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TOWARDS ICE THICKNESS MEASUREMENT WITH GROUND PENETRATING RADAR

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ABSTRACT

This document considers the research of developing Ground Penetrating Radar (GPR) based ice thickness measurement that can be used, for example, in inspecting ice thickness of ice cover in snowmobile track or for ice breakers. As a result we present some crucial prerequisites of the measuring system which is based on the use of single GPR antenna.

We used two different radars in our studies GSSI SIR 10 and SIR 20 with 1 GHz horn antenna which were installed in a snowmobile. We tested driving tracks on fresh water lake ice and on sea ice on a slight saline. The measured GPR data was analyzed in association with the holes bored to the ice. The ice thickness profile can be obtained from GPR measuring by using the physical relationship between the penetration speed of the signal in the medium and the permittivity of it. Dielectric constant of a medium represents the permittivity, and it can be determined from measured GPR signal together with the thickness that is measured manually from holes. Alternatively, dielectric value can be determined also by reference measuring on a metal plate in which the reflected surface pulse amplitude of the medium is compared to the one reflected from the metal plate. This method is widely used in GPR based road inspections.

Our case studies proved that the thickness profile can be determined quite accurately from GPR survey data by detecting the travelling time of the transmitted pulse through the ice layer. In order to obtain this accuracy the snow-ice conditions have to be dry. The wide variation of permittivity of snowpack structure does not affect the travelling time of the signal in ice layer and, hence, the accuracy of the method. However, it actually eliminates the possibility to follow changes in permittivity of ice by following the amplitude of the ice surface reflections. This amplitude based technique is also widely used in remote sensing of road structures. Slush and "sandwich" structures inside the ice may cause serious obstacles for the method.

INTRODUCTION

Northern lake and sea areas are covered by ice for a quite long period of the year. These areas have both recreational and professional usage over this period of time. The former consists of activities like ice fishing, skiing, skating, camping, trekking and snowmobiling, whereas in the latter case ice cover can be used, for example, as roads to improve efficiency on logistics. On the other hand, in sea areas ice cover is often opened by ice breakers to enable ship access to harbors on winter times.

Both forms of ice usage rely on the safety of ice and the main issue for safety is the thickness of ice. For this some remote sensing techniques like ground penetrating radar (GPR) are used in large areas to measure the thickness in an effective, non-destructive way. GPR transmits electromagnetic (EM) pulses on the ice that may be covered by snowpack. The radar records the reflections from the different layers of snow, ice and water. The bigger the difference of dielectric properties between two layers is the stronger the reflection is. Furthermore, the homogeneity of the layer medium creates an advantage as it enables better interpretations of the reflections. The relative permittivity of snow is around two, for fresh water ice it varies between three and four, for sea ice between four and eight, and for fresh water it is around 80. Therefore these mediums are, in principle, well suited for GPR surveys. However, the salinity of the sea ice can prevent GPR measurement. Greater increase of conductivity of the medium will prevent the propagation of EM pulse and it will not reach the bottom of ice. Similarly, the migration of water on the surface of ice or inside the ice layer can prevent the interpretation of reflected signals.

The aim of our case studies described in this document was to test GPR based method for ice thickness detection in different snow covered ice structures and varying salinity of ice. An ulterior motive for this work is to find out whether this method has potential commercial use, for example, in ice breaker development. We performed our measurements on a fresh water lake Norvajärvi, Ala-Mellalampi nearby Rovaniemi city and on Bay of Bothnia. The first measurement was done in 2008 and following cases were measured during January and February in 2013. The measurement system that we used in Norvajärvi was GSSI SIR 10 with air coupled 1 GHz horn antenna installed on sled (Figure 1. (a)) and in latter cases we used GSSI SIR 20 with air coupled 1GHz horn antenna installed on Lynx Ranger 69 Alpine snowmobile (Figure 1. (b)).

Figure 1. (a) GPR system used in Norvajärvi 2008 (b) GPR system used in Ala-Mellalampi 2013.

Third measurement was done Feb 2013 at Bothnia Bay near Kemi city. In this case water was slightly saline and the ice on it had roughly the salinity of zero. (Granskog & Ehn,2004).

Measurement configurations

In Norvajärvi 2007 we used GSSI SIR 10 with 1 GHz air coupled horn antenna. The track was 30 meters long and the snow was cleaned off. The track was measured several times for reliability analysis.

In Ala-Mellalampi 2013 we used GSSI SIR 20 with 1 GHz air coupled horn antenna. The measuring tracks were over 500 m long and survey wheel was used to synchronize data. One track has soft fresh snow on the ice and the other track was on a hard packed snowmobile route. The latter measurement was done twice for reliability analysis. In order to ensure results of survey measurement we performed also additional point wise measurement in which the snow was cleaned off from the ice surface. Both tracks included different kind of circumstances of snow and ice layers, which was very valuable in analysis.

In Bothnia Bay 2013 the SIR 20 was used with the same configuration as in Ala-Mellalampi. The measurements followed the same procedure as in Ala-Mellalampi.

Theoretical background

The velocity of an electromagnetic (EM) wave in a medium depends on its permittivity ε_r as follows

$$v = \frac{c}{\sqrt{\varepsilon_r}},$$

where *c* is the speed of light in vacuum. The thickness h of a layer in medium can be measured from GPR signal by the following formula

$$h = \frac{c}{2\sqrt{\varepsilon_r}}\Delta t \qquad (1)$$

where Δt is the double way travel time of EM pulse through the layer.

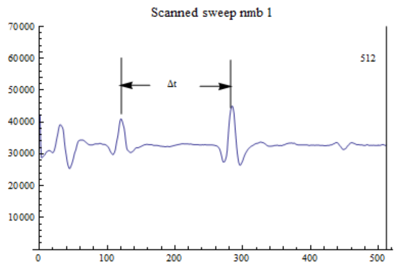


Figure 2. The GPR signal

The principle of GPR based ice thickness measurement is to detect the double way travel time Δt from GPR signal (Figure 2.). In addition, it is essential to know the dielectric value ε_r of the measured ice precisely enough.

The dielectric value can be verified, for example, manually by using the thickness of the ice which can be measured from reference holes in the ice. Alternatively, it can be verified by using metal plate calibration. According to the electromagnetic (EM) wave theory the amplitude of a pulse that is reflected from an interface of two mediums relates to the difference in permittivity of the mediums. When the incidental signal comes from air to a medium, the dielectric value (ε_1) of top layer can be determined by a reference measuring. The surface pulse amplitude that is reflected from the medium is compared to the one reflected from a metal plate as follows:

$$\varepsilon_1 = \left(\frac{1+A_1/A_m}{1-A_1/A_m}\right)^2, \qquad (2)$$

where A_m and A_1 are amplitudes of metal pulse and surface pulse respectively. This calibration method is widely used, for instance, in GPR based asphalt and concrete pavement quality inspection (Saarenketo & Scullion, 1995, Loizos and Plati, 2006). The detailed theoretical facts of this method can be found, for example, in Loulizi thesis (Loulizi, 2001).

CASE STUDIES IN GPR BASED ICE THICKNESS DETECTING

Lake Norvajärvi study

The first case study was a 30 meters long track on lake Norvajärvi where the snowpack was cleaned off. The GPR survey was done 10 times on the track and the radar used was GSSI SIR 10. Although the variation of the ice thickness was minimal the results show that the thickness profile detected from GPR data correlates well with the one measured from the holes that were made in every 2 meters distance (Figure 3.). Figure 3. Further shows that the repeatability of the radar on the track was good. Similar result of the repeatability of GPR was achieved on asphalt pavement in the earlier project Mara in Rovaniemi University of Applied Sciences (Karjalainen & Kämäräinen, 2008).

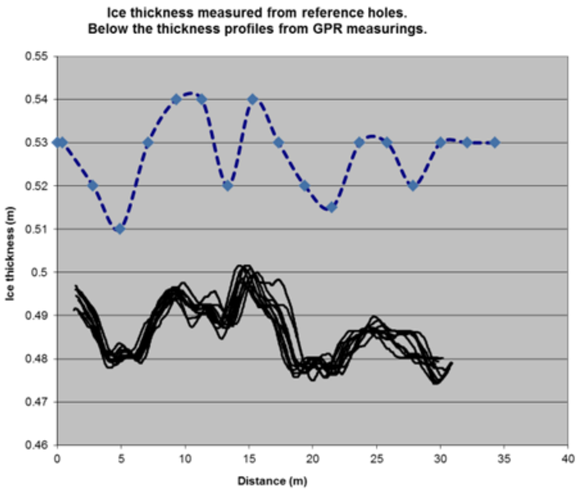


Figure 3. Ice thickness measurements in lake Norvajärvi 2008.

Lake Ala-Mellalampi study

The second study was carried out on lake Ala-Mellalampi with a newer radar version GSSI SIR 20 and with a snowpack on the ice. The test tracks turned out to be interesting, since they included very different kinds of snowpack and ice structures. We got measurement data from several surfaces: ice covered by fresh dry snowpack, hard packed snow, or slush, and also from ice-water-ice sandwich layers. Our data supports earlier research (Lalumiere, 2006) and we can conclude that with dry ice and snow condition the structure profile can be interpreted from GPR data very clearly (Figure 4.). Also the ice thickness profile can be detected from GPR data with high accuracy provided that the data is calibrated with a manually measured reference thickness (Figure 5.). When there is water (or slush) on the ice surface or water layer in the ice, the analysis gets more complicated which will be showed later in this document.

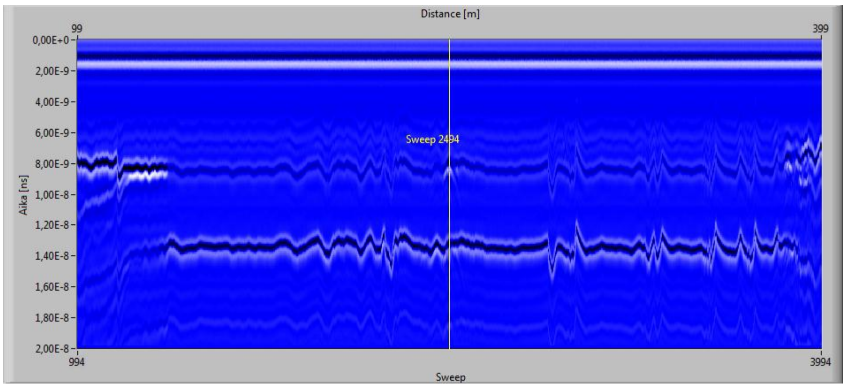


Figure 4. Structure profile of lake Ala-Mellalampi 2013.

The detection of the reflection pulses from the signal is a crucial problem in determining ice thickness profiles dynamically from GPR data. When the snowpack on the ice is dry, we were able to use a simple “following the peak” based algorithm with high accuracy. However, wet slush on the ice and "sandwich" structures, i.e ice-water-ice, caused serious obstacles for our detecting algorithms.

Figure 5. displays the result of ice thickness GPR survey on a new unpacked snow done on lake Ala-Mellalampi. In Figure 5. (a) the positions of detected reflection pulses from ice and water surfaces are plotted against the distance in meters. Parts of the survey that included slush were removed. Figure 5. (b) presents the thickness profile produced from the time difference data Figure 5. (a). The dielectric value of 3.37 was used in formula (1) as ice permittivity, since it was the average results from the calibrations with reference holes. The error margin ± 0.09 with 95% confidence level of the dielectric values in manual calibration corresponds to an error less than 1.0 cm in ice thickness given that the permittivity of ice is somewhat constant.

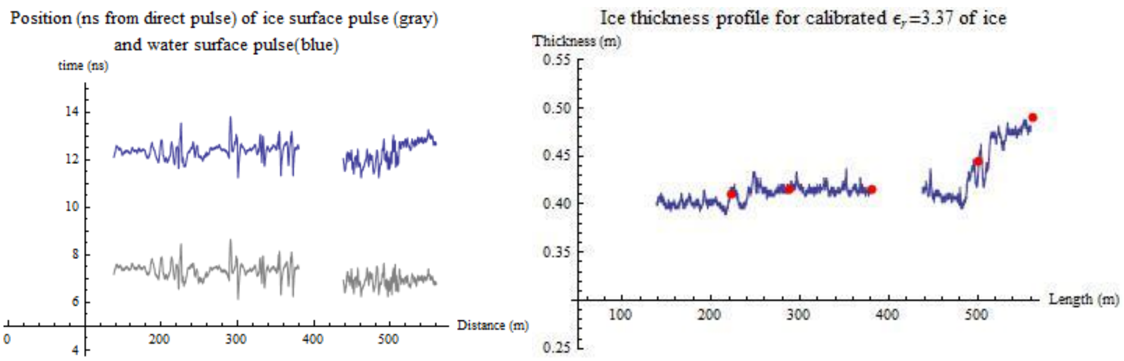


Figure 5. (a) Time difference profiles (b) Ice thickness profile with holes

We tested the reliability of measuring ice thickness profile also by repeating a GPR survey on a hard packed snowmobile trail. In this case the trail was measured twice in opposite directions and comparison was done by displaying the other survey in the reverse order. The data including wet slush was removed as in earlier experiments. Figure 6. displays the indexed positions of detected pulses against the measured distance from the marker for both surveys in the same diagram. The consistency of the red and blue lines shows that the detecting algorithm produces repeatable data.

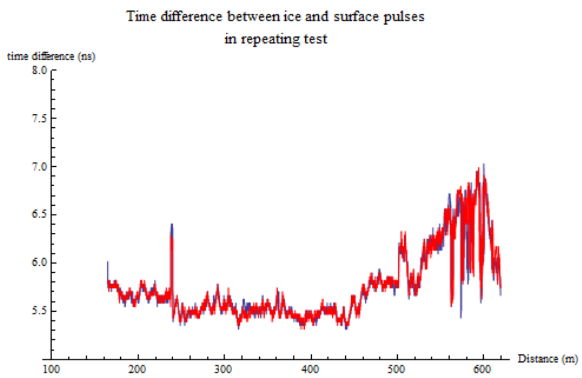


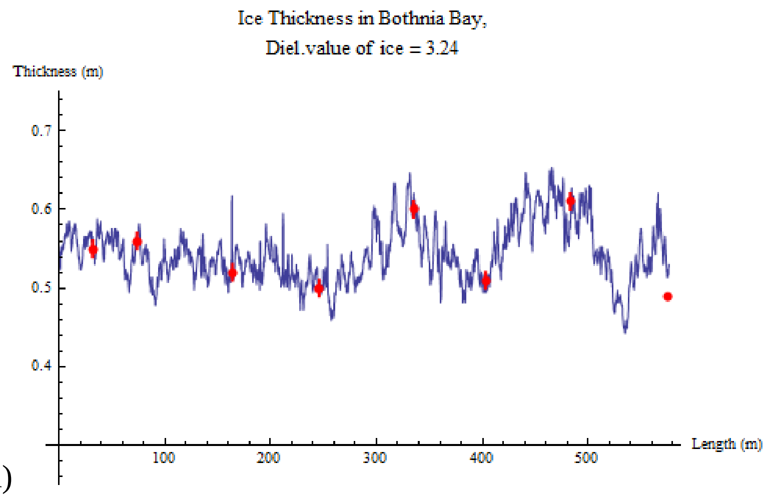
Figure 6. Repeating test of used detecting algorithm

Metal plate calibration

Due to geometric attenuation the detected EM energy of responded GPR signal decreases when the height of antenna from the surface increases. Therefore, the use of equation (2) in

metal plate calibration requires that the distance of the metal plate from the radar antenna must equal to the one of the surface.
To verify the dielectric value of ice by using both manually bored ice holes and metal plate calibration we use only GPR data that was associated with dry snow-ice conditions. At each position of the holes the mean of 5 travel times through the ice layer in consecutive pulses was used in calibration. The sample of five pulses corresponds a distance of 0.5 meter in the survey. The mean travel times together with the measured thicknesses were applied to formula (1), and as a result the dielectric value for ice $\varepsilon_{ice} = 3.37 \pm 0.09$ (95% confidence level) was achieved. With metal plate when the height of antenna was 50 cm the dielectric value for ice $\varepsilon_{iceMet} = 3.33$. If we assume the dielectric value of ice to be constant 3.37, the error margin ± 0.09 in dielectric value corresponds to an error less than 1.0 cm in ice thickness in this survey.
It is highly recommended to use manufacturers advised height of the antenna in metal plate calibration. This was proven to be true as we tested several heights of antenna in metal plate measurements. When the height antenna differs from the recommended height 0.46 – 0.51 m, the difference between the calculated dielectric value and the manually calibrated one increased.

Bothnian Bay study
The third study was carried out on Bothnia Bay near Kemi city with radar version GSSI SIR 20. The study contributes to the results of lake Ala-Mellalampi study in spite of the slight saline (Figure 7.). As a matter of fact the sea ice on Bothnia Bay near cost does not include salt (Granskog & Ehn,2004), which was also found in our measurements. The dielectric value of sea ice $\varepsilon_{ice} = 3.24 \pm 0.16$ (95% confidence level) is a typical value for fresh water ice. This result was obtained by a similar method as in the second case study. The metal calibration method yielded a dielectric value of $\varepsilon_{iceMet} = 3.14$ to the ice. The small end part of the survey that contained slush was removed due the poor reliability of this part. In this survey the error margin ± 0.16 in dielectric value corresponds to an error ca. 1.3 cm in ice thickness, if we assume that dielectric value does not alternate during the survey.



(a)

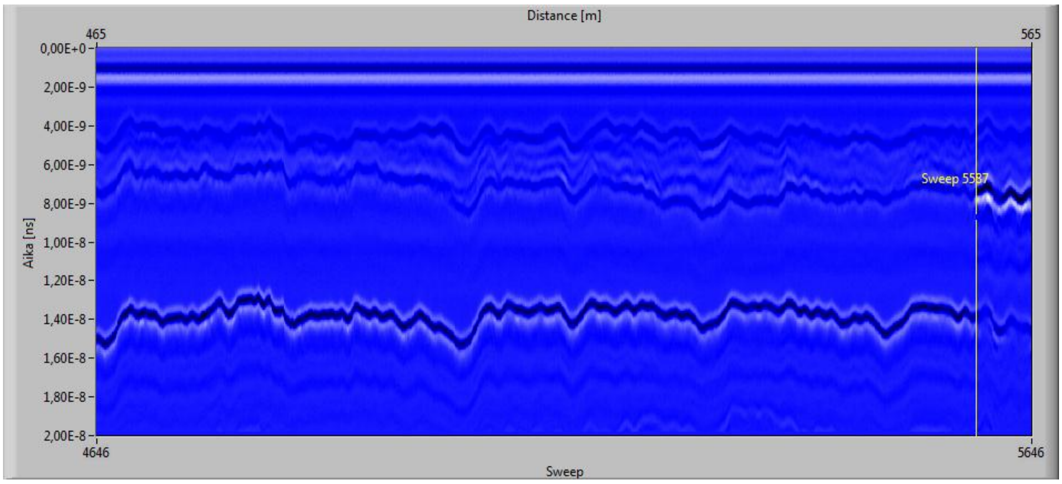
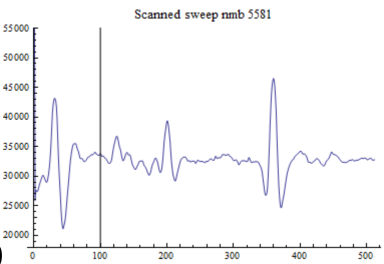
(b)


Figure 7. (a) Ice thickness profile (b) and end part of the structure profile on Bothnia Bay

CONCLUSION

Our case studies contribute the use of GPR in ice thickness measurement when the snowpack does not include slush or the ice does not have water layers inside it. Several reported papers (Gusmeroli & Grosse, 2012) show results that support our observations. Furthermore, we showed that in dry condition and without inner water layers, the ice thickness can be detected accurately by a simple “following the peak” type algorithm.

We identified two different conditions, where detecting algorithm did not succeed to produce appropriate travelling times for ice thickness calculation. The first was slush-on-ice and the second was ice-water-ice sandwich. The form of responded signal in the former condition of slush-on-ice does not obey any regular shape. When the slush appears, the respond pulse from the first wet surface starts to grow strongly. At the same time all the latter surface reflections become weaker and move toward the end of signal. This is caused by weakened propagated energy and increased travelling time through the first snow layer. However, in some cases of slush we can interpret the signal given that the ice surface pulse can be detected as a pulse which is polarized at negative. In these cases the pulse can be overlapped with the first wet surface pulse, when the slush layer is thin, or be a separate pulse with thicker slush layer. This can be seen in cases (2) – (4) of Figure 8 that displays the respond signals in positions (1) 558.1 m, (2) 558.9 m, (3) 565.0 m, and (4) 567.5 m of the survey on Bothnia Bay. In all measurements we found that the strong water surface pulse will remain detectable. We can link our results with surface conditions as follows: (1) dry snowpack, (2) slush appears, right side of pulse most probably an overlapping ice surface pulse, (3) ice surface pulse at position 222 polarized at negative, and same with case (4) at position 226.

(1)


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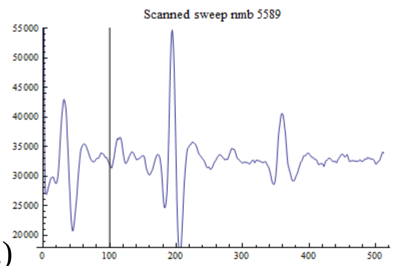

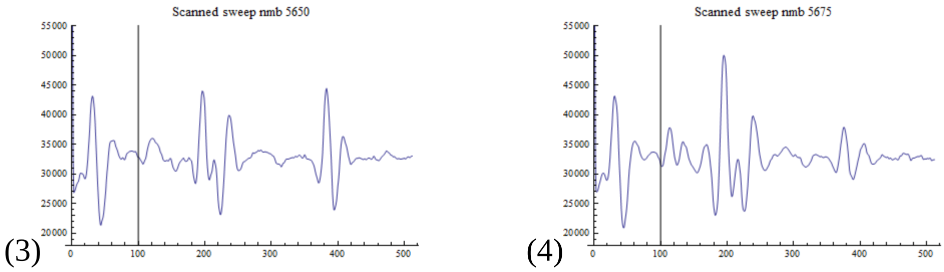

Figure 8. Respond signals for (1) dry snowpack, (2), (3) and (4) for slush covered ice

The responded signal of the ice-water-ice sandwich structure was also interpretable under certain conditions. Given that the surface of ice is dry, the form of the signal includes four clearly detectable pulses: surfaces of the top ice layer, inner water layer, surfaces of sub ice layer, and surface of water layer. Figure 9. displays one example of the responded signal in sandwich case which was also analyzed by a reference hole. The length of the signal is 20 ns and the time difference between consequent indexes is 20/512 ns.

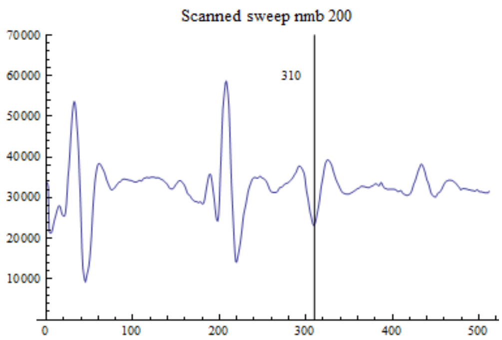

Figure 9. Ice-water-ice sandwich signal response.

The four detected pulses are placed in positions 190, 208, 309, and 434 respectively. The pulse 309 polarized at negative, since it is reflection from interface water-to-ice, i.e. from higher to lower permittivity. Distances between the pulses are 0.07 ns, 3.9 ns, and 4.9 ns which correspond thicknesses around 6 cm, 7 cm, and 40 cm, when $\varepsilon_{r(ice)} = 3.37$ and $\varepsilon_{r(water)} = 80$. These thicknesses were also observed from the bored hole.

DISCUSSION

If the salinity, i.e. conductivity, of ice has variation during the survey, the permittivity of ice may vary too. In this case we should be able to detect also the amplitudes of reflected pulses that can indicate changes in permittivity.

To verify the changes in dielectric value of ice we must, first of all, calibrate the measurements to correspond the same height of antenna to eliminate geometric attenuation. This height calibration is common procedure in GPR measuring in road surveys and it can be done by determining the dependence between height and pulse amplitude.

Moreover, formula (2) can be used in GPR survey to determine the dielectric values of first surface layer. In general, the ice is covered by a snowpack and formula (2) is not usable. In GPR based road surveys we found formulas which yield the dielectric value also for the base layer beneath the top layer. One of these, Loizos and Plati (Loizos & Plati , 2006), presents the following formula

$$\varepsilon_2 = \varepsilon_1 \left(\frac{1-(A_1/A_m)^2+(A_2/A_m)}{1-(A_1/A_m)+(A_2/A_m)}\right)^2, \qquad (3)$$

where A_{m}, A_1 and A_2 are the reflected pulse amplitudes from metal plate, surface of top layer and surface of base (second) layer respectively, and ε_1 is the dielectric value of the top layer. Formula (3) presupposes that the top layer is rather homogeneous and that no attenuation of the GPR signal occurs in the top layer. Although formula (3) is found to work well with asphalt pavements by Loizos and Plati, it was proven to be unworkable in our measurements due to the electrically inhomogeneous snowpack layer.

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