GPR results for indicating layers of snow strata

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Abstract. The authors of this article describe the results of GPR tests for indicating the layers of snow strata and determining their properties, allowing for forecasting of avalanche hazards. The GPR tests were carried out during the winter season 2021/2022. Trenches were dug in the snow, in the wall of which long metal rods (markers) were installed, which are the reflectors for the GPR and make it possible to distinguish the boundaries of layers on the radarogram. As a result of conducting GPR sounding of the snow cover, radarograms were obtained, on which the layered structure of snow can be read. Using the GeoScan32 software, dielectric permittivity values were obtained for 19 layers of snow strata with different properties. Correlations were obtained between dielectric permittivity and temperature, crystal diameter, snow layer density, and snow layer water storage. The resulting dielectric permittivity relationships reveal the strongest correlations between dielectric permittivity and density, with a higher correlation coefficient for dry snow than for wet snow. The values of dielectric permittivity obtained from GPR were also compared with calculated values derived from a number of empirical correlations with snow density.

1 Introduction

Snow cover accumulates annually on almost all of the territory of Russia, with more than half of the country covered with snow for most of the year. In many mountainous regions, snow is present all year round.

Snow cover, as a heterogeneous and constantly changing environment in time and space, is a complex subject of research, dependent on constantly changing weather conditions, landscape conditions, and anthropogenic impact.

Snow cover plays an important role in the functioning of ecosystems and also has a significant impact on human activity. Snow cover is used as a road bed; for some regions, there is a permanent risk of avalanche and flooding as a result of snow melting. All this requires the development and application of tools to monitor snow cover. One of the promising areas is the method of georadiolocation, as a nondestructive method of snow cover research with the possibility of studying vast territories and hard-to-reach areas. [1-3].

At present, snow and glacier thicknesses are determined with sufficient accuracy, inclusions and cavities are identified, detailed maps of spatial distribution of snow cover are

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developed, and water reserves are estimated for forecasting floods on rivers.

The use of GPR for identifying avalanche-prone layers of snow strata in avalanches is also being considered [4, 5]. The use of GPR in avalanches would make it possible to estimate the volumes of accumulated snow and anticipated volumes of avalanches, identify the presence of avalanche hazard layers in the snow strata, and determine their depth and thickness. At the same time, the relative simplicity and speed of obtaining such information using ground-penetrating radar would help to cover a large area of avalanche-prone territories, to study the patterns of snow cover distribution, as well as the features of the occurrence of snow strata, their structure, density and water content.

Currently, there are theoretical developments that allow the radiolocation method to be considered to study the properties of the snow cover. For example, the electrical properties of the snow cover, its dielectric permittivity and calculation formulas for its determination have been described, the velocity of radio wave propagation in the snow cover depending on density, humidity, snow structure and the presence of ice layers in it have been calculated, and the issues of modeling the propagation of electromagnetic waves in the snow strata have been considered [4, 6-9].

Despite the apparent promise, in practice, the method of indicating the layers of the snow strata using GPR has so far only been applied in the form of experimental studies. So far, there is no practical confirmation, sufficient validity and necessary accuracy of application of this method, there is no methodology of conducting such works, there are no examples of successful application of the GPR method not only for forecasting avalanche danger, but even for approximate determination of snow cover density, let alone for determining the structure of the snow layer.

It becomes obvious that in order to develop a methodology for indicating snow strata and determining their properties, it is necessary to perform numerous tests on the use of GPR in natural conditions of snow cover occurrence in different types of landscape. Thus, the purpose of their research is to develop a methodology for indicating layers of the snowpack and determining their properties using non-destructive GPR methods, with an accuracy that makes it possible to forecast the avalanche danger. This work reflects the results of the first GPR tests to achieve the goals set.

2 Description of the research object

The objective of the study is snow, namely the snow cover in its natural occurrence. Snow is a mixture of three water phases: solid (ice crystals, snowflakes), liquid (water), gaseous (water vapor and air), i.e., it is a mixture of three components whose radiophysical parameters are essentially different [8].

One of the main properties of snow cover is density, temperature, and water reserve in snow, which in turn determine many other parameters. Snow cover is also characterized by layering, which is caused mainly by meteorological factors, such as snowfalls, wind, air temperature variations, as well as the properties of the underlying surface and relief. The layers of snow strata have different properties depending on the conditions of their formation. For example, snow layer density depends on the factor of time, depth of occurrence, and meteorological conditions.

One of the most important characteristics of snow cover is its structure (shape and size of ice crystals) and texture (mutual arrangement of crystals and pores in the snow layer). The structure and texture of the snowpack is described by the morphogenetic classification of E.G. Kolomyts, based on the theory of snowpack evolution. The theory of snowpack evolution is based on the idea of certain regularities in its development, which result in the transformation of crystals of one type into another (Fig. 1) [10-12]. In this case, the character and speed of snow cover metamorphism depend on landscape conditions. This circumstance makes it possible to predict changes in the structure and texture of snow strata, which is especially important for predicting the danger of avalanche [10].

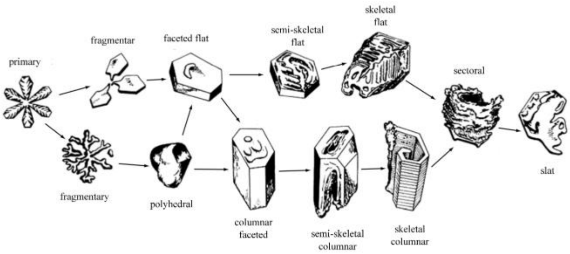


Fig. 1. Diagram of crystal growth stages in the dry snow cover (according to E.G. Kolomytz) [11].

Three stages of snowpack metamorphism are distinguished: destructive, constructive, and regressive. During the destructive metamorphism stage, the primary forms of precipitated crystals decay and round off, and polyhedral forms of crystals are formed. At the same time, settling and compaction of the snow cover occur. The texture of the snow cover is monolithic at this stage.

During structural metamorphism, polyhedral particles begin to evaporate (sublimate) under the influence of the temperature gradient and the elasticity gradient of the water vapour. As a result, small snow particles evaporate and condense on larger ones. Simultaneously, with the growth of the crystals, their faceting occurs. During the stage of structural metamorphism, both planar and columnar crystal shapes can develop and undergo three growth stages: faceted, semi-skeletal, and skeletal. In some cases, the crystals may reach a size of more than 1 cm. At the same time, the mutual arrangement of crystals, i.e., the texture, also changes: the crystals form vertically orientated links as a result of the direction of vapour transport. This texture is called columnar, which turns into a fibrous texture with further opening. The faceting and increase in size of the crystals leads to a reduction in the bonding between them. At the same time, this process prevents snow from settling, compacting and hardening.

At the stage of regressive metamorphism, structural metamorphism crystals break up, their partitioning, the appearance of sectorial and lamellar forms, and the compaction and hardening of snow.

Thus, the described evolution of the snowpack results in the formation of layers of low strength - avalanche-prone layers (ALP), through which the entire overlying snowpack - avalanche-forming layers (ALF) - collapses.

The FOS structure can be represented by different types of crystals of the structural stage of metamorphism. It is important that only at a certain ratio of layer density and diameter of the crystals composing it, the layer becomes avalanche-prone (Figure 2).

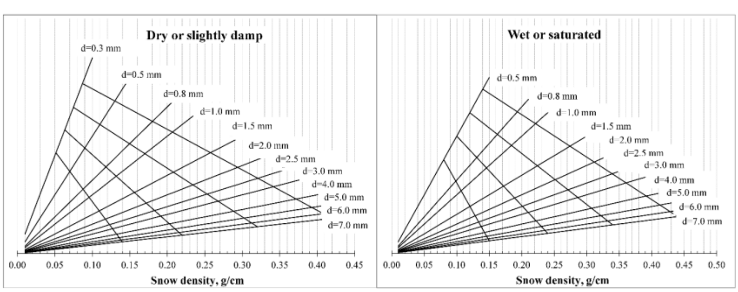


Fig. 2. Diagnostic nomogram of snow stability on a slope (according to V.R. Bolov) [13], where d defines crystal diameter, mm, ρ is density of the snow layer, g/cm³.

An avalanche can also occur along the contacts of layers, e.g., ice crust inside the snowpack, along voids often formed between the underlying surface and the snowpack as a result of removal of substance from this zone. Avalanche formation is also influenced by snow humidity, the increase of which leads to an increase in snow density and a decrease in strength at the same time.

When studying the snowpack, stratigraphic observations are used. The entire depth of the snowpack is excavated, the pit wall is cleaned and levelled, the layers of the snowpack are visually distinguished on the basis of colour and texture, then the hardness is determined, and the boundaries of the layers, their depth, and thickness are marked. The density of each layer, the temperature at the boundary of the layers, macrophotographs of the crystals in the layer and a description of the texture are taken using a blotter and weights. Other characteristics such as strength, humidity, and shear resistance can also be measured. Subsequent camera processing determines crystal size, shape class, and percentage of crystals of different shape classes from the photographs taken. As a result of the measurements, a stratigraphic column of the snow cover is obtained (Figure 3).

Location:		Site on the SKB SAMI south side	
Date: 25.02.2022		**Time:** 11:45-12:30	
Site description		**Weather conditions**	
Absolute height, m:	65		
Exposition:	-	**Weather:**	clear
Slope, deg..:	0	**Air temperature, C°:**	-3.0
Bedding surface:	grass	**Cloudiness, point:**	0/1
Vegetation:	meadow	**Wind, m/s**	1-2
Soil condition:	melted	**Air humidity, %:**	79

Layer No.	**Contact height, cm**	**Layer thickness, cm**	**Snow type and crystal shape class (according to E.G. Kolomytz); layer texture**	**Density, g/cm³**	**Water reserve, mm**	**Crystal diameter, mm: Average**	**Crystal diameter, mm: Maximum**	**Temperature, C°**
								-10.0
11	101	1		-	-	-	-	-10.0
10	100	4		0.15	6.0	-	-	-7.0
9	96	11	///	0.12	13.2	-	-	-10.0
8	85	11	///	0.24	26.4	-	-	-7.0
7	74	11	///	0.20	22.0	-	-	-4.5
6	63	16		0.42	67.2	1.1	2.0	-3.0
5	47	8		0.28	22.4	1.0	1.2	-2.0
4	39	13		0.33	42.9	0.9	1.3	-1.5
3	26	10		0.39	39.0	1.0	1.5	-1.0
2	16	9		0.32	28.8	2.0	3.0	-0.5
1	7	7		0.28	19.6	2.00	3.00	0.5
	0	0						
Total water reserve, mm				287.5		**Implemented by:**		
Average density, g/cm ³				0.3		D.A. Bobrova		
Average height from snow survey data, cm				99.0				
Water reserve, mm				281.8				

Legend

1. Snow type and ice crystal shape class (according to E.G. Kolomytz): Class of ice crystal shapes	**Snow type**	**2. Secondary idiomorphic snow texture**	
1.1. Primary idiomorphic			columnar
	freshly fallen		fibrous
	fragmentary	///	monolithic
	sublimation polyhedral	**3. Snow condition**	
	corrusion-polyhedral		wet
	relational-polyhedral		sleet
1.2. Secondary idiomorphic			regelatic crust
Constructive metamorphism phase			ice crust
	faceted flat		undissociated clusters of regelatic crystals
	faceted columnar		
	semi-skeletal flat		
	semi-skeletal columnar		
	skeletal flat		
	skeletal columnar		
Regressive metamorphism phase			
	sectoral		
	slat		

Fig. 3. Stratigraphic column of snow strata, Yuzhno-Sakhalinsk. Pit date: 25.02.2022.

Avalanche hazard forecasts are based on determining the stability of the snowpack on slopes as well as on meteorological factors. The forecast of meteorological conditions is based on the readings of hydrometeorological stations, and stratigraphic observations are required to determine the stability of snow on the slope and to identify avalanche hazard layers in the snowpack.

Thus, avalanche hazard forecasting based on determining the density, structure and humidity of layers allows the georadiolocation method to be considered as one of the promising forecasting methods.

3 Theoretical background to the use of georadiolocation to determine layers of snow strata

The GPR method is based on the phenomenon of reflection of electromagnetic waves from surface interfaces where electrical properties change. The basic parameter of a medium is its dielectric permittivity. The GPR transmitting antenna emits electromagnetic pulses, then the electromagnetic pulse emitted by the transmitting antenna into the environment is reflected from objects in the environment or any inhomogeneities that have a different dielectric permittivity or conductivity than the environment. Such inhomogeneities can be local objects (both metallic and non-metallic), voids, interfaces between layers of different rocks, areas with different humidity, density and temperature.

As a result, the receiving antenna receives a signal, which is a combination of the signal emitted by the transmitting antenna and received directly by the receiving antenna (direct wave or direct wave) and the signals reflected from the various inhomogeneities of the medium under study. This resulting signal is called the trace and represents the dependence of the signal amplitude on the arrival time of the reflection.

The propagation velocity of a wave and its travel time for radiolocation are described by the relations [14, 15]:

$$v = \frac{C}{\sqrt{\varepsilon}},$$

here $c=3*10^8$(m/s) is electromagnetic wave propagation speed in a vacuum, ε – dielectric constant of the medium under study;

$$t = \frac{2h}{v},$$

here *h* is a wave travel distance.

Snow has low electrical conductivity, which makes it a dielectric, the most important characteristic of which is dielectric permittivity - the response to an electric field. The relative dielectric permittivity of snow is characterised by a dimensionless coefficient representing the ratio of capacitance of a capacitor in snow and vacuum:

$$\varepsilon = \frac{E_0}{E}$$

For any insulator $\varepsilon>0$. Relative permittivity for air is ε=1; for dry solid ice (no air inclusions)) ε= 3.20±0.02; for meltwater ε= 87.9. For ice, this corresponds to a velocity of Vi= 169±2 m/μs, for water - velocity V= 32 m/μs. The dependence of the permittivity of cold ice on temperature t is as follows: ε = 3.1884+0.00091t. For hard ice - at t = 0 °C ε = 3.19±0.04, and in the range of temperatures from 0 to –20 °C, typical for subpolar and warm glaciers, this relationship is described by the equation ε = 3.1968 + 0.061t [7].

Snow is a mixture of three media, the ratio of which in a layer is constantly changing as a result of a combination of many factors, and does not have a constant dielectric value. The representation of snow as a two- or three-component medium has resulted in many empirical formulas for dielectric permittivity, based most often on relationships with density, humidity and temperature. The formulas are well presented in other works [4, 7, 8], so in this work the authors will not dwell on them in detail. It should only be noted that the possibilities of georadiolocation, as well as the established dependences of dielectric permittivity with the medium density, humidity and temperature, agree well with the parameters of the snowpack necessary for predicting the avalanche danger. The exception is the structure of the snow layer, namely the class of crystal forms that make up the snow layer. The dependence of dielectric permittivity on the structure and texture of the snowpack has not been established.

4 Working methodology

The works on snow strata indication were carried out during the winter season of 2021/2022 using OKO-2 GPR with an antenna unit AB-1700 (1700 MHz). Throughout the winter, several pits were made in the snowpack and parameters of its constituent layers were determined, such as density, temperature, structure and texture (according to E.G. Kolomyts), diameter of crystals composing the snow layer and snow humidity (determined as a qualitative indicator "wet/dry" without quantitative values of water content percentage by compressing the snow by hand). Trenches 10-15 metres long were then dug from the pit, depending on the number of layers. At a distance of 1 metre from each other, long metal rods (markers) were placed on the trench wall at the boundary of the snow layers, which are reflectors for GPR and allow the boundaries of the layers to be highlighted on the radarogram (Figure 4).

Fig. 4. GPR survey of snow cover using metal reflectors (markers) (indicated by black arrows), 25.02.2022.

After preparatory work, GPR was installed over the trench wall and the GPR was dragged along the entire trench over all markers on a plastic sled to obtain a section of the snow thickness on the radarogram. This allowed a radarogram to be obtained with the boundaries of the snowpack layers in order to further relate the thickness of these layers to the thickness actually measured in the stratigraphic work (Figure 5).

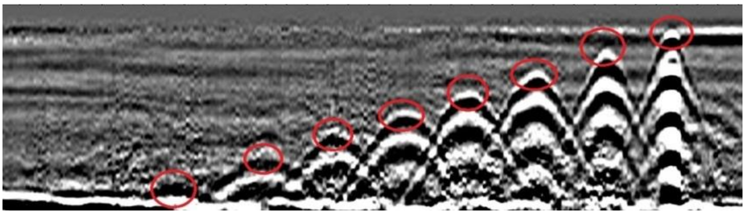


Fig. 5. Radarogram obtained from a GPR survey using markers. Reflected signals from markers placed at the layer boundary are highlighted in red, 25.02.2022.

The radarogram was processed using the software, GeoScan32.

Determination of electromagnetic wave propagation velocities and correspondingly dielectric permittivity of layers can be done in the following ways [14, 15]:

1. Using travel time curves of diffracted waves. On a radarogram a hyperbola is superimposed on the in-phase axis of the diffracted wave. Using the comparative measurement method, the velocity of propagating waves in the thickness from the observation surface to the diffracting object, the depth and the place of projection on the profile are determined. On real radarograms, the travel time curves of the diffracted waves are not always clearly distinguished, most often only the upper parts of the hyperbolas are observed. In this measurement method, the accuracy of the profile length measurement plays an important role. When the GPR antenna unit is driven in snow, the displacement sensor is inoperative, as it is only designed for hard surface and continuous survey mode is used during the measurement. Therefore, even if the profile length scale is corrected, there is no exact location of objects along the entire length of the profile, so it is not possible to use the "travel time curve" method.

2. Using travel time curves of reflected waves. Same as in the first method, the travel time curves are used, but not the diffracted waves but the reflected ones. This method also requires accurate measurement of the profile length during GPR survey.

3. Velocity estimation or matching method. It is executed in case of time section, radarogram with arrival times of reflected waves, lithology and thicknesses of layers according to drilling data (applicable to geology). Similarly for snow, it is performing stratigraphic work at a reference point. The referencing is done from top to bottom. Having the distance, i.e., the thickness of the layer and the arrival time of the reflected wave, the electromagnetic wave propagation velocity and the dielectric permittivity for the given layer can be calculated accordingly. If the values are real, the calculation is made for the layer below, if not real, the power of the layer below is added to the power of the upper layer. And the procedure is repeated up to the radarogram border. Criterion for correctness of selection is correspondence of layers with stratigraphic information on pothole.

4. Direct measurement of dielectric permittivity in the layer with special device and subsequent calculation of propagation velocity $V=c/\sqrt{\varepsilon}$. Applicable as a rule under laboratory conditions.

In our work the third method of determination of electromagnetic wave and dielectric penetration and propagation velocities was used. Having a stratigraphic column measured in the study area, we know the thicknesses of the layers, using "markers" we linked the layers in the radarogram to those in the study area. The values of the transmission rate and dielectric constant are calculated automatically by the software after setting the layer power.

Different empirical relationships of dielectric constant and snow density were used to obtain the calculated values of dielectric constant [16–19].

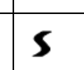
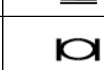
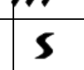
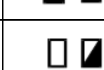
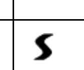
5 Results and discussion

As a result of georadiolocation sounding of the snow cover, radarograms were obtained, on which the layered structure of snow can be read (Figure 5). At the same time, as in natural snow cover occurrence, the layers change their thickness along the route, merge with each other or, on the contrary, split apart. This peculiarity of snow cover occurrence is related to uneven terrain, changing vegetation, as well as to meteorological conditions such as wind. In addition, the radarogram of 03.03.2022 showed a layer that was not identified as a separate layer in the stratigraphic works due to insignificant differences in properties, in the expert's opinion. The data obtained suggests that it is possible to carry out stratigraphic work by non-destructive method using GPR.

Data were also obtained on the humidity, density and structure of the layers (crystal form class and size) and their dielectric permittivity (Table 1).

Figures 6-8 show the values of the correlation coefficient *r* between ε′ and temperature, crystal diameter, density, water reserve. The resulting dielectric permittivity relationships reveal the strongest relationships between ε′ and *ρ,* the correlation coefficient for dry snow is higher than for wet snow. The results obtained agree quite well with the studies of other authors [9]. Dry snow is a two-component medium (air-ice), while in wet snow another component is added - water, the percentage content of which in the snow layer is not exactly known. It is probably the lack of values for the volume of the liquid phase that results in little consistency. Correlation ε′ with the average crystal diameter and water reserve is close to zero, the r-value for temperature shows a weak relationship.

Table 1. Summary table of parameters of snow strata derived from stratigraphic works.

no.	Pit date	Snow layer thickness, h, cm	Class of crystal shapes (by E.G. Kolomytz)	Average crystal diameter, d, mm	Snow layer structure	Humidity	Water storage capacity, W, mm	Density, ρ, g/cm ³	Temperature at the layer boundary (above the layer), *t*, C°	Relative permittivity determined by GPR , ε′	Wave velocity determined by GPR, U, mm/ns
1	25.02.22	11.0		0.3		dry	26.4	0.24	-7.0	1.0	300
2	25.02.22	11.2		0.2		dry	22.4	0.20	-4.5	3.4	162
3	25.02.22	8.0		1.1		dry	33.6	0.42	-3.0	1.9	217
4	26.02.22	8.0		1.2		dry	33.6	0.42	-3.0	3.3	165
5	25.02.22	9.8		1.0		dry	27.44	0.28	-2.0	1.0	300
6	25.02.22	13.3		0.9		wet	43.89	0.33	-1.5	1.2	278
7	25.02.22	10.2		1.0		dry	39.78	0.39	-1.0	1.4	253
8	25.02.22	9.1		2.0		dry	29.12	0.32	-0.5	1.5	244
9	03.03.22	9.0		-		wet	18	0.20	-3.0	2.9	176
10	03.03.22	8.9		-		wet	20.47	0.23	-5.0	1.4	253
11	03.03.22	7.0		-		wet	16.1	0.23	-4.0	1.0	300
12	03.03.22	6.4		-		wet	19.84	0.31	-3.0	3.0	173
13	03.03.22	10.0		-		wet	29	0.29	-2.5	2.0	212
14	03.03.22	11.2		-		dry	36.96	0.33	-2.0	1.0	300

15	03.03.22	8.9	□ ◪ ■	-	S	dry	32.04	0.36	-1.5	1.8	223
16	03.03.22	7.0	□ ◪ ■	1.2	S	dry	26.6	0.38	-1.0	1.7	230
17	31.03.22	9.9	-	-	///	wet	74.25	0.75	0.0	1.8	223
18	31.03.22	9.0	-	-	///	wet	61.2	0.68	0.0	4.1	148
19	31.03.22	4.8	-	-	///	wet	31.68	0.66	0.0	6.0	122

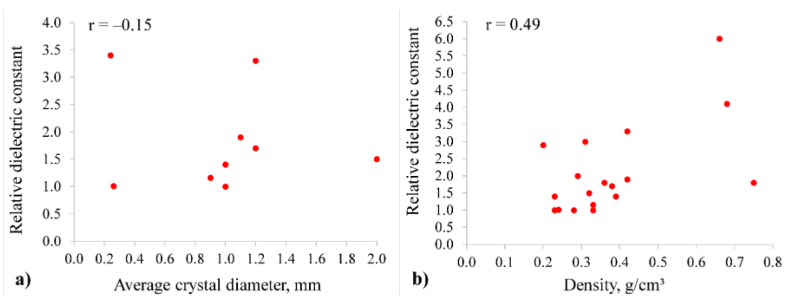


Fig. 6. Dependence of ε′ relative permittivity: a) - on average crystal diameter *d*, mm; b) - on layer density ρ, g/cm^3. The correlation coefficient is denoted as *r*.

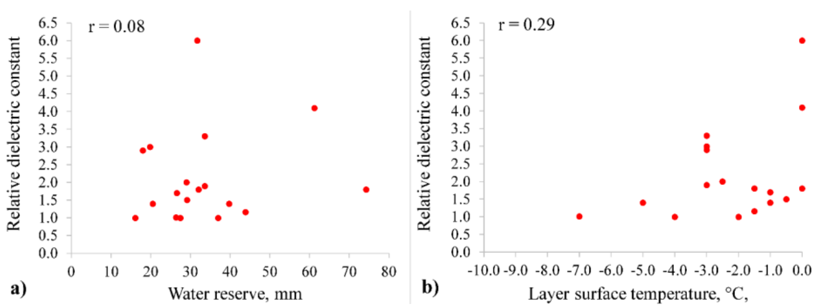


Fig. 7. Dependence of ε′ relative permittivity: a) - on the water reserve in the snow cover W, mm; b) - on the temperature at the layer surface t, °C. The correlation coefficient is denoted as *r*.

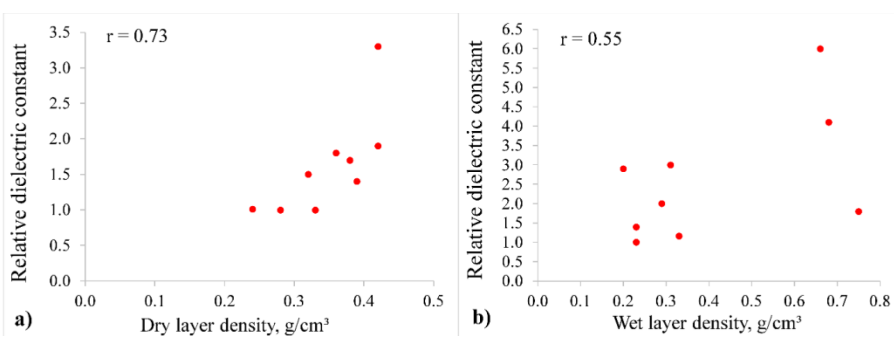


Fig. 8. Dependence of ε′ relative permittivity: a) - on the density of dry layers ρ, g/cm^3; b) - on the density of wet layers ρ, g/cm^3. The correlation coefficient is denoted as *r*.

Although there is a notable relationship between ε′ and ρ dry snow, the resulting correlation coefficient of r=0.73 is not sufficient to apply the relationship in practice. In addition, the sample is too small for any unambiguous conclusions. In this case, we can only speak about the prospects of GPR application for determining the density of snowpack layers. It should also be noted that, in this sample, ranking according to the snowpack structure was not performed due to the great diversity of the classes of crystal shapes in the studied layers and the impossibility of combining them into identical groups, which is again related to the insufficient sample volume.

At the same time, many authors have previously established empirical relationships between snow density and its dielectric permittivity, which should make it possible to use them to determine the density of the snow layer using GPR. In order to verify this assumption, calculations of the ε'_Σ dielectric permittivity of snow were carried out as a multi-component medium according to a number of empirical formulas developed by different authors and based on the ratios ε'_Σ with snow density ρ (Table 2). The densities of each layer measured in the stratigraphic work were used for the calculation. The results obtained are shown in Table 3.

Table 2. Empirical formulas used to calculate the dielectric permittivity of dry snow relative to snow cover density, where ρ is the relative density of snow cover (relative to water density), ε_i=3.17 is ice dielectric constant, ρ_i= 0.917 g/cm^3– ice density, ε_0 = 1, $\nu=\rho/\rho_i$ – snow to ice density ratio.

The author of the calculation formula and the terms of the equation	The equation that defines ε'_Σ
Tiuri M. E. (at 1.9; 5.6; 12.6 GHz) [17] for dry snow	$\varepsilon'_\Sigma = 1 + 1.7\rho + 0.7\rho^2$
Hallikainen M. (in the frequency range 4-18 GHz) [18] For dry snow	$\varepsilon'_\Sigma = 1 + 1.91\rho$
Frolov A.D., Matcheret Yu. Ya [19] For dry snow	$\varepsilon'_\Sigma = \left[\frac{\rho}{\rho_i}\left(\varepsilon_i^{\frac{1}{3}} - 1\right) + 1\right]^3$
Matzler C. [8] For dry and wet snow, at a density of P<0.4	$\varepsilon'_\Sigma = 1 + 1.5995\rho + 1.86\rho^3$
Robin G. [9] For dry snow (ρ expressed in kg/m^3)	$\varepsilon'_{c.c} = (1 + 0.000851 \cdot \rho_{c.c})^2$

Table 3. Dielectric permittivity values calculated using the methods from Table 2 and obtained by fitting in GeoScan32.

Snow density, ρ, g/cm ^{3}	**Humidity**	**Relative dielectric constant**					
		Found by fitting method in the software GeoScan32, ε'	**Estimated , ε'_Σ**				
			Tiuri M. E.	**Hallikaienen M.**	**Frolov A.D. Matcheret Yu. Ya**	**Matzler C. P<0.4**	**Robin G.**
0.24	dry	1.00	1.45	1.46	1.41	1.41	1.45
0.20	dry	3.40	1.37	1.38	1.33	1.33	1.37
0.42	dry	1.90	1.84	1.80	1.78	1.81	1.84
0.42	dry	3.30	1.00	1.00	1.00	1.00	1.00
0.28	dry	1.00	1.53	1.53	1.49	1.49	1.53
0.33	wet	1.16	-	-	-	1.59	-
0.39	dry	1.40	1.77	1.74	1.72	1.73	1.77

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0.32	dry	1.50	1.62	1.61	1.57	1.57	1.62
0.20	wet	2.90	-	-	-	1.33	-
0.23	wet	1.40	-	-	-	1.39	-
0.23	wet	1.00	-	-	-	1.39	-
0.31	wet	3.00	-	-	-	1.55	-
0.29	wet	2.00	-	-	-	1.51	-
0.33	dry	1.00	1.64	1.63	1.59	1.59	1.64
0.36	dry	1.80	1.70	1.69	1.65	1.66	1.71
0.38	dry	1.70	1.75	1.73	1.69	1.71	1.75

The calculation of the dielectric permittivity using empirical relationships showed that the calculated values obtained do not practically differ from each other. However, there is little agreement between the calculated values and the results found with GPR. Only half of the results diverge by less than 30%, and some values differ by more than a factor of two. At the same time, according to [14], if the values of dielectric permittivity obtained with GPR correspond or are comparable with the reference values of this parameter, the interpretation result is considered to be correct. Thus, there is no reason to believe that the dielectric permittivity values measured by the authors with GPR have significant errors. It follows that the existing empirical relationships ε' and ρ do not accurately reflect the degree of dependence of these parameters, which is confirmed by the correlation relationships obtained by the authors.

At the same time, the differences between the values of ε' can be related to layer power measurement errors in the radarogram as a result of an incorrectly defined layer boundary. Such measurement error may be related to the antenna unit used. Thus, in the experiments conducted by the authors, the AB-1700 antenna unit was used, which has the smallest measurement step of 3 cm. With a layer thickness of 6-10 cm this may cause a large error. Such an error in the case when the method of georadiolocation is used to determine the thickness of the entire snow cover or in geology, where the thickness of rock layers is several meters, an error of a few centimeters is not of great importance. In avalanche science and snow science, however, it is necessary to determine all layers of the snowpack, including those of low thickness. Also, one of the causes of errors in measuring the thickness of layers, and consequently ε' may be the use of metal markers as reflectors. In these experiments, markers made of metal rods were used to identify the layers and placed at the boundary of the layers. Metal has the property of reflecting radio signals, which makes it possible to see the marker on the radarogram, but the reflecting properties of metal do not allow the underlying snow cover layers to "see" on the radarogram. In addition, there is a phenomenon of signal over-reflection, which also complicates radarogram processing. Separately, it should be noted that the structure and texture of the snow cover layers were not taken into account in this work. It is likely that the ratio of ice, air and water in the snow layer affects the value of ε', so the layer structure should also be taken into account when searching for dependencies ε' and ρ.

6 Conclusion

As a result of applying the georadiolocation method as an indicator of snowpack layers, radarograms have been obtained, which visually identify the layered structure of the snowpack. The data on the number of layers on the radarogram coincide with the data of the stratigraphic column obtained as a result of field observations. This makes it possible to say that the electromagnetic wave propagation speed in the snow cover is unequal and depends on the properties of a single layer. In turn, the possibility of obtaining a dependence between the values of the wave velocity and, consequently, the dielectric permittivity of the layer on the parameters of the snow cover makes the method of indicating the layers of the snowpack using ground-penetrating radar promising.

Despite the fact that the sample is too small, amounting to only 19 values, the first results have been obtained, allowing us to estimate the probability of detecting avalanche hazard layers using GPR. The density of dry snow and its dielectric permittivity were found to have a moderate to close relationship.

Comparison of dielectric permittivity values calculated using empirical relationships developed by other authors and values obtained using GPR showed that the results are in poor agreement with each other. This may indicate both large errors in the measurement of dielectric permittivity with GPR and imperfection of existing empirical relations. The authors found that the data on the dependence of dielectric permittivity and snow cover parameters, allowing to estimate the degree of avalanche danger, are insufficient.

The use of markers makes it possible to determine the boundaries and thicknesses of layers on the radarogram and to link them to in-situ stratigraphic observations. However, the use of metal markers makes it impossible to see the snow layers below the marker. In addition, the resulting overreflexion effect makes it difficult to identify the layers above, as well.

The application of the GeoScan32 software product and the fitting method in determining the boundaries and power of layers on the radarogram makes it possible to obtain dielectric permittivity values. In turn, when the correlation between dielectric permittivity and such parameters of a snow layer as density, humidity, layer structure and diameter of crystals is established, it will allow to use the georadiolocation method as an alternative method for forecasting avalanche danger. Also, the use of georadiolocation as one of the snow cover research methods will make it possible to come closer to solving other scientific and practical tasks of glaciology.

To use the GPR method for the indication of snow strata, it is necessary to obtain a large sample volume, measure dielectric permeability of snow layers both by GPR and a special device, measure dielectric permeability of snow layers having different structure and texture, obtain numerical values of snow moisture, and use as markers the material which will allow to determine the boundaries of layers on the radarogram with the smallest errors.

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