PROPAGATION OF ELECTROMAGNETIC WAVES IN ICE DERIVED FROM ITS DIELECTRIC PROPERTIES 2. ATTENUATION

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ABSTRACT

Based on the measured dielectric properties of ice, attenuation of electromagnetic waves in ice at MHz and GHz frequencies is discussed. The relative complex dielectric permittivity of acid-doped ice shows that attenuation is significantly influenced by the concentration of hydrogen ions or the pH value in ice. The penetration depth of the microwave from J-ERS1 SAR and E-ERS1 SAR are estimated as a function of pH value.

1. INTRODUCTION

The present authors discussed the propagation velocity and the birefringence of electromagnetic waves in another paper in this volume. This paper discuss the attenuation of electromagnetic waves in ice at MHz and GHz frequencies from the measured dielectric loss or conductivity of ice.Whereas the real part of the complex permittivity is constant at these frequencies, the values of the loss tangent (tanδ) which have ever reported are contradictory with each other by factors larger than 10 [1, 2 and 3]. This discrepancy was considered to be caused mainly because the loss tangent at these frequencies is so small to measure precisely but also because small impurity in ice may influence the absorption of electromagnetic waves [2]. In fact, Mätzler and Wegwüller [2] showed that slightly saline ice had the larger value of tanδ than pure ice based on the precise measurement of the complex permittivity of ice carried out by the cavity resonator method and rediometric method [2]. In addition, Fujita et al. [4] measured the complex permittivity of acid-doped ice at 9.7 GHz and found that it increases linearly with concentration of doped acid. They showed the influence of acid to tanδ is significantly larger than that to the real part. Using these experimental facts, the attenuation due to dielectric loss is estimated as a function of pH value of ice.

2. ATTENUATION DUE TO ACIDITY IN ICE

Attenuation of the electromagnetic waves is determined by the dielectric loss, tanδ, or conductivity in ice, σ_∞. The penetration depth, p, of the intensity is given by

$$p = \frac{\lambda_0}{2\pi \tan\delta \sqrt{\varepsilon'}} \tag{1}$$

where λ_0 is the vacuum wavelength. Equation 1 indicates that attenuation is determined by tanδ and frequency since ε' is constant as described in another paper in this volume.

Fujita et al. [4] showed that tanδ of acid-doped ice at 9.7 GHz is expressed as a function of temperature and acid concentration as follows:

$$\tan\delta(C,T) = \tan\delta_{pure}(T) + g(T)\,C \tag{2}$$

where $\tan\delta_{pure}(T)$ is tanδ of pure ice. $g(T)$ is a temperature dependent factor. C is the concentration of acid expressed by molarity. $g(T)\,C$ expresses the increase of tanδ due to acid in ice. Equation 2 was obtained by the dielectric measurement of HCl-doped ice, HNO_3-doped ice and H_2SO_4-doped ice. Acid is assumed to exist in the liquid phase in the polycrystalline ice [4 and 5]. Since each acid molecule dissociates only one hydrogen ion in the liquid phase, one can express C as the molarity of hydrogen ions. When eq. 2 is expressed as a function of pH value of ice, it becomes

$$\tan\delta(C,T) = \tan\delta_{pure}(T) + g(T)\ 10^{-pH} \tag{3}$$

At frequencies, f, well away from the relaxation frequency of a dielectric dispersion, $f\tan\delta$ is constant and the conductivity, σ_∞ [S/m], in ice is expressed as follows;

$$\sigma_\infty = \varepsilon_o\, \varepsilon' 2\pi f\ \tan\delta \tag{4}$$

The increase in conductivity due to acid is,

$$\sigma_\infty = \varepsilon_o\, \varepsilon' 2\pi f\ g(T)\ 10^{-pH} \tag{5}$$

Using $\tan\delta$ of acid-doped ice measured by Fujita et al. [4] at 9.7 GHz, molar conductivity which means the increase of conductivity due to acid equivalent to 1 mol per litre is shown in Fig. 1. We assume that σ_∞ is expressed as

$$\sigma_\infty = \sigma_0 \exp\left(-\frac{E}{RT_K}\right) \tag{6}$$

where R is the gas constant, E is an activation energy and T_K is absolute temperature. From Fig.1 we obtain σ_o becomes exp(10.3) [$Sm^{-1}mol^{-1}$] and E becomes 18.8 [kJ/mol] at temperatures between - 5 °C and - 30 °C.

Moore et al. [5] compared the conductivity due to acidity in natural ice at low frequency (LF) and that in artificial ice at 9.7 GHz. They found that conductivity is well fitted by a model where concentrated liquid acid at three grain boundary forms a network, earlier proposed as an explanation for the DC conductivity of polar ice [6]. Therefore, σ_∞ obtained by eq. 6 can be applied to frequencies between LF and 9.7 GHz. Substituting eqs. 5 and 6 to eq. 3, eq. 3 becomes

$$\tan\delta = \tan\delta_{pure}(T_K) + \frac{\sigma_0 \exp\left(-\frac{E}{RT_K}\right)}{\varepsilon_0 \varepsilon' 2\pi f}\, 10^{-pH} \tag{7}$$

One can calculate the penetration depth of electromagnetic wave as a function of pH value using eqs. 1 and 7.

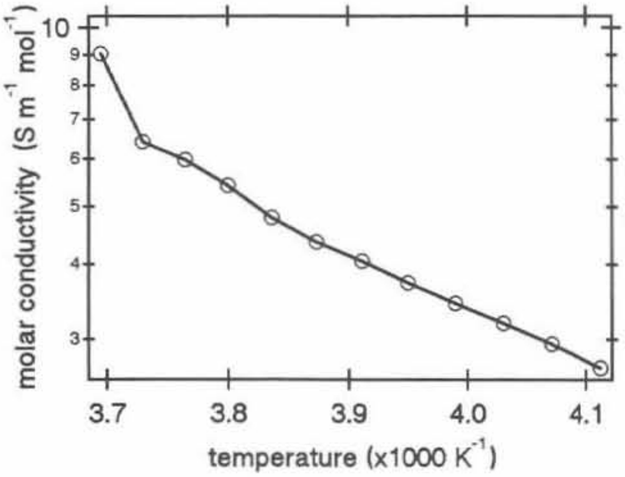

Figure 1. Arrhenius plot of molar conductivity of acid-doped ice against reciprocal temperature.

3. PENETRATION DEPTH OF THE MICROWAVE BY SAR

As for tanδ of the pure ice, very few data are available at MHz range. The best data on natural polar ice are those of Westpal (reported in [7]), but the work was done before the significance of differing impurity levels had been established. Little is known of the chemical composition of Westpal's samples or the extent of any contamination introduced during their handling. Johari and Charette [8] investigated the absorption of artificial pure ice at 35 MHz and 60 MHz, and found higher absorptions than Westpal had done: these studies are difficult to reconcile. At microwave frequencies, although the reported value of tanδ are contradictory with each other, the most reliable data seems to be those presented by Mätzler and Wegmüller [2]. The reasons are as follows: 1) They used cavity resonator method for the dielectric measurement; 2) Their data show that tanδ varies smoothly with varying frequency over a wide range of frequencies; 3) They investigated impurity levels of their samples.

Using their data as $\tan\delta_{pure}(T_k)$ in eq. 7, we show the penetration depth of the microwave to large ice masses at frequency of SAR in J-ERS1 (1.275 GHz) and that in E-ERS1 (5.3 GHz), as a function of acid impurity. For the calculation, it is assumed that attenuation is due to only dielectric loss. Attenuation due to volume scattering is not considered. Figure 2 show the penetration depth from 1 GHz to 11 GHz at -15 °C. The penetration depth decreases significantly with increasing frequencies. In addition, Fig. 2 clearly shows that the penetration depth decreases significantly with decreasing pH value. It is interesting to note that the penetration depth of J-ERS1 SAR ranges between 200 m and several 10 m depending on the pH value, whereas that of E-ERS1 SAR is only around several 10 m, also depending on pH value. But the dependence is smaller than that of J-ERS1. Table 1 also shows the penetration depth of J-ERS1 SAR and E-ERS1 SAR as a function of pH value at -5 °C and -15 °C. It is clear that the penetration depth increases with decreasing temperature.

The pH value of so called "acid snow" is around 4 and 5. In such medium, Fig. 2 and Table 1 show that penetration depth is significantly smaller. Kamiyama et al. [20] investigated the pH value of snow and ice at a lot of sites in the polar regions in the world. They showed average pH value in inland region and coastal region in Antarctica were 5.14 and 6.08,

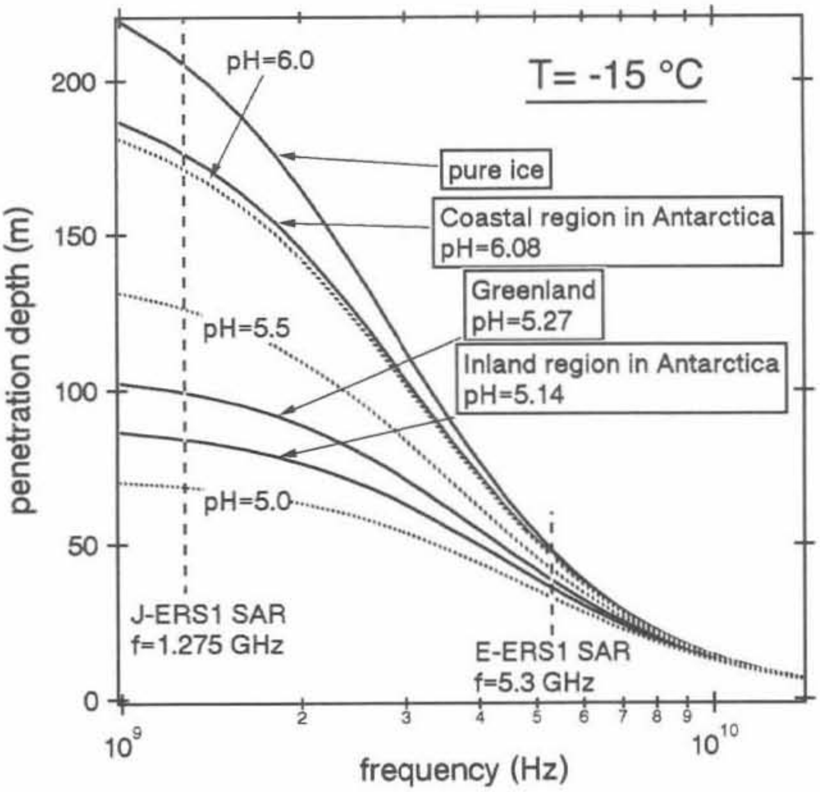

Figure 2. The penetration depth of microwave to large ice mass at frequencies between 1 GHz and 11 GHz at -15 °C. The penetration depth significantly depend on pH value of ice.

TABLE 1: Penetration depth of microwave used by SAR to the large ice mass as a function of pH value.

pH	Penetration depth (m)			
	1.275 GHz (J-ERS1, SAR)		5.3 GHz (E-ERS1, SAR)	
	-15 °C	-5 °C	-15 °C	-5 °C
7 (pure ice)	206	120	48	32
6	172	103	46	31
5	69	46	33	22
4	10	7	8	6
Greenland Ice Sheet pH=5.27	99	64	38	26
Inland Region Antarctica pH=5.14	84	55	36	24
Coastal Region Antarctica pH=6.08	177	106	46	31

respectively. They also showed the average pH value in Greenland was 5.27. The penetration depth for these pH values are also shown in Fig. 2. It shows that the penetration depth depend on the pH value of each locality.

FURTHER STUDIES

We showed the propagation velocity, birefringence and attenuation of electromagnetic waves in ice at MHz and GHz frequencies in this paper and in our another paper in this volume. It should be pointed out that few data about dielectric loss are available at these frequencies still now. They should be studied to interpret the remote sensing data of the cryosphere correctly. The reflection and the scattering of the electromagnetic waves in the large ice mass, which is also of interest with respect to the propagation, will be discussed elsewhere.

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