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Modeling of Through-the-Snow Electric Field Propagation for Rescue Systems

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Abstract: Propagation models for avalanche rescue systems are studied here. The paper focuses on the through-the-snow electric field propagation at ISM frequencies for air, snow and three-layered models. The latter includes geometrical optics and Sommerfeld-type integrals using numerical solution in Matlab. Furthermore, FEM analysis by COMSOL serves to validate numerical integration. In addition, the simulation results are fitted to experimental data, finding the optimal model for the problem under study. The FEM method allows considering more realistic geometries for the problem, albeit the other solving methods are simpler and require fewer computational resources.

Keywords: Through-the-Snow propagation, avalanche rescue system, electric dipole, three-layered model.

1. Introduction

Snow avalanches claim every year more than 150 lives worldwide, a number that has been increasing over the past few decades. Studies over avalanches report that burial time is the main factor that decides if a victim is recovered alive or dead. During the first 15 minutes of burial, the probability of survival is more than 90%, falling to 25% after 45 minutes because of suffocation [1].

Nowadays, there are two devices that allow recovering fully buried victims: the RECCO systems based on harmonic radar and the avalanche beacons based on standardized signals at 457 kHz [2]. The latter offers the greatest chance of survival due to members of the affected party can start the search immediately after the accident has occurred. However, current devices are technically limited in range and accuracy, especially at great burial depths. In addition, their usage is complex, particularly in the case of several victims, and intense training is required.

In recent years, the potential usefulness of GPS based systems in the location of snow avalanche victims has been shown [3, 4]. This type of devices simplifies the search as the GPS receiver of the victim could transmit its own position to the rescuer to be used for navigation. Very recently, avalanche beacons and GPS navigation facilities have been integrated in a commercial system [5]. This device is intended to increase the accuracy of the location estimation during the rescue tracking. In the current framework and expected evolution of satellite navigation, GPS positioning and tracking appears promising in avalanche rescue. However further research on GPS based positioning accuracies and data link for efficient communications in this environment is still necessary.

Data communications are shown basic in rescue operations. Due to the urgency of the snow victim recovery, they are of vital importance in snow avalanche scenarios. The information obtained by other sensors as location, vital signs or orientation can be communicated to the rescuers. Only a few rescue systems that make use of data communications between devices in avalanche accidents have been developed. The PULSE Barrivox Arva allows the transmission of the vital signs of the victim to the rest of the party [6]. In [7] a prototype has been tested in sending vital signs from a snow buried victim to the surface. The ARVA-LINK [8] also incorporates a data communications module.

The SICRA project [9] aims to develop a rescue system complementary to the avalanche beacons. This device will make use of the GPS navigation and the communication based geolocation. The SICRA devices will share its position with the other party devices forming a cooperative network. The communications are thought to work in the ISM band.

The study of the through-the-snow propagation results of outmost importance for avalanche rescue applications. In the present work, the snow cover wireless channel is characterized for frequencies in the ISM band, frequencies subject to be used by avalanche rescue systems. Several models are proposed for representing the through-the-snow propagation for rescue communications in avalanche scenarios. Three solving methods are applied in order to simulate the problem, comparing the obtained results to experimental data.

2. Problem description

In the problem under study a vertical electric dipole located under the snow has been considered as source. Another vertical dipole in surface receives the electric field generated by the first. The scheme of the problem is shown in Fig.1 in cylindrical coordinates. The receiver dipole is located near the surface and moves away from the source to simulate the rescue communication system response with the distance.

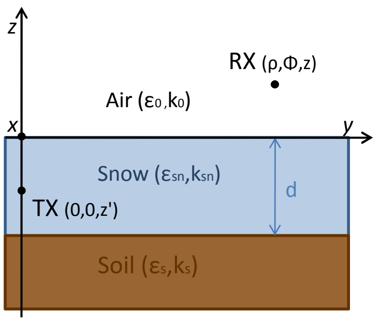

Figure 1. Problem scheme.

Through-the-snow electric field propagation has not been widely studied. It can be found several papers analyzing the propagation in the presence of a dielectric layer such as vegetation or snow covering. Propagation models of two or three layers [10-12] are considered in them. However, these studies only deal with the situation where both source and observation points are located on the surface. In [13] a closer solution to the problem under study is offered. In this publication the case where transmitter and receiver are above or under the snow are studied, computing asymptotic evaluations for the electric field.

On the other hand, the publications focused on snow propagation that include experimental measurements are scant, or deals with other frequencies or applications [14].

In this paper, both simulation and experimental validation of the through-the-snow propagation model are presented. Simulated models are fitted to experimental data proposing an optimal propagation model for the application.

2.1 Propagation models

Three propagation models have been proposed for the problem (Fig. 2). The simplest one considers the entire medium as air. The second model sees the medium as snow with its electrical properties. The last one, more complex, is a three-layered medium composed by air, snow and underlying soil layers.

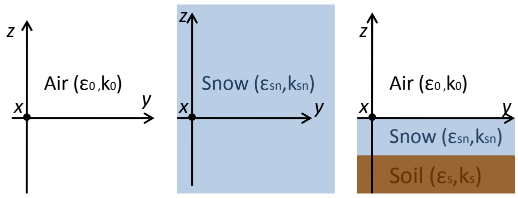

Figure 2. Propagation models: a) air b) snow c) three-layered.

2.2 Governing equations

For the two first models (all air, all snow) the electric field propagation in free space equations are considered changing the wave number k_i according to the medium (Eq. 1). Both transmitter and receiver dipoles l_z long, are configured in vertical orientacion and I_0 is the current circulating by the transmitter dipole.

$$\boldsymbol{E_{zz}} = \frac{\boldsymbol{j\omega\mu_0 I_0 l_z e^{jk_i\rho}}}{\boldsymbol{4\pi\rho}} \text{ (V/m)} \quad (1)$$

For the three-layered model, manipulations of the dyadic Green's function give the transmitter field in z direction as [13]:

$$\boldsymbol{E_{zz}} = -\frac{\boldsymbol{\omega\mu_0 I_0 l_z}}{\boldsymbol{8\pi}} \int_0^\infty \boldsymbol{f_{zz}(k_\rho) e^{jk_{oz}z} dk_\rho} \text{ (V/m)} \quad (2)$$

where the function f_{zz} follows the expression (3), that includes the transmission coefficients between the different mediums T_{TM} (see Appendix):

$$f_{zz}(\boldsymbol{k_\rho}) = \frac{2k_\rho^3}{k_{1z}k_0^2}[T_{TM}^{up} e^{jk_{1z}|z'|} + T_{TM}^{dwn} e^{jk_{1z}(2d+z')}] \cdot J_0(\boldsymbol{k_\rho}) \quad (3)$$

3. Solving methods

The problem described has been solved applying three different methods. The first one computes the numerical solution of the exact propagation expressions with MATLAB software. The adaptive Gauss-Kronrod quadrature function [15] allows numerically evaluating the electric field integral for the three-layered model previously shown.

A second method uses the geometrical optics to solve the problem in a simplified way [16]. For this problem the contribution of only one ray linking transmitter and receiver has been considered. This ray suffers from refraction in the snow-air interface.

The last method applies the finite element method with COMSOL. This is used to both validate numerical integrations and simulate more complex scenarios. Due to the huge dimensions of the problem under study and operation frequencies, COMSOL guidelines have to be carefully applied in order to obtain accurate solutions. Next, the main characteristics of COMSOL models used in the study are described.

3.1 COMSOL models

Owing to the fact that the source can be modeled by a vertical electric dipole; 2D axial symmetry models have been used. Furthermore, geometries have been truncated in a convenient way to reduce the size of the problem and obtain accurate results. In doing so, perfect match layers with scattering boundary conditions have been used. Besides, the soil layer has been also truncated using the perfect electric boundary condition (Fig. 3). In order to the increase the mesh density in the region of interest, several points have been included in the geometry.

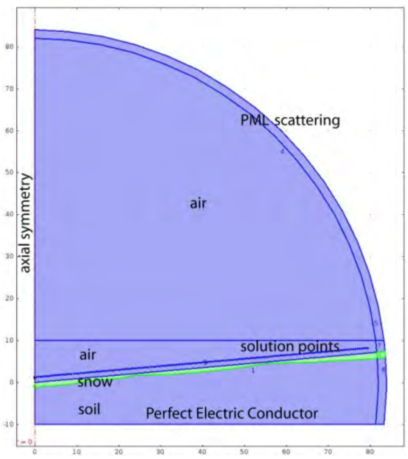

Figure 3. Geometry of the COMSOL truncated three-layered model

The electrical size of the problem implies a high-frequency modeling. The full electric field components have been solved, modeling the source by a magnetic current point. In the case of the source immersed in the snow media, the effects of the dielectric properties of the layer have to be considered.

The mesh parameters have been set taking into account the quadratic electric field discretization, the solution accuracy and the model size. As a result, 10 MDOF have been obtained.

Finally, the simulation results have been exported to MATLAB using the points inserted in the geometry.

4. Experiment description

The experiment took place on April 2011 in Formigal ski resort, Huesca (Spain) in a flat field with a maximum snow layer of 150 cm. The snow, wet in this season moment, and the underlying soil were characterized measuring the electrical conductivity and the complex relative permittivity.

A module RF-explorer working at 433 MHz [17] and an IEEE 802.11 WIFI node working at 2.45 GHz, were buried under the snow at a depth of one meter. The receiver's antennas for each frequency were fastened to a tripod at 1.2 m over the snow. The tripod was moving away from the transmitter measuring the RSSI every two meters until 80 meters. In WIFI frequency the maximum communication range was 30 meters. In each location the snow depth was also measured.

Figure 4. Picture of the experiment with the tripod and the receiver's antennas.

4.1 Simulation parameters setup

In order to compare the experiment measurements with the simulations, the values of the parameters for the different models were taken from the snow characterization data. In Table 1 the snow and soil complex permittivity values are presented for 433 MHz and 2.45 GHz. The measured soil and snow conductivity were 30µS/m and 1.88µS/m respectively.

Medium	433 MHz	2.45 GHz
Snow	2.72-j0.02	2.69-j0.1
Soil	10.35-j0.37	5.26-j0.58

Table 1. Snow and soil relative complex permittivity measured

For additional simulations of through-the-snow electric field propagation, two extreme snow conditions were selected; very dry snow and very wet snow. In Table 2 the snow and soil relative permittivity values are shown. These values have been obtained applying the formulae of Looyenga [18] from the snow density and volumetric water content values. The soil conductivity is set to 1 mS/m for both conditions and frequencies and the soil permittivity is computed from empiric formulas.

Medium	433 MHz	2.45 GHz
Dry snow	1.1292-j0.0001	1.12-j0.0001
Wet snow	3.37-j0.0324	3.2-j0.067
Dry soil	17.35-j0.693	3.33-j0.172
Wet soil	35.64-j1.523	9.98-j1.76

Table 2. Snow and soil relative permittivity for snow extreme wet and dry conditions

4. Experimental results

In Fig. 5 it is represented the snow propagation models at 433 MHz. The solutions for the three solving methods previously described are represented. The figure also includes the received power measurements taken in the experiment.

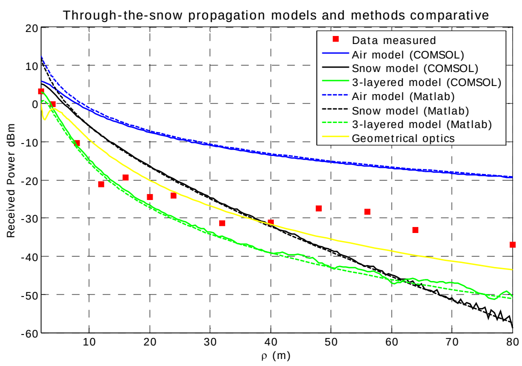

Figure 5. Through-the-snow propagation models at 433 MHz with different solving methods.

As can be seen in previous figure, COMSOL and numeric MATLAB solutions fit for the three propagation models proposed. Regarding the models and data fitting, the three-layered model matches better the measurements. However, for distance larger than 30 meters this model differentiates from the data.

A more realistic COMSOL model has been proposed including the depth of the measurement stations. The slope of the soil surface and the soil humidity percentage were also modified (both data were not measured in the experiment). The results of the COMSOL simulations are presented in Figure 6. Despite real data are not better suited by these models, numerical results show the effects of the slope and snow depth.

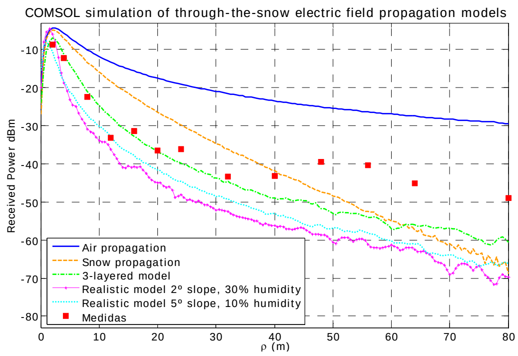

Figure 6. COMSOL snow propagation models at 433 MHz with realistic model.

Figure 7 shows the study for 2.45 GHz. In the realistic model some oscillations appears due to the soil surface irregularities modeled.

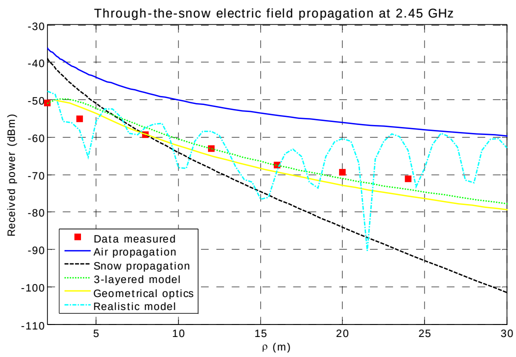

Figure 7. COMSOL snow propagation models at 2.45 GHz.

As can be seen in previous figures, for both frequencies studied the three layered model can be considered valid to represent the through-the-snow electric field propagation. In addition, several simulations have been carried out for the different snow conditions presented in previous sections. In next figure a comparison between dry and wet snow propagation for 433 MHz and 2.45 GHz is shown.

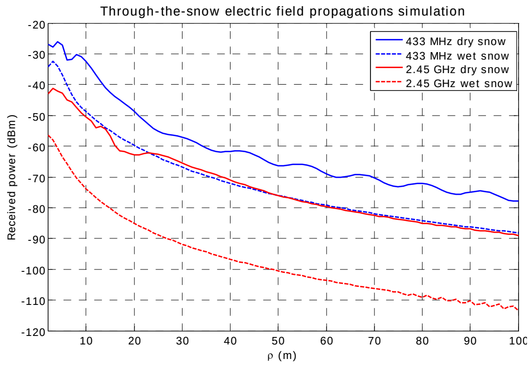

Figure 8. Through-the-snow propagation simulation at 433 MHz and 2.45 GHz for dry and wet snow conditions.

5. Discussion

In the previous figures it has been seen that the proposed models do not completely fit to the measurements, receiving more power than expected for certain distances values. This effect can be due to the contribution of the multipath propagation. This situation cannot be represented with the simplified 2D axial symmetry COMSOL model used.

On the other hand, it can be seen a great difference between the propagation at 433 MHz and a 2.45 GHz in received power terms. Moreover the snow attenuation increases with the frequency, having a larger difference in receiver power between dry and wet snow conditions for 2.45 GHz than for 433 MHz.

6. Conclusions

In the present paper a channel model for through-the-snow propagation has been proposed. Several models and solving methods have been simulated trying to fit the results to experimental data.

COMSOL allows modeling in a more realistic way the communications between vertical electric dipoles buried into the snow.

From simulation results it can be concluded that 433 MHz suffers from lower levels of snow attenuation than 2.45 GHz and is less sensible to the snow conditions, working out optimal for through-the-snow communications for avalanche rescue devices.

Future works will be focused on a 3D COMSOL model studying different dipole orientations and including a digital terrain map. Moreover, experiments with a more controlled soil topology must be done in the future.

7. References

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8. Appendix

The transmitter total coefficients are:

$$T_{TM}^{up} = \frac{T_{TM}^{10}}{1+R_{TM}^{01}R_{TM}^{12}e^{j2k_{1z}d}} \qquad \text{(A.1)}$$

$$T_{TM}^{dwn} = \frac{R_{TM}^{12}T_{TM}^{10}}{1+R_{TM}^{01}R_{TM}^{12}e^{j2k_{1z}d}} \qquad \text{(A.2)}$$

where the simple reflection and transmission coefficients for a wave going from layer *m* to *n* are the following:

$$R_{TM}^{mn} = \frac{\varepsilon_{rn}k_{mz}-\varepsilon_{rm}k_{nz}}{\varepsilon_{rn}k_{mz}+\varepsilon_{rm}k_{nz}} \qquad \text{(A.3)}$$

$$T_{TM}^{mn} = 1 + R_{TM}^{mn} \qquad \text{(A.4)}$$

The wave number k_{uz} , with *u* the layer (*u*=0,1 or 2) is:

$$k_{uz} = \sqrt{k_u^2 - k_\rho^2} \qquad \text{(A.5)}$$

$$k_\rho = k_0 sin\omega \qquad \text{(A.6)}$$