CREVASSE DETECTION IN ALPINE AREAS USING GROUND PENETRATING RADAR AS A COMPONENT FOR A MOUNTAIN GUIDE SYSTEM

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ABSTRACT:

Snow covered crevasses are of great danger for mountain tourists, especially if the snow cover is rather thin in late spring or early winter. This was the motivation to investigate methods and techniques for crevasse detection with the future aim to establish a „secure navigation system" for mountain tourists. Ground penetrating radar (GPR) is a promising tool for the detection of snow covered crevasses, since the transition from snow to ice can easily be detected due to the change of several material parameters, like density, water content and most important the dielectricity. The feasibility and reliability of GPR crevasse detection was investigated by a field study. During the summer season a number of open crevasses were surveyed by differential GPS. In late winter a thick snow cover obscured these "test crevasses" and provided a secure crossing. The surveyed crevasses were marked on the snow surface and afterwards crossed by GPR in different directions. A regular profiling was carried out, as well as crossings in different traversing angles. After the usual processing steps to synchronize and enhance the reflected signals, the anomalies in case of an occurring crevasse can be seen clearly:
- the reflection horizon from the snow/ice boundary is non continuous
- internal snow layers above a detected crevasse show curvatures towards the crevasse
- diffraction from the walls of the crevasse appear as hyperbolas
The results from the combined application of GPR and GPS suggest that a system for safe glacier travel on alpine glaciers could be developed, based on clear crevasse detection combined with high accuracy positioning. So called "safe tracks" are monitored using a GPR system and differential GPS for reliable profile localization. The safe tracks are surveyed by GPS and the coordinates are made available to mountain tourists via download from the internet. These tracks can be utilized in the tourist´s GPS navigator in order to guide them on safe tracks.

1. INTRODUCTION

Mountain tourists, as well as mountain guides and rescue services are facing the danger of falling into glacier crevasses if they are covered by thin snow layers. Encouraged by the successful use of Ground Penetrating Radar (GPR) for crevasse detection in the Antarctic (Delaney et al. 2004, Nath & Vaughan, 2003) on a cold, dry snow pack, this method was tested on an alpine glacier with temperate conditions and a certain water content in the snow layer. Basically, a combination of high precision GPS and regular GPS profiling along frequently travelled routes, should provide the required crevasse location information, readily implemented into existing navigation systems. In a test area several crevasses were surveyed during the summer season and later on have been detected successfully by GPR while covered with snow. The emphasis of the investigations at this stage was to develop a simple and fast technique for clear crevasse detection and quantification. Based on these results an alpine navigation system is suggested, which should be able to guide tourists and professionals on safe tracks.

2. BASIC PRINCIPLE OF GPR

Basically a GPR system operates in a way where electromagnetic waves are sent from an emitter and received by a receiver. The antenna configuration basically determines the final frequency spectrum of the emission which can be more or less directional. The permeability and also the transmission velocity of a material for electromagnetic waves depends besides other parameters, on the dielectricity. Abrupt changes in wave velocity, e.g. at material boundaries, lead to a partial reflection of the signal. The run-time and the amplitude of these reflected signals is recorded continuously within a given time interval for each pulse emission.

Since the run-time is dependent on the penetrated material, it is obvious that different velocities within different materials allow for the detection of the layer thickness of these materials (Neal 2004). In case of using GPR for crevasse detection the transition between snow and ice, as well as between snow and air has to be discovered.

2.1 GPR in Snow and Ice

The penetration depth as well as the spatial resolution of a GPR system is strongly influenced by the losses of the signal due to energy absorption in the penetrated material. Therefore it is

necessary to determine the attenuation for dominant materials in glaciological GPR applications. Table 1 gives an overview for the attenuation of some materials using 100MHz and 1GHz antenna.

Material	Attenuation per meter for	
	100MHz	1 GHz
Water	100 dB	1000 dB
Ice	0.1 - 5 dB	1-50 dB
Sand	0.01 – 2 dB	0.1 – 20 dB
Clay	5 – 300 dB	500 – 3000 dB
Limestone	0.4 – 1 dB	-

Table 1. Energy absorption of electromagnetic waves for different materials (Daniels 2004, Davis & Annan 1989)

The main conclusions drawn from this table are:

- the higher the frequency the higher the attenuation of transmitted electromagnetic waves
- the absorption of water is very high
- the absorption of ice is rather low

The attenuation in snow is not included in table 1 because it is very much dependent on its water and air content. Table 2 shows the vertical resolving limits for the media water, wet snow, dry snow and ice using ¼ to ½ of the wave length λ (Sheriff & Geldart 1982). Wavelength was calculated using the equation λ=v/f.

Antenna frequency (f)	**Medium**			
	water	**wet snow**	**dry snow**	**ice**
velocity (v)	0,03 m/ns	0,1 m/ns	0,23 m/ns	0,16 m/ns
100 MHz	0,075 - 0,15 m	0,25 - 0,5 m	0,575 - 1,15 m	0,4 - 0,8 m
500 MHz	0,015 - 0,03 m	0,05 - 0,25 m	0,115 - 0,23 m	0,2 - 0,4 m
1 GHz	0,0075 - 0,015 m	0,025 - 0,125 m	0,0575 - 0,115 m	0,1 - 0,2 m

Table 2. Theoretical vertical resolving limits of different media according to different frequencies

Using a 1 GHz antenna the depth of penetration within dry snow is in the order of 10-20 meter, whereas for ice only a few meters can be expected. For the task of crevasse detection this might be not sufficient and a higher penetration depth especially in ice is required.

For this reason a 500 MHz antenna was chosen which offers a penetration depth of > 10 m at a velocity of v=0.16 m/s, which is sufficient for crevasse detection. Also it ensures that even for some humidity in the snow pack still the upper metres of glacier ice can be investigated with the GPR method. Tests with this frequency proved the assumptions and the suitability of the system (figure 1).

Figure 1 also shows that the snow/ice transition causes a reflection of the signal at about 4.5 meters in depth, dipping towards the left of the figure. Travel time to depth conversion was applied using the wave velocities determined by the CMP measurements. This snow cover thickness was also verified by field measurements. It is clearly seen that there are some internal layers in the snow pack which also can be resolved with this system.

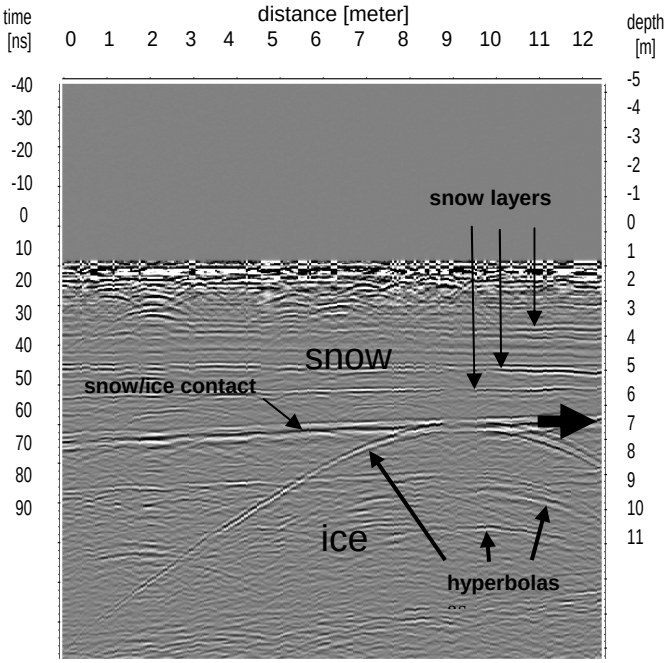

Figure 1. GPR test profile on a snow covered glacier with a signal frequency of 500 MHz.

2.2 Depth of penetration versus resolution

The penetration depth is inversely proportional to the frequency used, as shown in the previous section. The vertical resolution of the system, however, is related directly to the frequency, which makes it necessary to find a balanced solution between desired penetration depth and required signal resolution. In the case of the proposed 500 MHz antenna a vertical resolution of 0.2 m can be expected. In relation to the penetration depth of several tens of meters, this resolution will allow a clear identification of the snow ice interface. Field experiments have shown, that crevasses of about 0,5 m in width still can be detected under a snow cover of several meters.

2.3 Common mid point (CMP) measurements

CMP measurements have been carried out using an antennae frequency of 100 MHz and a step size interval of 0.1 meter to determine the velocity of propagation within different layers and to determine thickness and depth of different layers such as snow/ice or ice/rock (figure 2). The velocity within the water saturated snow was 0.1 m/ns, within the upper ice body (7 – 12 meters) 0.14 m/ns whereas the lower ice body (12 – 35 meters) showed a velocity of 0,16 m/ns. Layer horizons were detected at a depth of 7 meters (snow/ice), at 12 meters (wet ice/ pure ice) and at 35 meters (ice/rock). Values are constant with examples given from the literature (e.g. Davis & Annan 1989, Eisen et al. 2002, see also table 3).

Material	ε'	σ [mS/m]	v [m/ns]	α [dB/m]
Air	1	0	0.30	0
Dest. Water	80	0.01	0.033	2×10^{-3}
Fresh water	80	0.5	0.033	0.1
Sea water	80	3×10^{4}	0.01	1000
Dry sand	3-5	0.01	0.15	0.01
Saturated sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Table 3. Parameters of selected materials relevant to GPR (Davis & Annan 1989)

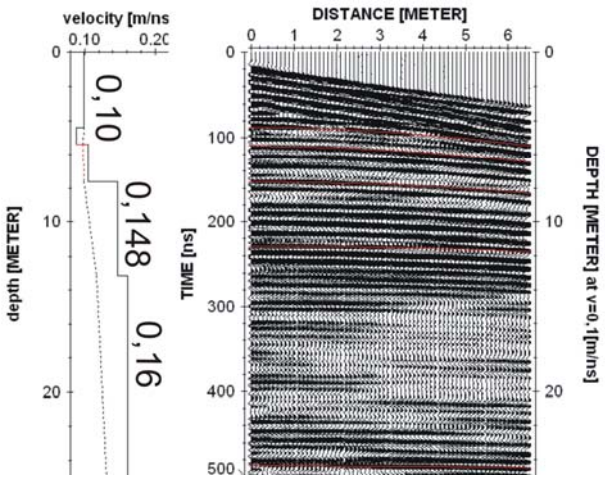

Figure 2. 1-D velocity model and CMP-analysis

3. FIELD STUDY

3.1 Test site

As test area the "Hallstaetter Gletscher" in the Austrian Alps was chosen. This glacier is highly frequented by tourists, because a lift provides easy approach onto the glacier. Several alpine huts can be reached from there. But on these paths the glacier has to be crossed although many crevasses are existing and most of the tourists are not experienced and therefore are underestimating the danger. Logistic and safeguarding support was ensured by an experienced mountain guide.

3.2 Equipment

A GPR system of the following specifications was used:

Brand: MALÅ Geoscience
Model: RAMAC CUII
Pulse rate: 100 kHz
Data rate: 16bit/s
Sample rate: 0.4 - 50GHz
Antenna: 500 MHz

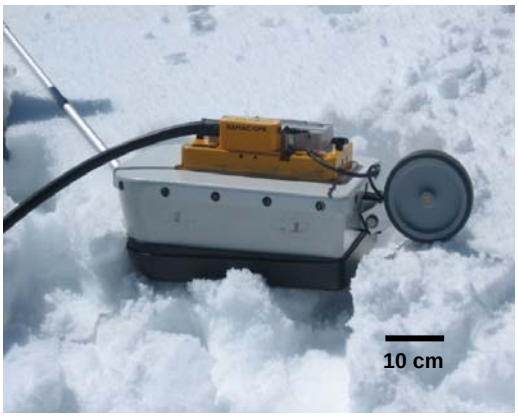

Figure 3. Shielded 500MZ antennae with distance wheel

3.3 GPS survey

During the summer season the position of a number of open crevasses were surveyed by differential GPS. Typically one edge was determined by a polygon and the width of the crevasse was estimated. A local reference point was used in addition to two permanent reference stations. Base line lengths were less than 2 km and observation times around ten minutes. The accuracy after post processing, as given by the processing software Leica Geo Office, was in the order of 0.1 meter. After snow coverage all surveyed crevasses were staked out by repositioning of the former surveyed locations.

3.4 GPR profiling

The marked crevasses now were crossed by GPR survey lines. Within a test area an equidistant (5 meter interval) profiling was carried out with the aim to detect and determine the position of the crevasse crossing points (Figure 4, left). The start point and the end point of each profile was surveyed by differential GPS using the same reference configuration as during the survey of the open crevasses. Positioning along a profile was done by distance measurement. Another test crevasse was crossed diagonally (Figure 4, right) in order to test the system under more realistic conditions, because unknown crevasses unlikely are crossed orthogonally.

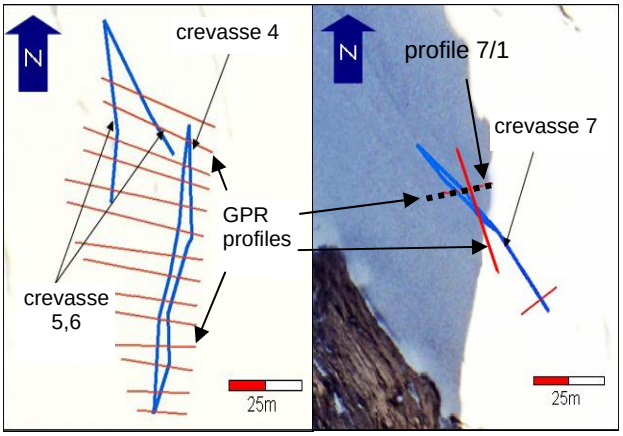

Figure 4. Marked crevasses crossed by GPR profiles

3.5 Data processing and interpretation

The recorded GPR profiling data were analyzed in different steps using the software package RFLEX W 4.5.5 (Sandmeier, 2004).

The following post processing sequence was applied to the raw data in order to improve visibility of the reflected and diffracted signals:

- subtract mean dewow filter
- time zero correction
- background removal filter
- paramterized gain functions

After these signal processing steps an interpretation of the GPR profile is possible. As an example profile 7/1 is given in figure 5. In case of a hidden crevasse the following effects can be observed in the radar profiles:

- the reflection horizon from the snow/ice boundary is non continuous
- the snow layers above a crevasse detected in the radar sequence show curvatures towards the crevasse
- diffraction on the walls of the crevasse appear as hyperbolas

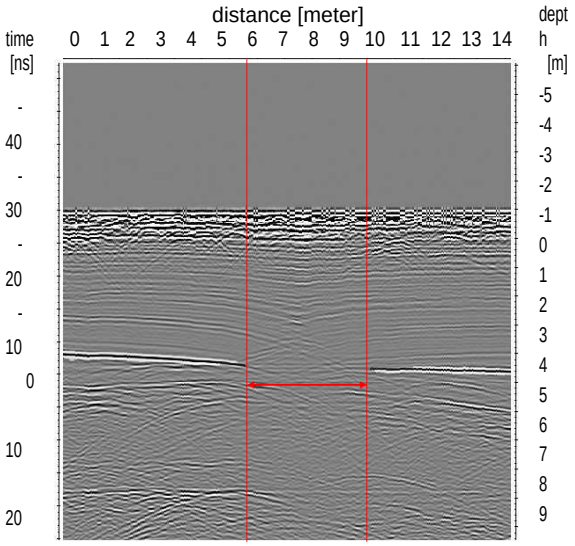

Figure 5. Pre processed GPR profile 7/1

3.6 Automated profile analysis

It is obvious, that a system for crevasse detection has to be very robust and fast, therefore interpretation of the GPR profiles has to be automated. The proposed procedure is based on the fact that in case of a hidden crevasse there is no reflection on the snow/ice horizon. An algorithm is applied which normalizes the signal amplitude according to the snow/ice horizon. In case of a

covered crevasse, the signal is shifted vertically exactly on the position of the crevasse (figure 6). This way an alarm signal can be given immediately when reaching an edge of a crevasse.

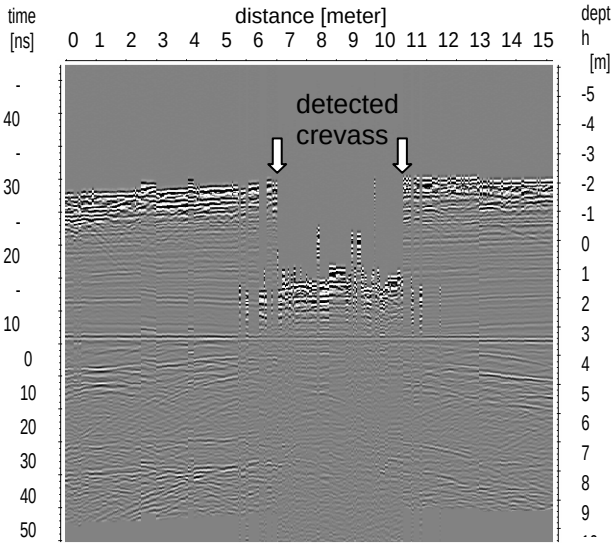

Figure 6. Profile 7/1 (automated analysis)

4. SUGGESTION OF A MONTAIN GUIDE SYSTEM

The first results from the combined application of GPR and GPS suggest that a system for safe glacier travel on alpine glaciers could be developed. This potential guiding system for mountain tourists could be realized in the following way:
During the winter season so called safe tracks are monitored using a GPR system and differential GPS for reliable profile localization. During the survey the operator will continuously observe the thickness of the snow coverage in the radar data for security reasons. In case a crevasse is crossed a warning message is given. On the fly alternative routes can be searched which are free of crevasses. The safe tracks are surveyed by GPS and the coordinates are made available to mountain tourists via download from the internet. These tracks can be stored in the tourist´s GPS navigator to guide them on safe tracks.

5. CONCLUSION

It can be stated that all test crevasses were detected by visual interpretation of the processed radar images. The accuracy of the reproduced locations of the centre axis of the crevasse can be specified with 2 meters.

It is obvious, that an operational warning system needs an automatic procedure for interpretation of the radar images. A first step towards automatic detection has been achieved by a normalization of the amplitudes of the radar signals in respect to the amplitude of the ice horizon. Then the existence of a crevasse can be observed as a very strong amplitude decay in the direct signal from the air wave. This “missing signal” in the direct wave traces can easily be detected by automatic means.

There are some limitations of the proposed method:

- crevasses with a width below 0.5 meters can not be detected reliably with the antennae configuration.
- crevasses have to be crossed with the radar equipment, hence crevasse detection is only possible during periods with high snow cover and with safeguarding.

- in case of very wet snow, the absorption of the signal is rather high and therefore crevasse detection is difficult after rainfall or during melt periods. More investigations on this issue are necessary.

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