The Cryosphere Discuss., 4, C844–C849, 2010
www.the-cryosphere-discuss.net/4/C844/2010/

The Cryosphere
Discussions

Interactive comment on "Monitoring of active layer dynamics at a permafrost site on Svalbard using multi-channel ground-penetrating radar" *by* S. Westermann et al.

S. Westermann et al.

swestermann@awi.de

Received and published: 29 September 2010

We would like to thank John Moore for this comment which will help to improve the description of the multi-channel-GPR method. In the following, we address all issues raised. The comments are given in bold face, while our response is given in normal font. Passages from the revised version of the paper are given in italics.

This paper presents a fairly thorough account of the calibration and use of multichannel radar to monitor the active layer depth and water content of permafrost. The paper is well written and accessible for the readers of The Cryosphere. My comments refer only to the radar part of the paper, especially section 3. I would like to have some more information on the critical parts of doing a multi-channel radar survey - I think this is a relatively niche subject in glaciology and while some specific details are given here, it would helpful to have some more introduction.

In particular the paragraph on p.292 line 26-p293 l5 detail modifications to a scheme that are, without further introduction simply obscure technicalities to the reader (at least to me).

For technical reasons, the exact point in time in the radargram where the signal was emitted by a GPR antenna is usually not exactly known. Hence, for surveys where absolute travel times are required (as in our study), a so-called "zero-offset calibration" is needed. Gerhards et al. (2008) inferred the zero-offset indirectly during the multi-channel evaluation procedure. In this study, we calibrated the zero-offset directly by doing a Wide Angle Reflection and Refraction (WARR) measurement with the antennas radiating in air. A WARR measurement is a standard technique in GPR surveys: the separation between the receiving and transmitting antenna is continuously increased, so that the travel times are inferred for a range of separations. If the antennas are directed into the air (by turning them by 90°), the signal travels at speed of light. From the linear relationship between travel times and antenna separations, the travel time at $t = 0\,\mathrm{ns}$ or of a pre-defined antenna separation (in our case those of the multi-channel survey) can be inferred. The channel-specific determination of this offset is the goal of the zero-offset-calibration. For the two short channels, the transmitter-receiver separation is fixed to 0.31 m by the casing of the antennas. Therefore, we do a one-point calibration for the offset using the air wave travel time between transmitter and receiver, the transmitter-receiver separation and the speed of light. As a range of transmitter-receiver separations contributes in the

WARR measurement, we presume it to be more accurate and use it for the calibration of channels with long antenna separations.
We have added a few explaining statements in the revised manuscript:

All radargrams are processed by employing a dewow filter and by semi-automated picking of reflected wave travel times which are required for the multi-channel evaluation. No amplification is applied to the data sets. In the multi-channel evaluation for each measurement date, a zero-offset calibration is performed for each individual radargram. For the two (short) box-internal channels, this offset is determined from recorded travel times in air (antenna turned by 90°), the transmitter-receiver separation of 0.31 m and the speed of light.
For the long antenna separations, we perform Wide Angle Reflection and Refraction (WARR) measurements in air (antennas turned by 90°) in addition to each measured transect, from which the offset is inferred by extrapolating the travel time to zero transmitter-receiver separation. With this, we are able to employ direct measurements of air wave travel times for calibration of each channel and circumvent the indirect airwave adaptation step of Gerhards et al. (2008) during the data evaluation procedure.

It seems to me that knowledge of the separation of the antennas is fairly critical to the success of the inversion scheme outlines in equations 1 and 2. Table 1 lists those separations to mm resolution. This seems rather unlikely to be achieved in reality given that we are told the antennas were separated by a rope. This implies that at the very least there would be changes in "long" separations simply according to the terrain, and of course bigger ones in negotiating turns around obstacles and valleys.

We agree with this comment. In reality, a mm resolution cannot be achieved in the field. In fact, Table 1 lists the measured antenna separations with a resolution of 5 mm,

which is a realistic accuracy for measuring the distance between the two antennas in the field, when the ground is completely flat and both antennas are aligned. The given separations have been determined before and after measuring each transect in this way, and we have added the accuracy of 5 mm in the caption of the table.
A different issue is of course, how the antenna separation behaves during the measurements, which is naturally affected by the microtopography, a potential flex of the rope, etc. While we took great care to avoid sharp turns and to choose as even terrain as possible, a slightly varying antenna separation cannot be avoided under field conditions. This may at least partly explain the noisy traces for the thaw depths, but it is hardly possible to single out the impact of this error source based on our data set.

I would like to see some discussion of errors introduced by the antenna geometry, and if these are really negligible then some general comments about how to select the suitable antenna separations since it is stated that "For the chosen antenna separations (Table 1), the absolute travel times of the radar signal do not differ strongly between the four channels (on the order of 5 ns, Figs. 2, 3), which leads to relatively noisy evaluations of reflector topography and soil water content." Does this imply that antenna geometry should be chosen beforehand to ensure that this does not happen. This would be useful information for people wanting to perform similar surveys which the authors presumably advocate. Additionally advice could be given on suitable antenna frequencies and any other practical details which their experience suggests may helpful to more novice practitioners of multi-channel radar surveys.

Four factors must be taken into account, when determining an optimal antenna geometry:

1. In principle, the accuracy and robustness of the method increase, the more the

travel times of the channels differ and if, especially, long antenna separations are available. So the shape of the reflection hyperbola which has to be evaluated during the evaluation procedure is better defined.

2. Choosing a longer antenna separation clearly decreases the lateral resolution of the evaluation. However, we do not expect this to be a major issue in our case, even if the antenna separation would be doubled. The lateral resolution would then still be very good.

3. The amplitude of the GPR signal recorded by the receiving antenna decreases with increasing antenna separation. This is caused by (i) geometrical spreading of the signal and (ii) signal attenuation due to specific ground properties (e.g. electric conductivity). Consequently, the optimal antenna separation has to be adapted to site specific conditions: If the antenna separation is chosen too long, the reflected signal eventually fades or at least becomes impossible to pick. This precludes the choice of too long separations. An example is displayed in Wollschläger et al. (2010), where eight channels are employed in a similar study. Here, the reflected signal disappeared for the longest antenna separations in some parts of the study site.

4. In addition to the reflected radar signal, a ground wave travels directly through the soil, resulting in an additional signal in the radargrams. If the antenna separations are chosen too long, the ground wave and the reflected wave will eventually begin to overlap, resulting in a signal of unclear origin, which in addition is not suitable to be picked. Therefore, the antenna separations must be chosen sufficiently short to prevent an overlap between reflected wave and ground wave. How short this must be, depends primarily on the combination of ε_c and d.

In field measurements, a suitable compromise between these four factors must be chosen according to the local conditions. We experimented with longer antenna separations before starting the measurements, but the two last points proved to be problematic here. As the presented data set does not systematically investigate the issue of choosing optimal antenna separations, we are reluctant to give a detailed account of this problem in the present paper. We have added a short sentence explaining the reasoning for the choice of the antenna separations:

The corresponding antenna separations of the 4-channel setup are summarized in Table 1. With the chosen separations, the reflected wave resulting from the frost table can be picked for all four channels and the ground wave and the reflected wave are clearly separated. All radargrams are recorded using a time window of 102 ns, 1024 samples and 4 stacks per trace, and a spatial trace increment of 0.1 m which is triggered by a survey wheel.

Regarding suitable antenna frequencies, from our experience (Gerhards et al., 2008; Wollschläger et al. 2010; this study), 200 MHz and 250 MHz antennas proved very well for multi-channel investigations of thaw depth and water content of the active layer. All studies have been conducted in sandy to gravelly environments with thaw depths between about 1 m and 2 m. However, the choice of the optimal antenna frequency depends mainly on site specific conditions. The standard rule for GPR surveys which may initially be applied is: higher frequency antennas provide a high vertical resolution but a low penetration depth while low frequency antennas will penetrate deeper into the ground with less vertical resolution. In clayey soils, the GPR signal may be strongly attenuated which may reduce the penetration depth significantly and potentially make the detection of the ice table with GPR impossible.

Interactive comment on The Cryosphere Discuss., 4, 287, 2010.