuous line corresponds to the real part of permittivity of the medium (left vertical axis) and the dash–dotted one corresponds to the imaginary part (right vertical axis).

The impurities – given in table 1 – influence the imaginary part of permittivity as presented in figure 3, as a function of frequency. Other material properties necessary for computations were taken from [19]. Variation is presented for three temperatures: 5, 7 and 12 degrees (the last one represents the temperature inside the 'Unirea' salt mine, in Slanic Prahova, Romania). The higher temperature implies a higher mobility of charges, which in turn increases the conductivity. Permittivity values correspond to the experimental ones found in [20] when studying salt domes in North America: the dielectric constant is in 5–7 range and the tangent loss δ (defined by eq. (3)) is in the range 0.015 – 0.030, at 300 MHz. Moreover, similar values were found in laboratory measurements of permittivity at 200 MHz [21].

As explained in §3.2, not all impurities increase the real part of the bulk permittivity. We considered the impurities as in [18] and varied in turn the concentration of each element 0.1–10 times its regular concentration (in table 1). It was observed that by increasing the concentration, the real part of permittivity decreases slightly, about ∼1%. Exceptions are Ti and Fe, as shown in figure 4. This is due to the high relative permittivity of these elements. For titanium the increase is considerable due to the regular high concentration in the medium. As expected, the imaginary part (associated with losses) increases for all analysed elements (figure 4).

We have also considered the case when the concentrations of all elements increase between 0.1 and 5 times their values found in [18]. The imaginary part of permittivity

Table 1. Concentration of main impurities in Slanic Prahova salt mine, according to [18].

	Al	Ca	Ti	Fe	V	Mn	Cu	Br
$C\,(\mu\text{g/kg})$	14.7	2190	2260	33	14.9	61.7	7.9	126
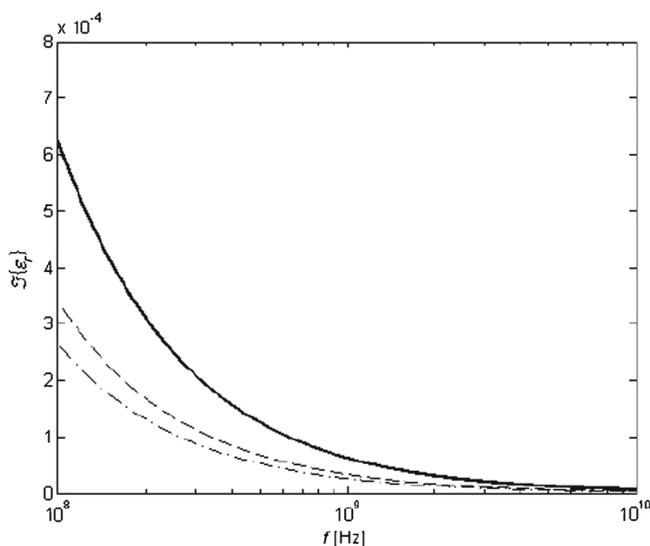
Figure 3. The effect of impurity concentration on the imaginary part of permittivity (computation details are given in the text). The continuous line corresponds to a temperature of 12°C; the dashed line corresponds to 7°C and the dash–dotted line corresponds to 5°C.

rises from 0.0003 to 0.002 because electrons of impurity have energy levels within the forbidden gap between the valence and conduction bands. Thus, more electromagnetic radiation can be absorbed (photons with energies smaller than the band gap). The relation between the real and imaginary parts of permittivity was explained at the beginning of this section.

Figure 5 presents the scattering effects of main impurities in salt. Compared to absorption, scattering is 40 orders of magnitude smaller so that it can be easily ignored. Waves at higher frequencies are more scattered as the corresponding wavelengths are smaller, approaching the size of the impurities.

As part of domal heterogeneity, anhydrite (calcium sulphate) is the main impurity in the salt stock and forms residual accumulation at the dome crest. Other geochemical processes convert the anhydrite to gypsum (hydrous calcium sulphate), calcite (calcium carbonate), and to a lesser extent, native sulphur and metallic sulphides [22].

We calculated the effect of anhydrite (as main impurity) on the permittivity of the medium. Its concentration in salt was varied from 1% to 80%. The resulting real part of permittivity varied from 6.16 to 6.36 and the imaginary part from $5.53 \cdot 10^{-5}$ to $6 \cdot 10^{-4}$. Such small differences will not produce large deviations in wave propagation.

If we add trace amounts of quartz, feldspars and carbonates in the form of SiO_2, $NaAlSi_3O_8$ and $CaCO_3$ (in concentration of 0.5–2%), the imaginary part of permittivity increases to $6.36 \cdot 10^{-4}$. As Romanian salt is mostly of greyish colour (due to metals) and is nearly transparent, we can disregard the presence of these traces.

Another simulation of interest is the effect of the presence of water, as it is one of the main absorber of radio waves. Using eqs (4)–(13) we have simulated the absorption

effect that connate water (considered to be crystallized water) has on the amplitude of radio waves after propagation on 50 m, 100 m and 150 m. The mass concentration varied up to 2 mg/kg. If propagation distances are greater than 100 m, almost all radio waves are absorbed (figure 6 presents the ratio of attenuated to incident field strength). Other atomic or quantum effects that would only increase the absorptions were not considered.

Rock salt is a conductor for electric current mostly due to interstitial water. The water-induced conductivity in rock salt can be determined using the equation of [23]. The value of conductivity induced by 0.02% water content is 2×10^{-6} Ω^{-1} m^{-1} [24], which should be included in eq. (13). Such a small water content is not expected to significantly decrease the transmission in salt beds. Geoelectrics is a valuable tool to assess various aspects of salt such as porosity and water content.

We have also estimated the effect of brine in forms of fluid inclusions and primary trapped water. We determined salinity of about 42.99 g/kg from experimental data given in [25]. Following [26,27] we calculated the brine-induced radio wave attenuation. If the waves travel a distance of 1.1 cm in brine, about 70% of their energy will be lost. If the distance increases to 1.4 cm, only 20% of the energy will remain. For propagation distances larger than 2.1 cm, the transmission coefficient will be smaller than 10%.
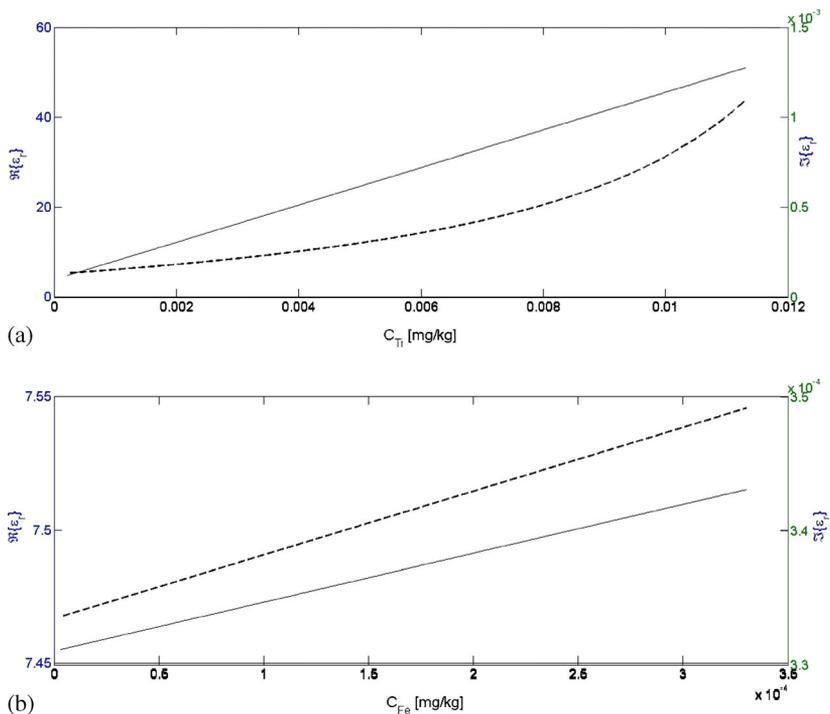
Figure 4. Permittivity of the medium for an increasing concentration of impurities of **(a)** Ti, **(b)** Fe, **(c)** Al and **(d)** Cu. The dashed line corresponds to the real part of permittivity (left vertical axis), while the continuous line corresponds to the imaginary part (right vertical axis).
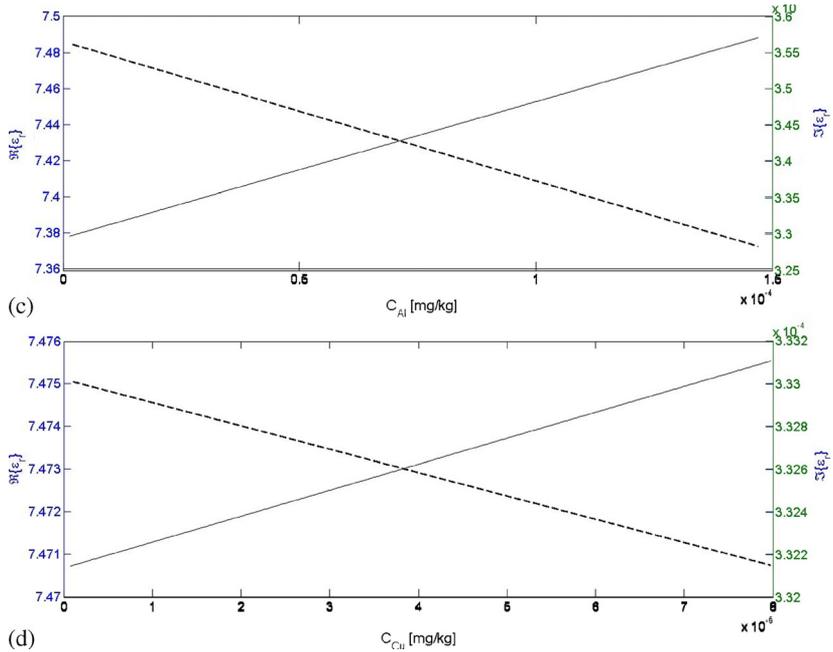
(c)

(d)

Figure 4. (*Continued.*)

It is clear that secondary trapped water will absorb all radio electromagnetic radiation. Location of such caverns must be known prior to experiment.

Another thing to consider is the faults in salt mines. They are not so common in salt rock as in the brittle sediments (gypsum, marl, limestone). A problem associated with the
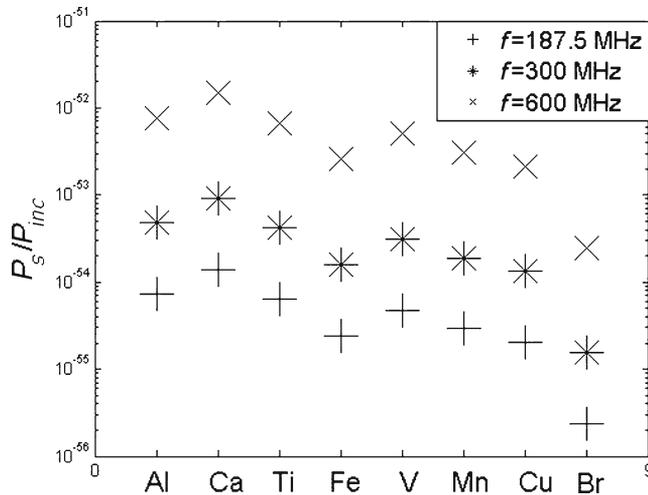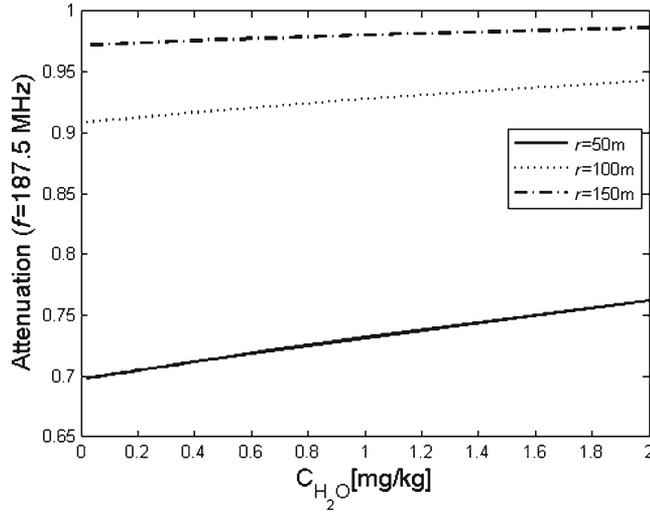

Figure 5. Scattering effects of main impurities in salt. The '+' marker shows the effect at 187.5 MHz, while the '*' marker shows the effect at 300 MHz and the '×' marker shows the effect at 600 MHz.

Figure 6. Ratio of attenuated to incident field strength as a function of the concentration of water molecules after 50 m (solid line), 100 m (dotted line) and 150 m (dash–dotted line) propagation.

step faults is that they can be a water feeder to the salt deposits (brine effect was discussed previously).

Fissures (air filled) can be regarded as very thin layers of relative permittivity equal to 1. Absorptions in such layers are close to zero, but induced reflections at interfaces of separation were evaluated and these represent about one half of the total power.

4. Conclusions

In this paper we simulated some effects that influence radio wave propagation in layered media. Our research was driven by the desire to build a neutrino radio-detector in the Romanian salt mine 'Unirea', Slanic Prahova. As stated in the first section, neutrino–salt interactions generate an electromagnetic field that can be measured by radio antennas. By studying this interaction, the main characteristics of the cosmic particle can be found. A good theoretical description and mathematical model of radio wave propagation at ∼200 MHz in salt are necessary.

Using only electronic and ionic polarizabilities, we found that the real part of the relative permittivity of salt is $\Re\{\varepsilon_r\} = 6.2$ and the imaginary part is $\Im\{\varepsilon_r\} = 4.69 \times 10^{-32}$. When naturally occurring impurities are not considered, the frequency dependence is extremely weak up to THz frequencies.

We determined the influence of one type of impurity on the permittivity of the medium. Its presence will clearly increase the losses (reflected by the imaginary part of permittivity). The real part of permittivity will also be modified by the growth of impurity concentration, density or physical dimensions.

After adding all impurities present in rock salt – considered in [18] – the equivalent dielectric constant becomes $\varepsilon_r = 7.4747 + i0.0003$ (at 187.5 MHz). If the concentration of

all elements increases up to 5 times their value in [18], the imaginary part of permittivity increases almost 10 times (up to 0.002).

Traces of quartz, feldspars and carbonates can increase the imaginary part of permittivity but not significantly (up to $6.36 \cdot 10^{-4}$), if in small concentration (in percentage of 0.5–2%). Anhydrite (the main impurity in salt), even in large concentration, will not significantly affect the relative permittivity of the medium.

When compared with absorption caused by impurities, the scattering effect is 40 orders of magnitude smaller and so it can be easily ignored. Waves at higher frequencies are scattered more efficiently as the corresponding wavelengths are smaller and approach the size of impurities. However, at ∼200 MHz, the dimensions of any heterogeneity that can be found in natural rock salt (including anhydrite, hydrocarbons etc.) are small when compared with the wavelength, thus scattering in the Mie regime is insignificant.

Another factor to consider is the presence of water. We estimated the effect of brine in forms of fluid inclusions and primary trapped water. If the waves travel a distance of 1.1 cm in a brine bubble, about 70% of their energy will be lost. If the distance increases to 1.4 cm, only 20% of the energy will remain. For propagation distances larger than 2.1 cm, the transmission coefficient will be smaller than 10%. It is clear that secondary trapped water in caverns will absorb all the electromagnetic radiation.

In a real neutrino detector the voltage measured by the antenna represents the only measurement from which information about the initial neutrino can be retrieved. This is the reason why the propagation medium should be carefully described.

The composition of the medium determines its permittivity and attenuation length. A direct consequence is reflected in the number of stations used for detection (e.g., a larger attenuation length allows a sparser array of antennas used for detection) and in the minimal energy of the cosmic particle that can be measured. Badescu and Petrescu [28] showed that dielectric absorption only in a lossy homogeneous medium increases the energy threshold to $10^{19.5}$ eV (compared to the 10^{17} eV limit found in an ideal medium [29]).

Another parameter that is directly influenced by the properties of the medium is the effective volume of the detecting element (antenna), which in turn will determine the total number of events measured by the experiment. By considering the propagation effects, the total number of expected events decrease from a few hundreds to a few tens [30].

Acknowledgements

References

[1] G Askaryan, *Sov. Phys. J. Phys. Soc. Japan* **17**, 7 (1962)
[2] R Gandhi, C Quigg, M Reno and I Sarcevic, *Phys. Rev. D* **58**, 9 (2006)

[3] R Milincic, P Gorham, E Guillian, D Saltzberg, D Williams, R Field and D Walz, arXiv:astro-ph/0503353v2 (2005)

[4] A M Badescu and T Petrescu, *Acta Astron.* **69**, 5 (2011)

[5] B Hapke, *Theory of reflectance and emittance spectroscopy* (Cambridge University Press, 1993), ISBN:0521307899

[6] G S Smith and W R Scott, *IEEE Trans. Geosci. Remote Sensing* **GE-27**, 8-3 (1989)

[7] DA Hill, *IEEE Trans. Geosci. Remote Sensing* **GE-26**, 6-2 (1989)

[8] A M Badescu, V Savu and O Fratu, *Preliminary tests in Unirea salt mine* (Slanic Prahova, Romania), University POLITEHNICA of Bucharest, Bucharest, Rep. No. 4 (2011)

[9] R Elliott, *Electromagnetics* (McGraw-Hill, 1966), ISBN:0780353846

[10] L Pauling, *The nature of the chemical bond* (Cornell University Press, 1960), ISBN:0801403332

[11] A Khare and A Swarup, *Engineering physics: Fundamentals & modern applications* (Infinity Science Pr Llc, 2007), ISBN:9780763773748

[12] R G Breckenridge, *J. Chem. Phys.* **18**, 3 (1950)

[13] K Kao, *Dielectric phenomena in solids: With emphasis on physical concepts of electronic processes* (Elsevier Academic Press, 2004), ISBN:0123965616

[14] P Gorham, D Saltzberg, A Odian, D Williams, D Besson, G Frichter and G Tantawi, *Nucl. Instrum. Methods A* **490**, 6-1 (2002)

[15] D Brogioli and A Vailati, *Phys. Rev. E* **63**, 1-4 (2001)

[16] L Chen and V Vardan, *Microwave electronics: Measurement and materials characterization* (John Wiley and Sons, 2004), ISBN:0470844922

[17] C F Bohren, E Clothiaux and D R Huffmann, *Absorption and scattering of light by small particle* (Wiley VCH Verlag GmbH, 2010), ISBN:3527406646

[18] C Cristache, C A Simion, R Margineanu, O A Culicov, M V Frontasyeva, M Matei and O G Duliu, *Radiochim. Acta* **97**, 333 (2009)

[19] L Bergstrom, *Adv. Colloid Interface Sci.* **70**, 5-9 (1997)

[20] A P Annan, J L Davis and D Gendzwill, *Saskatchewan Canada Geophysics* **53**, 6-4 (1988)

[21] A M Badescu, M Chiba, T Kamijo, T Petrescu, A Saftoiu, O Fratu, I Brancus, A Haungs, H Rebel, B Mitrica, O Sima, I Lazanu, S Halunga and G Toma, *Attenuation length measurements for salt samples from Cantacuzino Mine, Prahova, Interner Bericht KASCADE-Grande 2011-01* (Karlsruhe Institute of Technology, 2011)

[22] M Zhdanov, *Geophysics* **73**, 7-1 (2008)

[23] G E Archie, *Trans. Am. Inst. Mining Eng.* **146**, 4-2 (1942)

[24] U Yaramanci, *J. Appl. Geophys.* **44**, 1-6 (2000)

[25] M Jeremic, *Rock mechanics in salt mining* (CRC Press, Taylor and Francis Group, 1994), ISBN:905410113

[26] R Somarahu, *IEEE Trans. Antennas and Propagation* **54**, 1-8 (2006)

[27] T Meissner and F Wentz, *IEEE Trans. Geosci. Remote Sensing* **42**, 6-9 (2004)

[28] A M Badescu and T Petrescu, *Acta Astr.* **69**, 375 (2011)

[29] K Reil, SalSA: A teraton UHE neutrino detector, *Proc. Part. and Nuclei* (Santa Fe, 2005)

[30] A M Badescu, *J. Instrum.* **8**, P03010 (2013)