REGIONAL DIFFERENCE OF ATTENUATION OF RADIO WAVES WITHIN ANTARCTIC ICE SHEET

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Abstract: The attenuation of radio waves within the ice sheet is caused by absorption loss due to dielectric and electric properties of ice and geometric loss due to spreading of radio waves. The dielectric structure of the ice sheet can be derived by estimating the attenuation. This estimation is useful for the design of the future radio echo sounder.

The inland traverse party of the 23rd Japanese Antarctic Research Expedition in 1982 measured an ice thickness by radio echo sounding which operated on 60 MHz. Calculations of the attenuation rate of radio waves were made by reading the rate of decrease of the strength of internal echoes on the photographs of the A-scope display records. Values of the attenuation coefficient (dB/100 m) in the present study change between about 1.2 and about 3, and become smaller with increase of surface elevation of the ice sheet. But the attenuation coefficient in the bare ice field, the Meteorite Ice Field, around the Yamato Mountains is remarkably high. The regional difference of the attenuation coefficient is caused mainly by the temperature distribution with depth in the ice sheet. But it is considered that the high value of the effective attenuation coefficient in the bare ice field is due to not only different temperature distribution but also different dielectric properties of the bare ice.

1. Introduction

Radio echo sounding of the ice thickness of glaciers and ice sheets has been done as early as the 1950's. But for an initial duration of radio echo sounding, the ice thickness has not been measured due to the attenuation of radio waves. Therefore, the knowledge of the factors governing the attenuation was needed for an adequate thickness measurement and for development of the radio echo sounding technique. In the laboratory, the loss tangents of ice were measured as frequency dependent, and attenuation was shown to rise rapidly with increasing radio frequency above a few hundred megahertz and with increasing temperature near 0°C. The total absorption of radio waves was calculated by applying loss tangents to the temperature distribution with depth (ROBIN *et al.*, 1969). On the other hand, in field observations, attenuation within the ice sheet is estimated from radio echo sounding data, on the basis of the assumption that the reflection at the ice/bedrock interface has the same value in all places.

In the present study, the attenuation of radio waves within the ice sheet was estimated directly from attenuating the intensity of the internal radio echo on the A-scope display record measured by the 23rd Japanese Antarctic Research Expedition in 1982. The regional difference of attenuation ratio within the ice sheet was obtained in the vicinity of the Shirase Glacier drainage basin. Attenuation coefficients estimated in the present study have values between about 1.2 dB/100 m and about 3 dB/100 m, and decrease with increasing surface elevation of the measuring point. These ratio of the attenuation of radio wave will be useful data for the development of the future observations and are important for analyzing the bedrock echo (reflected signal from ice/bedrock interface) (OHMAE *et al.*, 1984) and the internal layering (reflected signals in the ice sheet).

2. Relation between the Attenuation of Radio Waves and the Dielectric Property of Ice

An electric field attenuates in propagation within a medium with loss. The propagation constant (γ) defines the variation of wave amplitude and phase with distance x according to $\exp(-\gamma x)$.

$$\gamma = \alpha + i\beta. \tag{1}$$

If $\alpha = 0$, the strength of an electric field is not attenuated because γ has only an imaginary part. Thus α is called an attenuation coefficient. This attenuation coefficient is the function of a dielectric constant (ε'), conductivity (σ') and the dielectric loss tangent ($\tan \delta$) of the medium. In a radio echo sounding, at different temperatures, the attenuation with respect to the thickness of ice is given by,

$$\alpha = \frac{\omega}{C}\left(\frac{1}{2}\varepsilon'(\sqrt{1+\tan^2\delta} - 1)\right)^{1/2} \quad \text{neper/m}. \tag{2}$$

If the loss tangent of a medium is much less than 1, eq. (2) reduces to,

$$\alpha = 1.449 \times 10^6 \omega\sqrt{\varepsilon'} \tan\delta \quad \text{dB/100m}, \tag{3}$$

where ω is the angular frequency, C the speed of light and $\tan\delta = \varepsilon'/\varepsilon''$. And as the loss tangent of ice is much less than 1, eq. (3) can be used for an ice sheet (JOHARI and CHARETTE, 1975).

In an ice sheet, the absorption of radio waves is caused by the dielectric loss tangent of ice. The dielectric constant of ice varies from place to place because of different ice flow and accumulation rates, and the dielectric constant of ice also varies with a depth due to density variation, the particle size of snow and ice crystals, crystal orientation, impurity inclusion, air bubble dispersion and temperature distribution with depth. Therefore, the absorption of radio waves changes with place and depth. It is possible to clarify the internal structure of ice sheet such as dielectric constant and temperature distribution by investigating absorption within the ice sheet.

3. Effective Attenuation Coefficient of Radio Waves within Ice Sheet

For the purpose of researching the internal structure of the ice sheet, the effective attenuation coefficient (α_1) is introduced in the present study.

The radar equation is shown in logarithmic expression as follows;

$$10\log\frac{P_r}{P_t}=10\log K+10\log\sigma-40\log R-8.68\Sigma\alpha R, \qquad (4)$$

where P_t and P_r are transmitted power and received power, respectively. K is a constant of the radar antenna, and σ is the reflective cross section of target. R is a distance from antenna to target.

The method of calculating the effective attenuation coefficient α_1 is as follows: A straight line was fitted to the strength of internal echoes on the A-scope display recorder (the instrument to describe one-dimensional time dependent signals on the synchroscope). The effective attenuation coefficient is obtained from the gradient of the fitted line divided by 2, because the value of the gradient indicated the value both going and returning along the propagating pass, whereas the effective attenuation coefficient is the value along a one-way passage through the ice sheet. Figure 1 shows schematically the method of calculating the effective attenuation coefficient (α_1). The gradient of the fitted line is 5.6 dB/100 m. Therefore, the effective attenuation coefficient will be 2.8 dB/100m at this observating point.

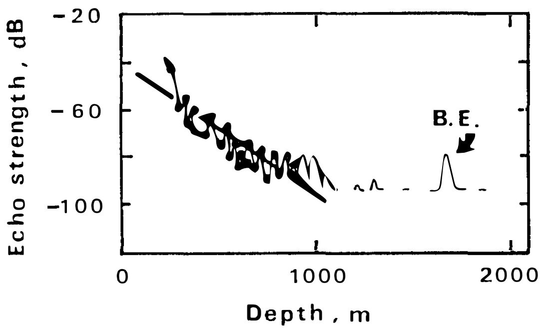

Fig. 1. Example of fitted line of the internal echo on the A-scope display for calculaitng the effective attenuation coefficient. The thick solid line is the fitted line, and "B. E." shows the bedrock echo.

The effective attenuation coefficient α_1 is the sum of the attenuation loss term (α_T) and the reflective cross section term (σ_T) in eq. (4). Figure 2 shows an example of the distribution of σ_T and α_T calculated based on a temperature distribution. When the operating frequency was 60 MHz, the reflective cross section term in radar eq. (4) was less than the attenuation loss term such as shown in Fig. 2. Therefore, the effective attenuation coefficient α_1 can be defined as the value indicating the attenuation within ice sheet.

Figure 3 shows the strength of internal echoes and the fitted line on these echoes at three observation points. G2 and G7 are stations of geodetic observation by a grid method (grid stations) along the Shirase Glacier drainage basin, and Z-100 is a point near Mizuho Station along the route Z. The surface elevations of three points are about 1800 m at G2, 2200 m at Z-100, 3200 m at G7 above sea level. The effective attenuation coefficient seems to be related to the surface elevation of the measurement point.

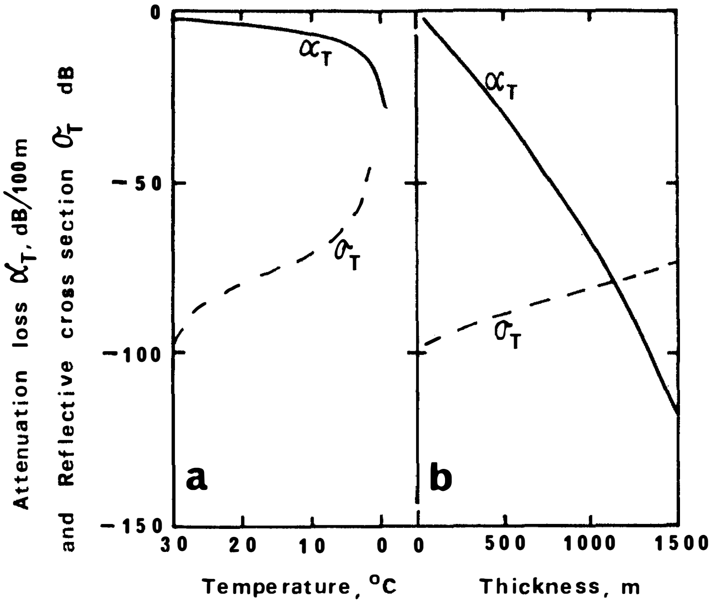

Fig. 2. Attenuation loss (α_T) and reflective cross section σ_T calculated from the dielectric permittivity distribution, which is obtained from the temperature distribution within ice sheet. The solid line and broken line represent attenuation loss and reflective cross section, respectively.

a) $\alpha_T = -8.68\,\alpha$ (dB/100 m) and $\sigma_T = 10 \log \sigma$ (dB) against temperature.

b) Example of α_T and σ_T integrated over depth.

The distribution of dielectric permittivity used in calculation has no 'anomalous' value of permittivity which products internal echoes. According to the result in (b), the reflective cross section is less than attenuation loss except in the basal layers.

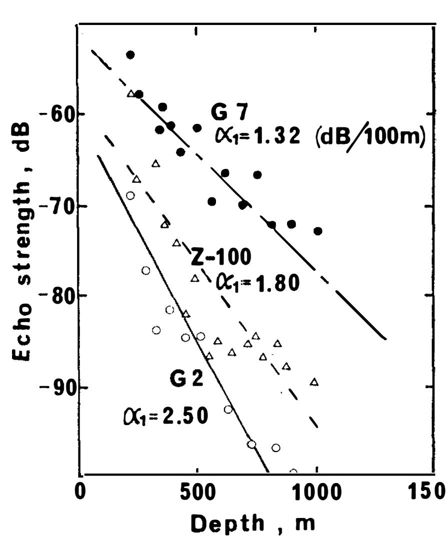

Fig. 3. Examples of the fitted line at three observation points. Solid circles (●), open circles (○) and open triangles (△) represent the strength of internal echoes on the A-scope display at G7, G2 and Z-100, respectively. The solid line, dashed line and broken line show the fitted lines for internal echoes at G2, Z-100 and G7, respectively. The values of the echo strength on the vertical-axis are values at Z-100, and the values at G2 and G7 are the values on the axis plus and minus 10 dB, respectively.

Figure 4 shows the average value of the effective attenuation coefficient at grid stations between SS-0 (G2) and SS-125 (G7) along route SS against the surface elevation of ice sheet. Route SS is a route in the vicinity of the Shirase Glacier drainage basin along the flow line of the Shirase Glacier. The average value of effective attenuation coefficient was calculated from about 20 observation records at 100-m intervals. The value at one observation point varies in places because of vibration of aerials in crossing irregularities of snow cover such as sastrugi.

The average value of effective attenuation coefficient at geodetic observation points decreases slightly with increase of the surface elevation of ice sheet (Fig. 4).

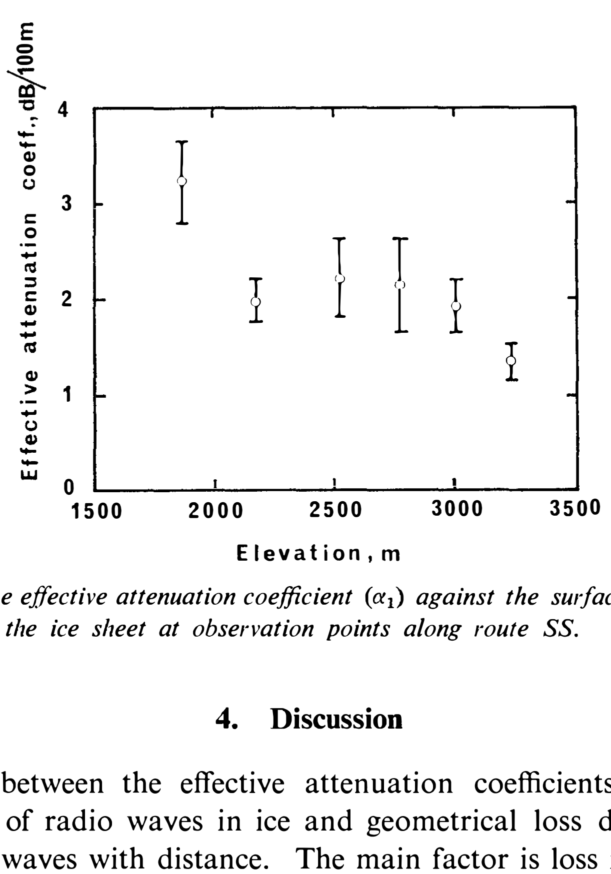

Fig. 4. The effective attenuation coefficient (α_1) against the surface elevation of the ice sheet at observation points along route SS.

4. Discussion

The difference between the effective attenuation coefficients (α_1) is caused by different absorption of radio waves in ice and geometrical loss due to expansion of the surface of radio waves with distance. The main factor is loss in the ice sheet such as dielectric loss. Geometrical loss is assumed constant since that the performance of the radio echo sounder can be assumed to not change. To find what governs absorption within the ice sheet, the relation between effective attenuation coefficients and snow temperature at the depth of 10 m, which are considered as mean annual temperatures, was studied.

Figure 5 shows the effective attenuation coefficient (α_1) along route SS, on a bare ice field and at Mizuho Station against 10-m snow temperature. The effective attenuation coefficient (α_1) tends to increase with the 10-m snow temperature increase. The rate of increase is about 0.1 (dB/100 m)/°C for a mean annual temperature in the range -30 to -50°C. The α_1 on the bare ice field near the Yamato Mountains also shows this tendency. Therefore, the α_1 is independent of surface types of snow and ice but depends on surface temperature. It is deduced that one factor governing α_1

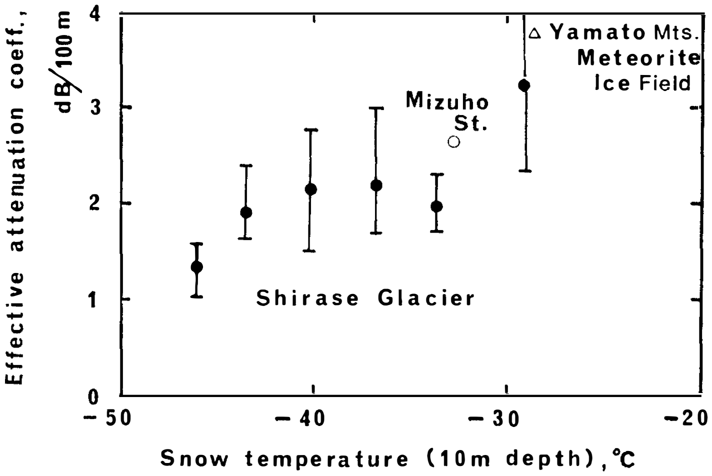

Fig. 5. The attenuation coefficient (α_1) against snow temperature at 10 m depth at an observation point along the route SS, at Mizuho Station (○) and on a bare ice field in the Meteorite Ice Field near the Yamato Mountains (△).

is the ice temperature. Dielectric permittivity, which causes absorption, is a function of snow and ice density and ice temperature, and also relates to impurity distribution. The effect of the density variation is limited above the depth of about 100 m. Because the ice sheet below about 100 m consists of ice, its density variation is very small.

The variation of the impurity changes abruptly at several depths. It is considered that internal layers (as determined from echoes on A-scope display records) are essentially impurity layers because the depths of reflections and the discontinuities in the rate of impurity variation agree. But throughout the thickness of the ice sheet, the contribution of impurity layers to the absorption of radio waves seems small; impurities rather produce reflection losses. Thus the attenuation coefficient is mainly a function of the temperature distribution in the ice sheet.

Next, we investigated the contribution of the temperature distribution within the ice sheet to the absorption. This was done by comparing α_1 with the attenuation coefficient from eq. (3) which is related to ice temperature. For the purpose of obtaining the attenuation coefficient in eq. (3), the temperature distributions within the ice sheet were calculated by the method of NISHIO and MAE (1979). Figure 6 shows the calculated attenuation coefficient (α) at different depths. According to the result at G2, the attenuation coefficient changes abruptly near basal layers due to rising of ice temperature to melting temperature, but the amplitude of the variation of attenuation coefficients becomes smaller with increasing surface elevation of the ice sheet.

The average attenuation coefficient ($\bar{\alpha}$) is defined by the arithmetic average values of attenuation coefficient (α) throughout thickness of the ice sheet. The comparison of $\bar{\alpha}$ with α_1 is shonw in Fig. 7, and shows a high degree of correlation at points along route SS. Therefore, the temperature distribution 'in the ice sheet is one of factors of α_1.

According to the relation of α_1 to snow temperature at the depth of 10 m and the

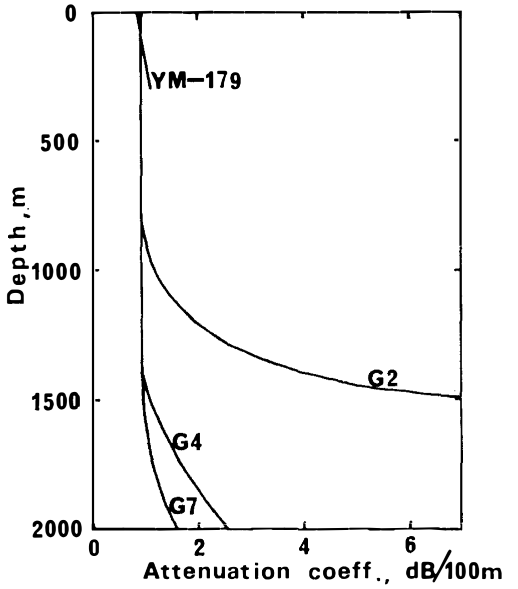

Fig. 6. The distribution of attenuation coefficient in eq. (2) with depth at G2, G4 and YM-179 (on the bare ice field). The present distributions are calculated based on the temperature distribution (after NISHIO *and* MAE, *1979).*

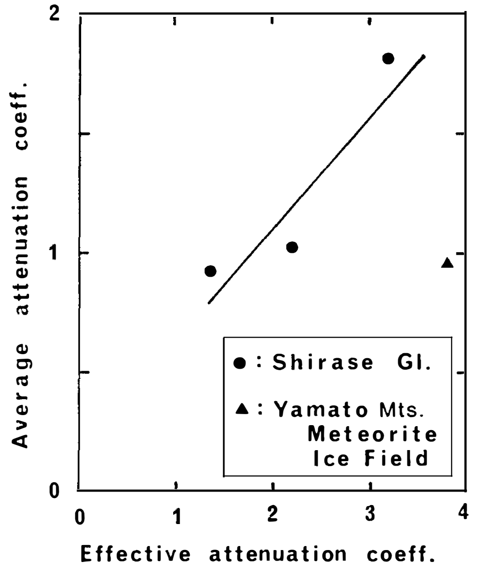

Fig. 7. Relationship between effective attenuation coefficient (α_1) *and average attenuation coefficient* ($\bar{\alpha}$).

attenuation coefficient (α_1), α_1 increases with increase of 10-m snow temperature and with increase of temperature within the ice sheet. If α_1 is large, it is expected that absorption of radio waves in ice will be large and the temperature of the basal layer will be near the melting point.

On the bare ice field, the α_1 for $\bar{\alpha}$ shifts from the tendency of the correlation between α_1 and $\bar{\alpha}$ indicated by the straight line in Fig. 7, and α_1 has large value. This suggests that the bare ice field has a different temperature distribution ice sheet with firn layer, and that the dielectric constant of the bare ice is anomalous, for example there might be a large loss due to impurity inclusions. In fact, many dirty layers were observed on the ice surface in the bare ice field. It is expected that the dielectric constant of the bare ice including dirt layers is different from pure ice and glacier ice.

5. Conclusion

The effective attenuation coefficient (α_1) varies in places, and decreases with increase of the surface elevation of the ice sheet. The cause of the variation of α_1 is mainly considered the temperature distribution within the ice sheet. But it is found that the result in a bare ice field cannot be explained by only the temperature distribution, and depends on the different dielectric constant of the bare ice due to impurity inclusions. The effective attenuation coefficient is easily calculated by the present method, and can be estimated the temperature distribution from α_1. Therefore, the α_1 is very useful value for investigating the thermal condition of the ice sheet, and in developing the hardware of radio echo sounder. In some cases, the fitted line to the internal echoes on the A-scope records is not a straight line, but a combination of many lines. A more complex temperature distribution is expected in these cases and more detailed analysis will be required.

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