Determination of Snow Cover Thickness using a Ground-penetrating Radar and a Laser Rangefinder

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Abstract. This article presents the results of processing the experimental data to determine the thickness of the snow cover in an area with a relatively flat terrain using a ground penetrating radar (GPR) and a laser rangefinder. It is shown that the GPR determines the thickness of the snow cover with an accuracy of 10-15 cm even in places under vegetation, however, in areas with sharp drops in the snow level, the error can be about 1 m due to the wide directional pattern of the antenna. The laser rangefinder is not suitable for measuring the thickness of the snow cover under vegetation, however, it detects local maxima and minima well, which can significantly supplement the GPR data in identifying critical zones. For surfaces that have a small area free from snow, it is possible to determine the thickness of the snow cover relative to this area with a laser rangefinder accuracy of ~ 1 cm, but it is necessary that this surface be free of vegetation. This criterion is met, for example, the roof surfaces of large structures, such as water parks. In the case of using only a GPR, sharp drops in snow level are averaged and inaccuracies in measurements at local sites are possible. When using both instruments, it is possible to determine the snow cover with an accuracy of ~ 10-15 cm on surfaces with vegetation and ~ 1 cm without vegetation, which is the basis for the joint use of instruments. This work is a continuation of a series of experiments started last year.

1. Introduction
Measuring the thickness of snow cover over large areas using a non-contact remote method is still considered an urgent task due to a number of factors, namely: preventing roof collapse in supermarkets and water parks, determining the degree of danger of spring floods, predicting crop yields, to prevent the danger of avalanches in mountainous areas, to establish the meteorological laws of the formation of climate in a certain area.

A method for measuring the thickness of snow on optical waves is known, for example [1], but it requires scanning the Earth's surface both in summer and winter in the presence of reference points; moreover, it is necessary that changes on the Earth's surface during the off-season period between scans was as small as possible.

The method for measuring the thickness of snow on optical and radio waves is also known [2], however, the characteristics and any experimental results on its implementation are not given, and the frequency ranges of sounding are indicated rather approximately. This method is attractive due to its
efficiency, because in a short period of time of the order of ten minutes it is possible to obtain data on the thickness of snow over a sufficiently large area [3-6].

The dielectric permittivity of snow in the radio range can vary widely depending on its looseness and humidity: from ~ 1.2 in dry frosty weather for freshly fallen snow to ~ 5 in wet weather for heavy snow [7-10]. When the dielectric constant approaches to 1, the reflection coefficient at the air-snow boundary tends to zero, making it difficult to obtain accurate data using a GPR. Due to this, to clarify the position of the upper edge of the snow, along with a GPR operating in the radio range, which has a consistently high reflection coefficient from the Earth’s surface and an unstable reflection coefficient from the snow surface, it is proposed to use a laser rangefinder, the light carrier of which has a reflection coefficient from snow of more than ~ 0.7 [11].

The aim of the work is to obtain operational data on the thickness of the snow cover using a GPR and a laser rangefinder on an area of about 100 x 100 m, to identify shortcomings in the technique used, as well as to formulate recommendations for the application of the technique for a specific application. The described experiment is a continuation of a series of experiments started last year [6].

2. Polygon and Equipment used in experiment

For the experiment, a polygon was chosen between the two outbuilding with a variable snow height from 0 to ~ 1000 mm and with a fairly flat surface of the terrain (Fig. 1). The measurement track passed over two rose hips that grow on this site. Through the center of the landfill there is a path to the building, on which there is no snow, and along its edges you can see large drifts resulting from clearing snow.

![Figure 1. Appearance of the polygon (site for experiments).](image)

The general view of the radio-optical meter is shown in Fig. 2. A working model of the GPR “Gerad 2200” was used as a radar sounding device [12]. The ultra-wideband GPR signal consists of one oscillation period (the distance between the minima is 0.5 ns), the pulse duration is about 1 ns. The working frequency band is in the region from 1.5 to 2.5 GHz, the spectrum width is Δf = 1 GHz. Power consumption less than 150mW, output power -45dBm/MHz. The GPR consists of an electronics unit, an amplifier of the transmitted signal, transmitting and receiving antennas, a system for collecting and displaying radar data based on a tablet PC. In addition, the complex includes a laser rangefinder, consisting of a laser-optical unit, an electronics and data recording unit, and an autonomous power supply. The characteristics of the laser rangefinder are as follows: distance measurement accuracy ~ 1-
10 mm, operating range up to ~ 100 m, wavelength range ~ 700 nm (red spectral region), light radiation power ~ 15 mW, power consumption ~ 15 W.

**Figure 2.** The general view of the radio-optical meter

3. **Description of experiments and Analysis of the results**

The measurements were made by moving the radio-optical meter along a cable stretched at the level of the third floor of the building. The trajectory of the device in height had a parabolic appearance, because the cable sagged under the influence of the weight of the device. The measurements were carried out from a height of ~ 7-10 m above the ground surface with a time interval of 0.5 seconds. Due to the complexity and laboriousness of the experiment at negative temperatures, measurements were carried out along one path only, but this was quite enough to determine the accuracy of measurements, identify the shortcomings of the method used, and develop some recommendations for its implementation. The measurement results are shown in Fig. 3. Control measurements at the most characteristic points of the landfill, carried out with a measuring ruler, confirmed the reliability of the results obtained.

In this experiment, the surface relief changed slightly (by no more than 20 cm), so the results of measuring the snow thickness with a laser rangefinder are reduced to an average constant level. The measurement of snow thickness using GPR was determined by the time delay between the first reflected pulse (from the upper edge of the snow) and the second pulse (from the ground surface) divided by the speed of propagation of the radio signal inside the snow cover. The estimate of the propagation velocity is obtained by comparing it with measurements with a measuring ruler. In this case, the discrepancies between the measurements of the ground-penetrating radar and the laser rangefinder caused by the terrain can be ignored, however, in the case of a more rugged surface, it may be necessary to adjust the measurements of the laser rangefinder taking into account the relief measured by the ground-penetrating radar.

Thus, we can offer two variants of the algorithm for processing the received data:

1) In the case of a perfectly flat underlying surface, such as paved areas or roofs of buildings and structures, only laser rangefinder data is used to determine the thickness of snow. In this case, the GPR data can be used, firstly, to establish the position of the zero level, and secondly, to determine the
structure of snow and measure its dielectric permittivity, which will allow us to estimate its density and moisture saturation.

2) In the case of a rugged terrain, the time of propagation of the radio signal to the upper border of the snow $t_s$ and to the ground surface $t_g$ is first determined, then the thickness of the snow cover is estimated using the formula $D_{GPR} = (t_g - t_s)c_s$, where $c_s$ is the speed of propagation of radio waves inside the snow, which can be taken either from known tabular values [8-10], or obtained by calibration measurements on areas with a known snow thickness. Then the snow thickness is specified according to the data of the laser rangefinder $\Delta D_{LR} = (t_g - t_{LR} - D_{GPR}/c_s)c$, where $t_{LR}$ is the time of propagation of the laser rangefinder signal to the upper border of the snow.

In the described experiment, two independent software tools were used to collect data from a ground radar and a laser rangefinder, which led to certain difficulties in the joint processing of these data. In the future, it is planned to aggregate data within a single collection program.

In the future, it is planned to install the developed complex on an unmanned aerial vehicle (UAV) with a carrying capacity of 1 - 2 kg. As this experiment has shown, the UAV's flight altitude should be about 10 m. It is possible to increase the altitude of the aircraft up to 100 m, but this will require significant revision of the GPR: increasing its power and complicating the design of the antenna system in order to increase the maximum sensing range and increase the spatial resolution. For an aircraft, the development of a positioning system, for this, one of the existing GPS systems can be used with an accuracy of determining the height of 1 - 5 cm.

In this experiment, the error in determining the position of the complex was caused by the sagging of the cable under the influence of the weight of the equipment and was eliminated using theoretical calculations. The error in determining the height is estimated from 1 cm at the beginning and end of the route up to 5 cm in the middle.

Some discrepancies in the measurement results are caused by the characteristics of the instruments used. The spatial resolution of the device is determined by several factors: the speed of its movement along the route, swinging of the device from wind and mechanical loads, directional patterns, geometry features, and in our case it was ~ 0.1 m for laser measurements and ~ 1 m for GPR data. The accuracy of measuring the distance by the rangefinder for these conditions was ~ 10 mm, and the GPR - tens of centimetres, therefore the local peaks measured by the rangefinder are more accurate and have greater significance, while the GPR averaged the heights in areas with sharp differences in range. This is most clearly seen near the central path to the building, Fig. 1 and Fig. 3, where relatively high snowdrifts with sharp changes in height were interspersed with an almost zero level on the path itself.

The terrain relief measured by GPR (ground level) was more homogeneous. It can be seen that the discrepancy between the results on the thickness of the snow, obtained using the GPR and the rangefinder, is significant in areas with vegetation (under a rose hip bush). This is because the size of the laser spot ~ 0.5-1 cm did not allow to accurately measure the height of the snow with a range finder under the rose hips. The laser spot hit the bush branches, the reflection height at these points is chaotic and this can be seen both on the right and left of the central track sections of the route, Fig. 3, where the height of the laser radiation reflection changes randomly depending on the impact on the bushes branches rose hips. At the same time, the height of snow in these areas, measured by GPR, coincides with the readings of the measuring ruler with an accuracy of ~ 15 cm.

The discrepancy between the snow cover thickness along the route in local places, measured by the GPR, with the rangefinder data can be about 0.5 m, and this is the main argument in favor of supplementing the GPR data with the data of the rangefinder measurements. Despite the indicated discrepancies, the characteristic features of the snow cover on the measurement route were identified. For example, it was determined that the snow height is significantly higher on the north side of the building (left side of Fig. 3) than on the south side (right side of Fig. 3), where the snow thickness tends to zero. This fact, naturally, correlates with the time of solar irradiation of the snow cover in both areas of the test site.
Figure 3. Change in the thickness of the snow cover along the measurement route: blue curve according to GPR data, yellow - laser rangefinder, red points - control measurements with a measuring ruler.

4. Conclusions

Thus, the following conclusions can be drawn.

1. GPR determines the height of the snow cover with an accuracy of ~ 10-15 cm at the selected polygon, even in areas with vegetation. The only exceptions are small areas with high snowfalls, where peaks and valleys are smoothed (averaged) due to the wide antenna pattern. In addition, GPR determines the terrain under the snow. This allows us to more accurately take into account the thickness of the snow in the studied profile.

2. The laser rangefinder in the used version with a narrow radiation pattern is completely unsuitable for measuring the height of the snow cover under the branches of vegetation, but it accurately determines the local maxima and minima, which can significantly supplement the GPR data in identifying the critical zones of the surveyed landfill.

3. For flat areas of surfaces with a small flat area free of snow, determining the ground level, it is possible to determine the snow level with the accuracy of a laser rangefinder. It is sufficient that the surveyed area is free of vegetation. This criterion is met, for example, on the roof surfaces of large structures, such as water parks. In this case, GPR data can be used to determine the structure of snow and estimate its density.

4. When using both devices, it is possible to determine the snow cover with an accuracy of a laser rangefinder of ~ 1 cm in areas without vegetation and with an accuracy of 10-15 cm in areas with vegetation, in addition, data aggregation makes it possible to mutually complement information, which is the basis for their joint practical application.

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