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Investigation of snow characteristics in the microwave range for avalanche forecasting

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Abstract. It should be noted that avalanches of accumulated snow masses are typically triggered by climatic factors, including abrupt weather changes (such as variations in atmospheric pressure and air humidity), precipitation, and heavy snowfall. The volume of snow in an avalanche can reach several million cubic meters. However, even avalanches with a volume of about 5 m^3 can be life-threatening. To reduce and prevent these negative factors, it is necessary to predict and prevent the occurrence of avalanches at an earlier stage. This task is solved by regular monitoring of snow and weather conditions on the proposed area of mountain slopes.

In order to achieve this objective, a variety of methods and techniques based on different physical and technical principles are currently used. One of the most promising directions is the use of radio waves of ultra-high frequency (UHF) range.

The present study is devoted to the examination of the possibility of UHF methods for the remote measurement of snow parameters.

Two experimental installations for measurement of various snow parameters in the microwave radio wave range have been constructed for avalanche forecasting. Predictors of avalanches are chosen based on physical considerations and methods of mathematical statistics. The objective of our research is to create an installation to study the characteristics of mountain snow in the avalanche-hazardous areas of the Shimbulak ski resort. The main parameters of electric snow that influence the process of transmission, propagation and reflection of radio waves are considered. As a result of the changes, the dipole moment increases, which causes the separation band of the alternating influence of water to expand and move to the low-frequency region. The results of experimental studies of radio-wave attenuation in snow used to calculate the absorption coefficient of microwave radiation in snow are presented. Dielectric permeability and tangent of the angle of snow losses have been measured using the waveguide method.

Keywords: snow, avalanche, distribution of radio waves, horn antenna, the waveguide detector section, complex permittivity, electromagnetic radiations, absorption of radio waves.

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Introduction

In general, forecasting of avalanche hazard means detection of place and time of avalanches. Long-term investigations and analyses of papers devoted to the identification of the main factors leading to the formation of avalanches allowed us to identify the most significant predictors of avalanches of different genetic types (Table 1) [1-5].

Table1. A set of the most significant predictors of avalanches of different genetic types

Types of information (parameters)	Genesis of avalanches			
	Fresh snow	Snowdrift	Thermal loosening	Sublimation loosening
Air temperature	+	+	+	-
Snow depth	+	(+)	+	(+)
Water equivalent of snow	(+)	-	(+)	(+)
Snow density	(+)	(+)	(+)	(+)
Snow humidity	-	-	+	-
Snow temperature	-	-	+	(+)
Snow humidity	(+)	-	-	-
Wind transfer	-	+	-	-
Duration of sunshine	-	-	(+)	-
Acoustic emission of snow	+	+	(+)	(+)
Wind speed	(+)	+	-	-
Avalanching time	+	+	+	(+)
Power of loose horizons	(+)	-	-	(+)
Crystal size	-	-	(+)	(+)
Atmospheric pressure	-	+	-	-

\+ the sign is informative
(+) the sign is conventionally informative
\- the sign is uninformative

The table shows that snow thickness is one of the informative parameters. It is well identified and can be used as a universal parameter for predicting avalanches in many mountainous regions. However, we must bear in mind that each snow layer was formed in different periods of time and varied under different weather conditions. It should be noted that the snow depth as an indicator of avalanche hazard must be used in combination with other avalanche factors.

Some authors state that for the purposes of statistical analysis it is not necessary to form large sets of data with signs for most avalanche situations [3-7]. Larger data arrays do not usually give more timely and more accurate forecasts.

Predictors of avalanches are chosen based on physical considerations and methods of mathematical statistics. Predictors for forecasting techniques must be chosen taking into account the area for which the forecast is made and the variability of values of predictors within the area. The objective of our research is to create an installation for investigation of characteristics of the mountain snow in the avalanche-hazardous areas of the Shimbulak ski resort.

Using radio waves in snow studies

Avalanche-forming factors are first determined when the thickness of the new snow on the observation site of the avalanche station reaches 7-8 centimeters. Then calculations are repeated periodically after a certain period of time. At a known rate of growth of the snow depth, the time preceding the avalanche hazard is defined as the time needed for formation of the critical snow thickness. It is very important to know the thickness of snow in the area of avalanche nucleation. As it is dangerous to conduct direct observations of the snow cover in this zone, its characteristics are determined on the basis of remote observations and measurements on the experimental ground.

Because of the lack of equipment and techniques for obtaining reliable information on the state and properties of snow in the avalanche nucleation areas, the methods of local forecasting are still poorly developed, and the precision of existing methods used to determine strength characteristics and indicators of the snow cover stability is low.

Therefore, it is very important to study electrical, radio wave, radiation, laser and acoustic properties of snow, which have not been well studied yet [8-10].

It is necessary to pay special attention to the radio wave method as the most convenient method for remote measurements of snow parameters. Let us consider basic electrical parameters of snow, which affect the process of transmission, absorption and reflection of radio waves.

Dry snow, first of all, is characterized by small electric conductivity, at the density of snow ranging from 100 to 500 kg/m^3 and temperature from -2 to -16 °C, its specific electric resistance ρ is quite high, ranging from 2.8*10^5 to 2.6*10^7 Om*m, and it is close to the specific resistance of artificial ice. On the contrary, damp snow has small electric resistance reaching values of 10Om*m. Dielectric permeability of the snow cover ε depends on the frequency of electromagnetic waves, their length and snow characteristics (temperature, density, structure, humidity). Dielectric permeability of snow is lower than that of the ice (εол =73... 95, ε ∞ l =3... 8) and increases with increase in its density and humidity [1,2].

It is also known that fog, rain and snow considerably weaken radio signals with a wave length less than 5cm. Noncontact radio wave methods enable scientists to control thickness, humidity, viscosity, kinetics of hardening, geometrical sizes, composition of components, existence of various defects and other snow parameters. Of special interest is absorption and dispersion of radio waves in the microwave range caused by the broadband rotary relaxation of polar water molecules in the microwave region. In this case the precision of measurements depends on the wavelength: the precision increases as the wavelength decreases. The other obvious advantages of microwave radio waves are:

– Non-contact control, which means that the sensor is not loaded and does not disturb the state of the surface of studied or controlled snow;
– Very low inertia of the reading system;
– Possibility of carrying out continuous measurements;
– Proportionality of the resulting signal to the measured value or its changes;
– Signals at the output of the system do not require additional conversion;
– Simplicity of system calibration and automation.

In most widely used methods of thickness measurements the signal is a function of two variables: geometrical thickness and dielectric permeability of controlled snow. Therefore, the precision of measurements depends on the uniformity of snow thickness.

We used the amplitude method based on the principle of attenuation of electromagnetic waves passing through the material (the "transmission" method) applicable for measurements in homogeneous isotropic media with constant scattering properties of the surface. When analyzing the results of such measurements, it is necessary to know the value of the total attenuation caused by the interaction with the medium. The wave energy will decrease due to the action of the following factors [8-11]:
– absorption in the medium;
– scattering by microparticles;
– attenuation caused by nonideal transparency of the boundaries of the section;
– attenuation caused by nonideal orientation of transceiver antennas.

A specific feature of water structure is the existence of dipolar moments. Electromagnetic waves can cause deformation of hydrogen bonds including changes in the O-H length or H-O-H angles. As a result of such changes the dipolar moment increases, which causes broadening and shifting to the low-frequency region of absorption bands in the oscillatory water spectra. Intermolecular bonds are even less stable and easily collapse under the action of short-wave electromagnetic waves. The hydrogen atom located between two atoms of oxygen can be in one of two states – either near the first or near the second atom of oxygen, and one of these states is stable. The energy of transition of the hydrogen atom from the stable state to the unstable one corresponds to the quantum of energy in the microwave range [1,2]. The absorption of radiation of the microwave range by water is caused by orientational polarization of molecules. Intermolecular interaction and thermal motion of molecules act as counteracting effects. Dielectric losses are caused by shifting of the polarization phase. The range of frequencies 10 GHz ÷ 50 GHz is the range of dispersion of dielectric permeability of free water caused by relaxation fluctuations of molecular dipoles of free water (macroscopic time of relaxation is 0.9, 10-11 c), which under the influence of a high-frequency alternating field do not have time to reorient [12-14]. The percentage of absorption of microwave energy by water is 50% at frequencies of 1 GHz, 90% at 10 GHz and 98% at 30 GHz.

The methodology

To study snow characteristics, we used the experimental setup, the block diagram of which is shown in Figure 1. The experimental setup consists of a microwave transmitter and receiver adjusted to measure snow attenuation at a fixed frequency. At the outlet (in the vicinity of the cutoff of the horn) the antenna gives a synphased plane field. Measurements are made by the method of direct conversion – the readings of the oscilloscope screen. As a source of microwave radiation, we used a special generator.

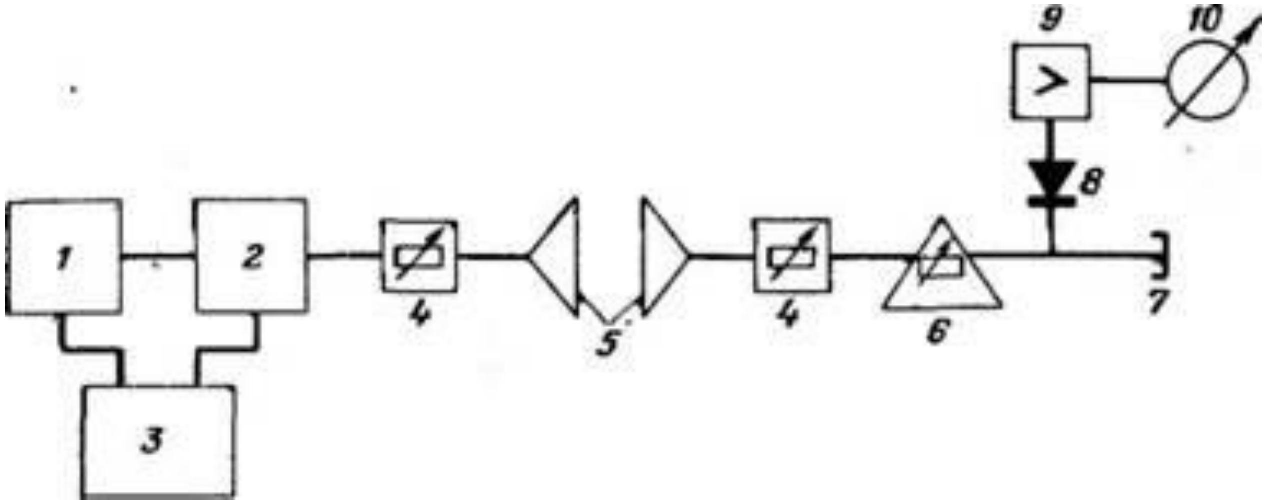

Figure 1. A block diagram of the microwave experimental setup for measuring snow parameters [15]

1 is a microwave generator, 2 is a modulator, 3 is a power supply, 4 are decoupling attenuators, 5 are two microwave antennas, 6 is a measuring attenuator, 7 is a matched load, 8 is a microwave detector, 9 is a narrow-band amplifier, 10 is a measuring instrument.

In our experiment the function of the microwave source was fulfilled by a special generator calibrated in frequency, output power and pulse modulation parameters. We used measuring UHF generator G4-126 in the centimeter range for 2-reflexing klystrons working in the frequency range from 8.8 to 12 GHz (in the 2.5-3.8cm wavelength range). The device has a built-in resonant frequency meter (frequency meter) measuring the frequency of the output signal with a precision of 0.2%. The device has an attenuator to adjust the output power of the microwave radiation in the range from +10 to -100 dB, or from 4 to 20 mW in absolute values. The H10 microwave electromagnetic wave with vertical polarization passes through a rectangular waveguide flange with internal dimension of the waveguide 23 • 10 mm. The generator provides several types of modulation. The power indicator is an independent unit and allows one to control the output power of the generator. The built-in power indicator consists of a thermoelectric converter, a dc amplifier and an indicator with a scale calibrated in dB. The modulator block provides the operation of the generator in the amplitude, pulse modulation with a frequency of 1 kHz. The pulse mode of the microwave generator is provided by the voltage modulator by sending modulating voltage to the klystron reflector circuit. Insulating attenuators reduce the action of the signal reflected from the measurement object on the generator. Figure 2 shows a pyramidal horn antenna [16].

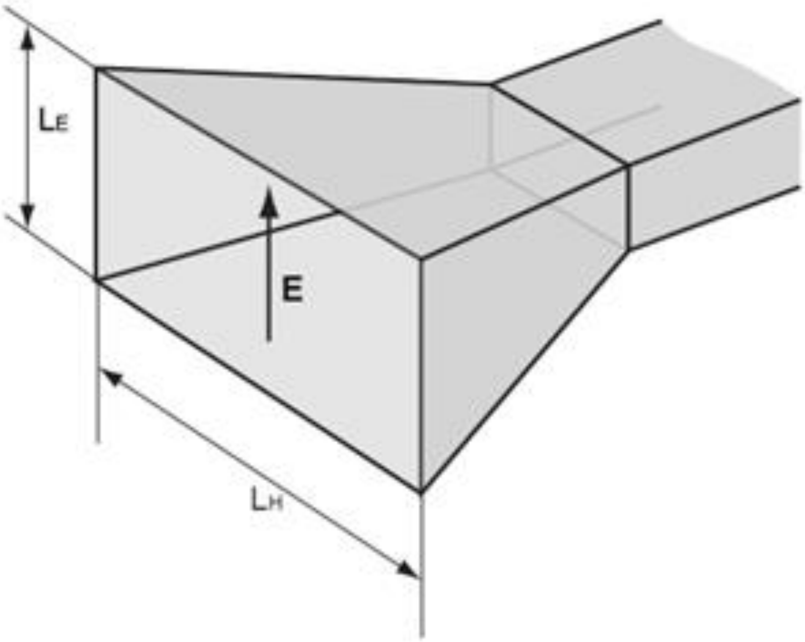

Figure 2. A schematic representation of a pyramidal horn antenna, LE is the height of the antenna aperture, LH is the width of the antenna aperture, E is the vector of the electric component of the microwave showing the vertical plane of polarization [14].

The radiation pattern is shown in Figure 3.

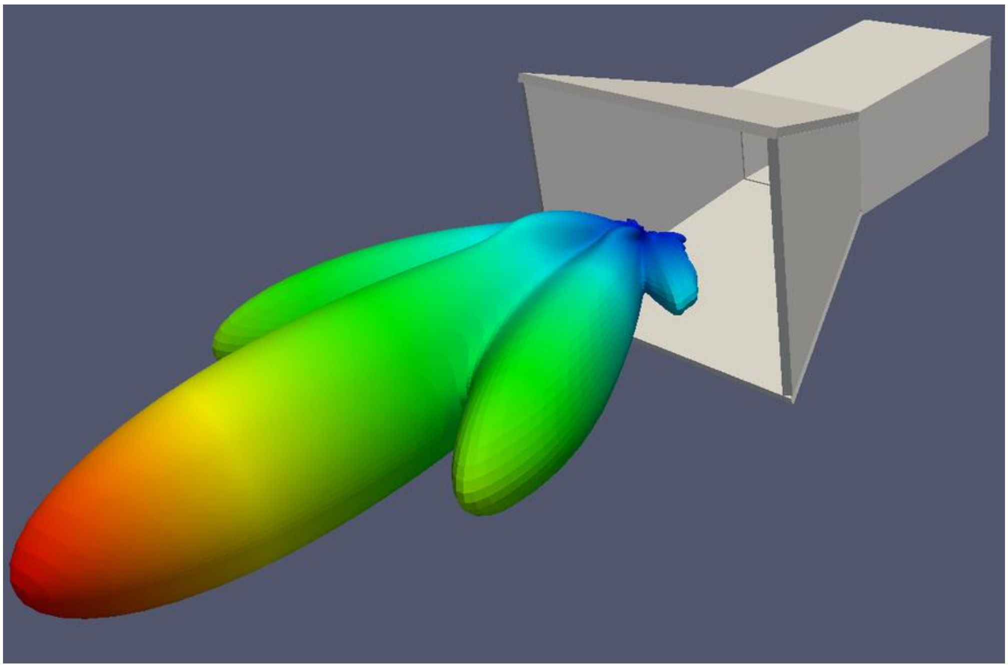

Figure 3. Spatial directivity of the pyramidal horn antenna [17].

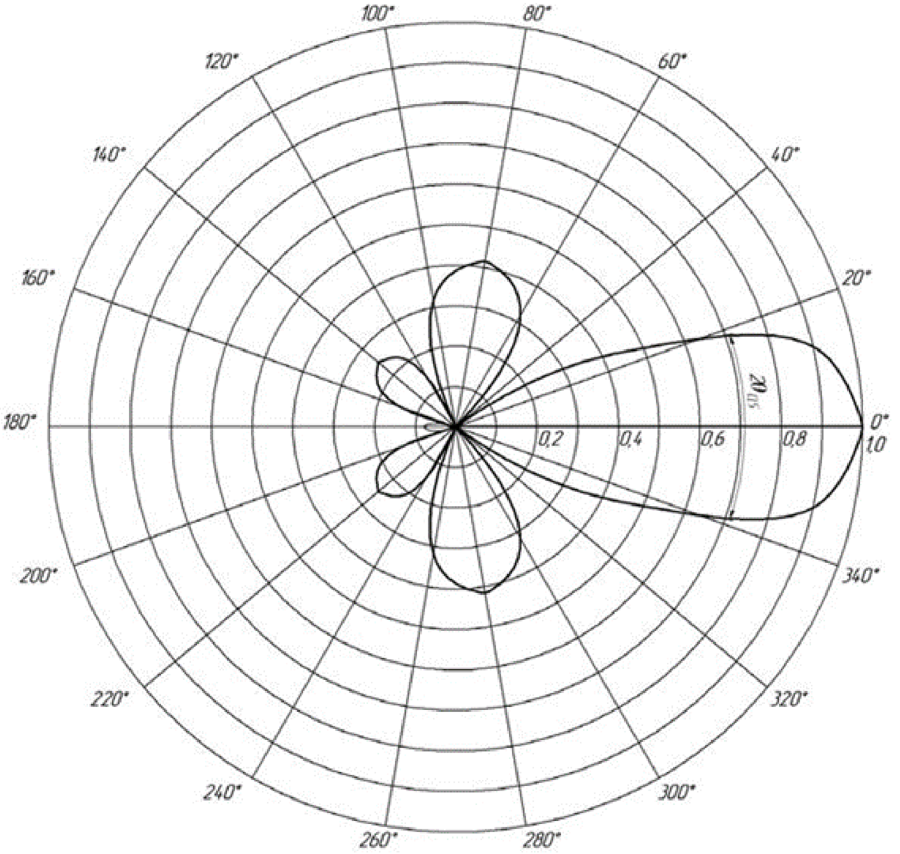

Figure 4. Directivity pattern of the pyramidal horn antenna in the polar coordinate system [18].

To detect and register electromagnetic waves in the microwave range, we used a semiconductor crystal point diode, which was placed in a high-frequency holder in the waveguide section of the detector (Figure 5). This section was connected to the microwave measuring circuit. The microwave diode is used to convert an amplitude-modulated microwave into electrical oscillations of low frequency. We observe and measure the low-frequency envelope of amplitude-modulated signals on the oscilloscope. It is part of the microwave signal frequency of demodulator used in devices measuring power, frequency and controlling signal waveform. The waveguide detector section with the amplitude microwave detector consists of an element providing connecting to the microwave path (a matching device), a diode, a low-pass filter (LPF) and an output to the woofer.

The microwave signal received by the horn antenna passes through the waveguide in the waveguide detector section.

The detector section is a waveguide segment 1 with a flange connecting the detector section to the horn pyramidal antenna.

The microwave diode is mounted in the waveguide section 1 of size of 23 • 10 mm (the cross-section perpendicular to the waveguide axis) parallel to the narrow wall of the waveguide along the electric field lines of the electromagnetic wave.

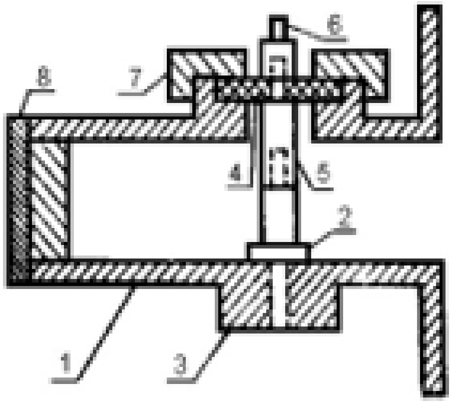

Figure 5. A waveguide microwave detector section, where 1 is a waveguide segment, 2 is a cathode of the microwave diode, 3 is a bronze bushing, 4 is a dielectric sleeve, 5 is a rod, 6 is an output terminal signal, 7 is a coupling nut, 8 is a piston [8]

The cathode of the diode 2 is connected directly to the wide wall of the waveguide. The bronze bushing 3 is coupled to the waveguide soldered to the wide wall of the waveguide. The anode of the diode is isolated from the waveguide dielectric sleeve 4 and through the composite rod 5 is connected to the output signal terminal 6. The dielectric sleeve, the rod and the diode are fixed with the coupling nut 7. The detector is adjusted by moving the piston 8 at a distance of the quarter-wave length from the diode to the piston, which serves as the rear wall, the diode is aligned with the maximum electric field, i.e. it is in the antinode (maximum) of the electromagnetic field, after which it is fixed.

The snow was poured into the rectangular container with dielectric walls placed in the space between transmitting and receiving horn pyramidal microwave antennas (Figures 6 and 7).

Figure 6. A photograph of the experimental setup for measuring microwave radiation without the container (the microwave generator connected to the transmitting horn antenna (light green color) and the receiving horn antenna (yellow))

Figure 7. An experimental setup for measuring transmitted microwave radiation in case of the maximum filling of the container with snow (the snow layer thickness between the openings of horn antennas is 53 cm)

To measure the dielectric permeability ε and the tangent of the angle of snow losses tgδ we used the waveguide method based on direct observation of reflected and transmitted waves (Figure 8), i.e. on the measurement of complex coefficient of reflection or passage of waveguide section where the snow is placed. In the first case the ε value can be determined by the difference between phases of the wave reflected by a short-circuited wave guide with the examined dielectric sample and the wave reflected by the same waveguide without a sample. The error in determination of ε and tg δ was about 10-15% [19].

From methodological and technical points of view it is more reasonable not to measure characteristics of the reflected wave but to monitor standing waves in the waveguide without snow formed as a result of interference of the total reflected - E1 and incident running + E1 waves.

The comparison of standing waves in the waveguide without snow and after its placing into the waveguide allows us to calculate snow parameters. The pattern of standing waves in the waveguide was studied in the waveguide measuring line P2-28.

Figure 8. An experimental setup for studying dielectric characteristics of snow using a waveguide instrument line. In the left part of the figure, you can see the microwave generator connected to the P1-28 measuring line by the flange connection, then follows the waveguide section with snow and the short-circuited waveguide load with variable phase NKP-7; the oscilloscope is connected to the detector section of the measuring line

The scheme of the setup for measuring electro-physical snow parameters using the waveguide method is shown in Figure 9.

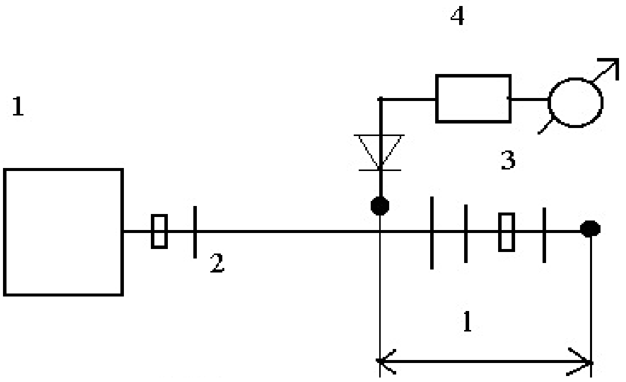

Figure 9. A scheme of the experimental setup for measuring dielectric permeability using snow waveguide method with a short-circuited line: 1 is a microwave generator, 2 is a measuring line, 3 is a part of the waveguide, 4 is a measuring amplifier, 1 is the distance from the probe to the short circuitor [14]

Measurements were made at a frequency of 10 GHz and a wavelength of 3.2 cm.

The perpendicular dimensions of the rectangular waveguide line were 10•23 mm. The radiation intensity was about 20-milliwatt, polarization was vertical. Before placing snow in the setup, the waveguide was cooled to a temperature of -2° C. The snow tightly adjoined the short-circuited end of the line.

The measurement process is shown in Figure 10.

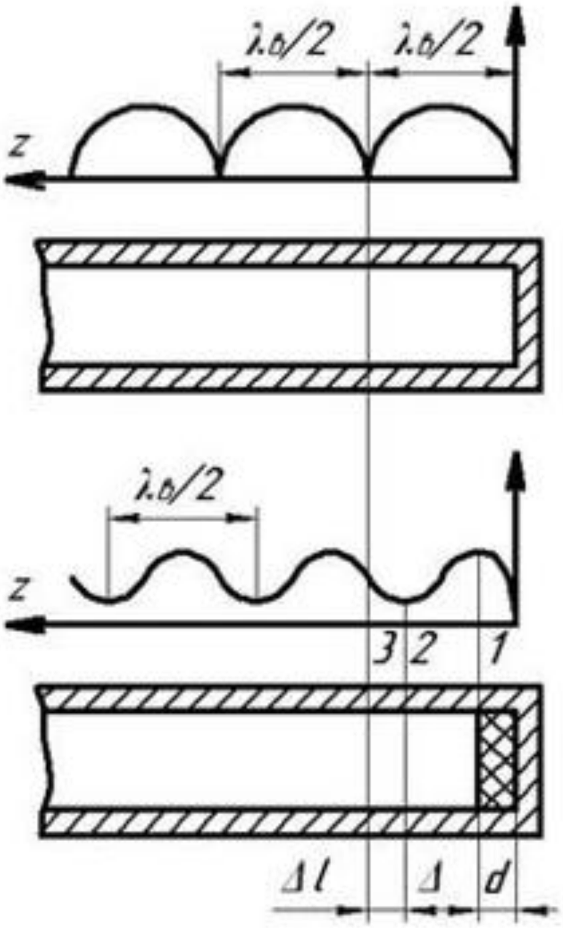

Figure 10. Interference patterns of the field in the waveguide without and with snow in the line [14]

The interference patterns show changes caused by the dielectric in the phase of the reflected wave (the minimum shifts) and in the amplitude of the reflected wave (the coefficient of the standing wave changes).

The dielectric permeability was calculated using the formula (1)

$$\varepsilon=\left(\frac{\lambda_0}{\lambda_в}\right)^2+\left(\frac{\lambda_0}{\lambda_{кр}}\right)^2 \qquad (1),$$

where $\lambda_{кр}=2a=2\cdot 23=46\,мм$.

To determine tgδ of the dielectric we used the following formula (2),

$$tg\delta = \frac{\alpha_{\partial} 2h}{\beta^{2}\varepsilon} = \frac{\alpha_{\partial}\lambda_{0}^{2}}{\pi\lambda_{в}\varepsilon} \qquad (2),$$

Where α_d is the attenuation due to dielectric losses, ε is dielectric permittivity, and $h = 2\pi / \lambda_{в}$ and $\beta = 2\pi / \lambda_{0}$

Findings/Discussion

The snow density was measured directly by weighing snow in the container, we obtained the mass of snow m=52 kg. The volume of the container was $V=0.17\ m^3$. The estimated snow density was d=306 kg/m3. We measured the temperature of the snow, which was -1 °C . The maximum thickness of snow was 53 cm. The transmitting and receiving antennas with their aperture sides adjoined the walls of the container from the opposite sides, and their geometrical axes coincided. Figure 11 shows the diagram of dependence of normalized signal amplitude on the thickness of the snow layer.

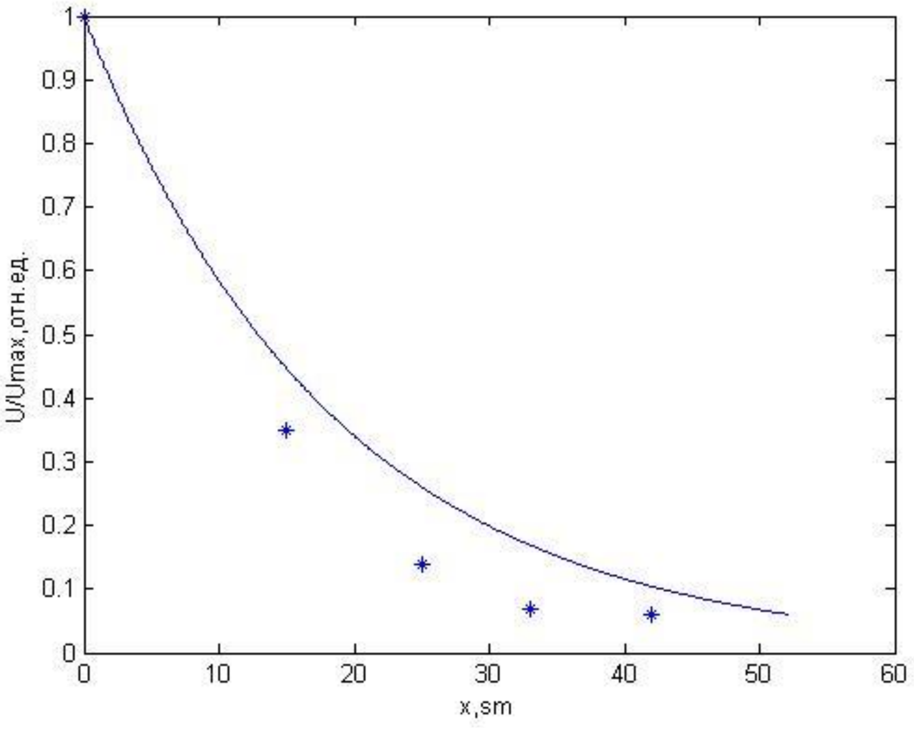

Figure11. Normalized amplitude of the microwave signal transmitted through the snow as a function of the thickness of the snow layer (* are experimental points, the curve was calculated using MatLab program)

The density of the flux of the microwave radiation I is proportional to the square of the electric field amplitude. To calculate the coefficient of snow absorption we used Bouguer's formula (3)

$$I_x = I_o \exp(-kx) \tag{3}$$

where I_o is the maximum intensity of microwave radiation measured in the empty container, Ix is the intensity of microwave radiation measured for the snow thickness x, k is the absorption coefficient of snow, x is the thickness of snow (I is proportional to the square of amplitude in units of voltage). To calculate k we took numerical values from the graph plotted using the experimental values. The calculations gave us the value of k=5.58. The calculations using the results of the waveguide method gave the following values of the snow parameters at a temperature of -1°C:

– Dielectric permeability $\varepsilon = 6.5$,

– tangent of the angle of losses $tg\delta = 1{,}4 \cdot 10^{-3}$.

Conclusions

The results of the experiments have shown the possibility of use of the microwave thickness indicator operating at a frequency of 10 GHz developed in our laboratory for snow measurements, and the microwave waveguide installation will enable us to measure dielectric properties of snow at the avalanche sites of ski resort Shymbulak.

Author contribustion

K.B. Kadyrakunov – concept,methodology
V.E. Nikulin – resources, data collection
A.K. Nurmagambetova – interpretation, editing
A.E. Aizhanova – modeling, data collecting
R.T. Nurgalieva – analysis, vizualization

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Исследование характеристик снега в микроволновом диапазоне для прогноза лавин

Аннотация. Сход со склона скопившейся снежной массы обычно провоцируется климатическими причинами: резкой сменой погоды (в том числе перепадами атмосферного давления, влажности воздуха), дождями, обильными снегопадами. Объём снега в лавине может доходить до нескольких миллионов кубических метров. Однако опасными для жизни могут быть даже лавины объёмом около 5 м^3. Для уменьшения и предотвращения указанных негативных факторов небходимо раннее прогнозирование и предупреждение возникновения лавин. Эта задача решается проведением постоянного мониторинга состояния снега и погоды на предполагаемом участке горных склонов.

Для этого в настоящее время используется множество различных методов и способов, основанных на разных физических и технических принципах. Одним из перспективных направлений является использование радиоволн сверхвысокочастотного (СВЧ) диапазона.

Работа посвящена исследованию возможности СВЧ методов для дистанционного измерения параметров снега.

Построены две экспериментальные установки для измерения различных параметров снега в микроволновом диапазоне радиоволн, предназначенные для прогнозирования лавин. Предсказатели лавин выбираются на основе физических соображений и методов математической статистики. Целью наших исследований является создание установки для исследования характеристик горного снега в лавиноопасных районах горнолыжного курорта Шимбулак. Рассмотрены основные параметры электрического снега, влияющие на процесс передачи, распространения и отражения радиоволн. В результате изменений дипольный момент увеличивается, что приводит к расширению разделительной полосы знакопеременного воздействия воды и перемещению в низкочастотную область. Результаты экспериментальных исследований затухания радиоволн в снегу использованы для расчета. Представлены коэффициенты поглощения микроволнового излучения снегом. Диэлектрическая проницаемость и тангенс угла снегозатрат измерены волноводным методом.

Ключевые слова: снег, лавина, распространение радиоволн, рупорная антенна, секция волноводного детектора, комплексная диэлектрическая проницаемость, электромагнитное излучение, поглощение радиоволн.

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Қар көшкінін болжау үшін микротолқынды диапазондағы қардың сипаттамаларын зерттеу

Аңдатпа. Жиналған қар массасының беткейінен түсу әдетте климаттық себептерден туындайды: ауа-райының күрт өзгеруі (соның ішінде атмосфералық қысымның өзгеруі, ауа ылғалдылығы), жаңбыр, мол қар. Қар көшкініндегі қардың көлемі бірнеше миллион текше метрге жетуі мүмкін. Алайда, тіпті 5 м3 көлеміндегі қар көшкіні де өмірге қауіп төндіруі ықтимал. Осы жағымсыз факторларды азайту және болдырмау үшін көшкіндердің пайда болуын алдын-ала болжау және алдын-алу қажет. Бұл міндет тау беткейлерінің болжамды учаскесінде қардың жай-күйі мен ауа-райының тұрақты мониторингін жүргізу арқылы шешіледі.Ол үшін қазіргі уақытта әртүрлі физикалық және техникалық принциптерге негізделген көптеген әртүрлі әдістер мен тәсілдер қолданылады. Перспективалы бағыттардың бірі ультра жоғары жиілікті (микротолқынды) диапазондағы радио толқындарын пайдалану болып табылады. Жұмыс қар параметрлерін қашықтықтан өлшеуге арналған микротолқынды әдістердің мүмкіндігін зерттеуге арналған. Қар көшкінін болжауға арналған радио толқындарының микротолқынды диапазонындағы әртүрлі қар параметрлерін өлшеу үшін екі эксперименттік қондырғы салынды. Қардағы микротолқынды сәулеленудің жұту коэффициентін есептеу үшін пайдаланылған қардағы радиотолқындардың әлсіреуін эксперименталды зерттеулердің нәтижелері ұсынылған. Диэлектрлік өтімділігі мен қар шығыны бұрышының тангенсі толқындау әдісімен өлшенген.

Түйін сөздер: қар, қар көшкіні, радио толқындарының таралуы, рупорлық антеннасы, толқындық детектор секциясы, кешенді диэлектрлік өтімділік, электромагниттік сәулелену, радиотолқындарды жұту.

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