Determination of Dielectric Constants using Reflection Coefficient Measurement and its Application to Snow and Ice Monitoring

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Abstract

The purpose of our research is to investigate and clarify the microwave response from snow and ice on a flat surface and to develop the measurement methods based on these results. The authors attempt to apply those methods to development of microwave sensor for road-surface condition monitoring of winter road maintenance operation, and to ground truth of SAR observations on a sea ice and a snow field. In this paper, a determination method of dielectric constants using reflection coefficients measurement with oblique incidence is introduced. This method is based on free space technique which is often used for determination of dielectric constants of various materials. The authors have conducted experiments and tried to apply the method to determining dielectric constants of snow and ice. And some results of those experiments are introduced here.

Keywords **:** Microwave remote sensing, Winter road maintenance, Dielectric measurement of snow and ice

1. Introduction

Every material has a unique set of electrical characteristics that depends on its dielectric properties. Complex dielectric constant defined by ε_r (= ε' - *j* ε'') is one of the important parameters which expresses electric properties of dielectric media. Snow and Ice are also dielectric media in microwave range. Dielectric properties of snow have been reported with many experiments so far, and the empirical models for dry snow and wet snow have been proposed. For example, dielectric constant can be expressed as a function of the physical parameters of snow, density, liquid water content, etc. Based on the results of measurement of the dielectric constants, the physical parameters of snow can be estimated by using those relations and the condition of snow can be estimated consequently. Therefore, it is very important for microwave remote sensing research on snow and ice to investigate the dielectric properties and accurate measurements of dielectric constants are required.

The purpose of our research is to investigate and clarify the microwave response from snow and ice on a flat surface and to develop the measurement methods based on these results. The authors attempt to apply those methods to development of microwave sensor for road-surface condition monitoring of winter road maintenance operation, and to ground truth method on dielectric properties of a sea ice and a snow field.

In this paper, a determination method of dielectric constants using reflection coefficients measurement with oblique incidence is introduced. This method is based on free space technique which is often used for determination of dielectric constants of various materials. The authors have conducted experiments and tried to apply the method to determining dielectric constants of snow and ice. And some results of those experiments are introduced here.

2. Dielectric properties of snow and ice

Snow and Ice are dielectric media in microwave range. Complex dielectric constant defined by ε_r (= ε' - *j* ε'') is a important parameter which expresses electric properties of dielectric media.

It is well known that the real part value of ice is around three and the imaginary is 10^{-3} at microwave ranges [1]. Snow is a mixture of ice particles and air voids. Dielectric properties of snow have been reported with many experiments so far. Hallikainen and Ulaby et al proposed the empirical models for dry snow and wet snow [2][3]. Dielectric constant ε_r can be expressed as a function of the physical parameters of snow, i.e. density and liquid water content. Based on the results of measurement of ε_r, the physical parameters of snow can be estimated by using those relations and the condition of snow can be estimated consequently.

Dielectric constant of snow (empirical model):

Dry Snow [3]:

$$\varepsilon_r = \varepsilon' = 1.0 + 1.9\rho_{ds} \qquad (\rho_{ds} \le 0.5[\text{g/cm}^3]) \tag{1a}$$

$$\varepsilon_r = \varepsilon' = 0.51 + 2.88\rho_{ds} \qquad (\rho_{ds} \ge 0.5[\text{g/cm}^3]) \tag{1b}$$

where, ρ_s is density of dry snow.

Wet Snow [3]:

$$\varepsilon' = 1.0 + 1.83\rho_S + 0.02\, m_v^{1.015} + \frac{0.073\, m_v^{1.31}}{1+(f/f_0)^2} \tag{2a}$$

$$\varepsilon'' = \frac{0.073\,(f/f_0)\, m_v^{1.31}}{1+(f/f_0)^2} \tag{2b}$$

where ρ_s is density of dry snow, m_v is liquid water content of snow, f is a frequency of incident wave and f_0 is the relaxation frequency of water.

3. Methodology

The measurement processes are 1) a measurement of reflection responses from specimens, 2) a calculation of reflection coefficients and 3) an estimation of dielectric constants. The outline of the processes is shown in Fig.1.

3.1. Measurement of reflection responses

Magnitude and phase of reflection responses from a specimen are measured with a vector network analyzer (VNA). These measured responses are expressed in S-parameters $S_{11}(\omega)$ in frequency domain. A continuous wave of angular frequency ω is generated with VNA and radiated from an antenna system. The reflected wave from the specimen is received by the antenna and measured as reflection response with the VNA.

3.2. Calibration of reflection coefficients

Because of reflections due to connectors, horn antenna and lens and losses due to cables and so on, the measured S-parameters includes these responses and is different from the actual reflection response of the specimen as following equation. Therefore, it is necessary to remove the residual responses and calibrate the measured values.

3.3. Estimation of dielectric constants

3.3.1. Inverse problem on dielectric constants

Reflection of incident wave occurs at the surface of dielectric medium because of electromagnetic discontinuity. R_1, the reflection coefficient at the boundary, is expressed by Z_0, Z_1, impedances of air and the medium.

$$R_1 \equiv \frac{Z_1 - Z_0}{Z_1 + Z_0} = \frac{1-\sqrt{\varepsilon_1}}{1+\sqrt{\varepsilon_1}} \tag{3}$$

In case of a dielectric medium, which has planer surface and infinite depth (Fig.2), R_1 can be determined by Γ, a ratio of electric field of the incident wave and reflected wave.

$$\Gamma(\omega) \equiv \frac{E_{reflected}}{E_{incident}} = R_1 = \frac{1-\sqrt{\varepsilon_1}}{1+\sqrt{\varepsilon_1}} \tag{4}$$

Based on the results of measurement of Γ, ε_1 can be estimated by solving the inverse problem.

3.3.2. Layered dielectric medium model (oblique incidence

Assuming that snow and/or ice on a road surface and road itself compose layered dielectric medium, which has two layers of different media, we measure the dielectric constants of those media. The illustration of the layered dielectric medium model is shown in Fig.3, where θ_0 is a incident angle. Using a continuous wave of angular frequency $\omega(=2\pi f)$, or frequency f, incident obliquely on the surface of the medium, microwave measurements are made and reflection coefficient $\Gamma(\omega)$ at the surface of the model is expressed by Eq..(5).

$$\Gamma(\omega) = R_1 + (1+R_1)\frac{R_2 e^{-2\gamma_1 d_1}}{1-(-R_1)R_2 e^{-2\gamma_1 d_1}}(1+(-R_1)) = \frac{R_1 + R_2 e^{-2\gamma_1 d_1}}{1+R_1 R_2 e^{-2\gamma_1 d_1}} \tag{5}$$

where γ_1 is a propagation constant in layer 1 perpendicular to boundary 1. c is light speed. θ_0 is incidence angle. γ_1 is expressed by Eq..(6). R_1, R_2 are reflection coefficients at boundary 1 and 2 respectively, which are expressed by Eq.(7a), (7b) for TE wave, by Eq.(8a), (8b) for TM wave.

$$\gamma_1 = j\frac{\omega}{c}\sqrt{\varepsilon_1 - \sin^2\theta_0} \tag{6}$$

for TE wave (H polarization):

$$R_{1H} = \frac{\cos\theta_0 - \sqrt{\varepsilon_1 - \sin^2\theta_0}}{\cos\theta_0 + \sqrt{\varepsilon_1 - \sin^2\theta_0}} \tag{7a}$$

$$R_{2H} = \frac{\sqrt{\varepsilon_1 - \sin^2\theta_0} - \sqrt{\varepsilon_2 - \sin^2\theta_0}}{\sqrt{\varepsilon_1 - \sin^2\theta_0} + \sqrt{\varepsilon_2 - \sin^2\theta_0}} \tag{7b}$$

for TM wave (V polarization):

$$R_{1V} = \frac{\sqrt{\varepsilon_1 - \sin^2\theta_0} - \varepsilon_1\cos\theta_0}{\sqrt{\varepsilon_1 - \sin^2\theta_0} + \varepsilon_1\cos\theta_0} \tag{8a}$$

$$R_{2V} = \frac{\varepsilon_1\sqrt{\varepsilon_2 - \sin^2\theta_0} - \varepsilon_2\sqrt{\varepsilon_1 - \sin^2\theta_0}}{\varepsilon_1\sqrt{\varepsilon_2 - \sin^2\theta_0} + \varepsilon_2\sqrt{\varepsilon_1 - \sin^2\theta_0}} \tag{8b}$$

4. Experiments

4.1. Measurement System

An illustration of the measurement system is shown in Fig.4. This system consists of a compact VNA, Anritsu MS2036A, and an antenna system. The antenna system consists of horn antennas and dielectric lenses, which are set up on a movable frame. Continuous waves generated with the VNA are radiated form the antenna system and incident oblique on the surface of a specimen. Reflected waves are received with the antenna system at the opposite side, and the reflection responses are measured with the VNA.

4.2. Measurement result of artificial snow

i) Specimen: To investigate the microwave response to snow, dielectric measurements for artificial snow were conducted on 20th thru 23rd July 2010 at the Snow and Ice Research Center (Shinjo, Yamagata), NIED. The measurements of artificial dry snow were made in the 4 to 6 GHz range with the incident angles of every 10 degree from 40 to 70 degree. The physical parameters of the specimens are shown in Table 1.

Table.1. Material of specimen.

No	Material of specimen		density [g/cm^3]	thickness [mm]	Temp [deg C]
	Layer1	Layer2	Layer 1	Layer 1	Layer 1
1	Snow	(EPS)	0.34	50	-2.4
2	Snow	(EPS)	0.34	20	-2.4

(EPS: expanded polystyrene foam)

ii) Measurement result: The measurement results of frequency variation of magnitude of reflection coefficients are shown in Fig.5. And estimation results for each specimen are shown in Table 2. Dielectric constants of dry snow can be calculated by the empirical model (Eq..(1)). Substituting the density of the specimen 0.34 g/cm^3, we get the dielectric constant, 1.646. The measurement value of 1.67 and 1.61 agrees well with this value.

Table.2. Measurement result.

No.	Material of specimen		Dielectric constant (real part)		Thickness [mm]
	Layer1	Layer2	Layer 1	Layer2	Layer 1
1	Snow	(EPS)	1.67	(1)	50.4
2	Snow	(EPS)	1.61	(1)	18.1

(EPS: expanded polystyrene foam)

iii) Angular variations of reflection coefficients: The angular variations of the magnitudes of Γ of V-pol. And H-pol. at 5GHz are shown in Fig.6 7 for specimen No.1 respectively. Furthermore the ratios of Γ of V-pol. by H-pol. at 5GHz are shown in Fig.8 for specimen No.1. From the angular variations of Γ of V-pol., the Brewstar angles θ_B described by Eq.(9) can be read. But also the angular variations of the Γ ratio can show the angle more clearly.

$$\tan\theta_B = \sqrt{\varepsilon_1} \tag{9}$$

5. Conclusion

The microwave measurement method of dielectric constants in order to detect snow and ice on a road surface were presented. Some examples of measurements for artificial snow using free space method were introduced. The results show reasonable estimations of the dielectric constants, and they indicate that the method could be utilized for detecting snow and ice on a road surface. Furthermore angular variations of reflection coefficients are shown and the Brewstar angles can be read from them. These results indicate that the angular variations of reflection coefficients with the Brewstar angles can be used to estimate dielectric constants.

However, it cannot be said that we have enough data to develop the sensor system, various cases should be examined. The authors continue to conduct measurements in order to investigate efficiency of the method and grasp the problem for practical use.

Acknowledgements

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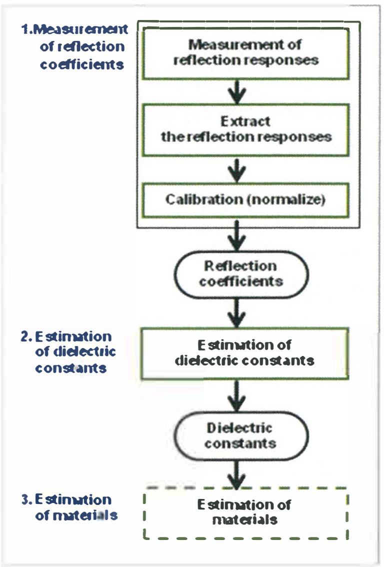

Fig. 1 Measurement process.

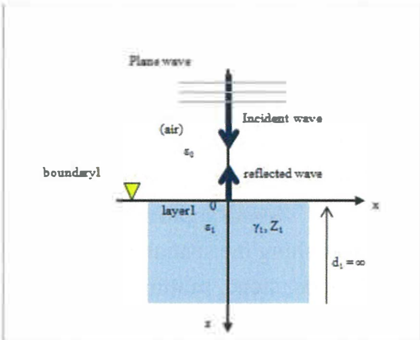

Fig. 2 Reflection at surface of a dielectric medium.

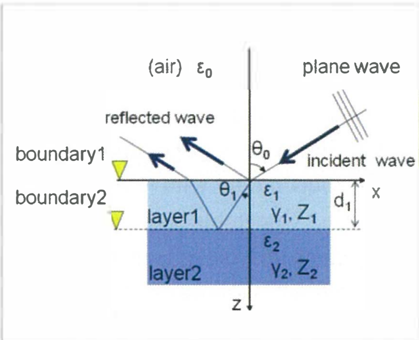

Fig. 3 Theoretical model.

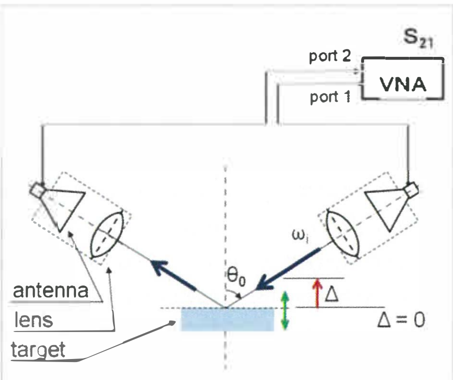

Fig. 4 Measurement system.

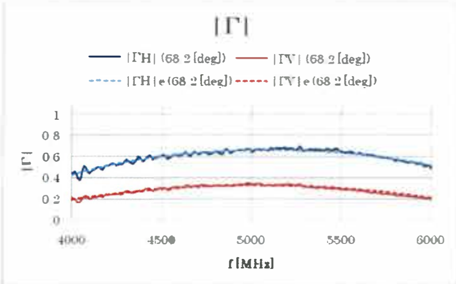

Fig. 5 Measurement result; frequency variation of magnitude of reflection coefficients (d1=50[mm]).

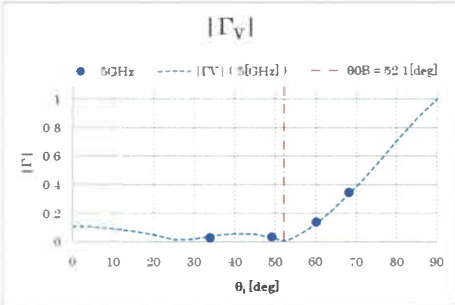

Fig. 6 Angular variation of magnitude of reflection coefficients at 5GHz of V-pol. (d1=50[mm]).

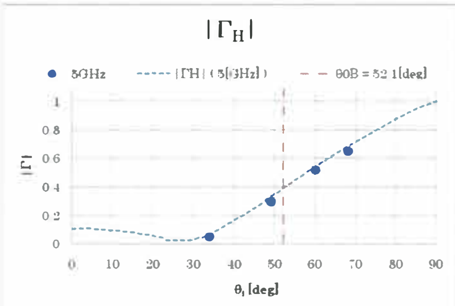

Fig. 7 Angular variation of magnitude of reflection coefficients at 5GHz of H-pol. (d1=50[mm]).

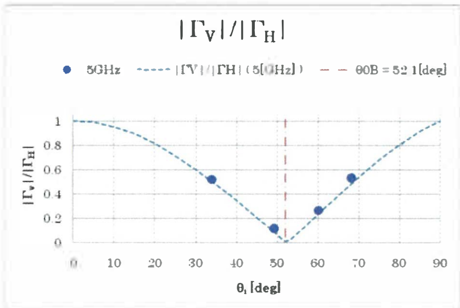

Fig. 8 Angular variation of reflection coefficients ratio of V-pol. by H-pol. at 5GHz. (d1=50[mm]).