Introduction

In this article we present results from numerical simulations of reflection scans with a low frequency pulsed radar system through permafrost host rock with embedded target layers of highly conductive sulfides. The goal of the simulations is to determine the signal to noise ratio needed to detect targets at various depths. Sulfide layers are of interest for mining as they often contain minerals. These layers are typically mined at depths up to a kilometer or more, and the question arises if they can be detected from the surface with a remote sensing method. At these depths seismic methods are not feasible because the targets do not have a strong density contrast, and therefore generate no appreciable reflections. However, as permafrost is highly resistive with resistivities up to $1\text{M}\Omega$ (Vanhala et al., 2009) the host rock is almost transparent to electromagnetic waves, and the sulfide layers act as mirrors due to their high conductivity, suggesting a survey with a pulsed radar system (Daniels, 2004; Jol, 2009). Feature detection down to several kilometers below the surface has been achieved with low frequency ($1-5\text{MHz}$) pulsed radar surveys in resistive environments such as Martian rock, ice, and permafrost (Berthelier et al., 2005; Ciarletti et al., 2003; Angelopoulos et al., 2013). Using such methods a reflector which is probably liquid water was recently detected on Mars at a depth of 1500m (Orosei *et al.*, 2018). The simulations are based on the emission and detection properties of the Adrok radar system (Stove and van den Doel, 2015) in a permafrost environment in which we place a conductive reflector (representing the mineral target) at various depths.

Wave propagation model

We implemented a $1+1$ dimensional time-domain finite difference simulation of Maxwell's equations in a medium described by dielectric $\varepsilon_r(x)$, static conductivity $\sigma(x)$ and a Debye polarization model (Debye, 1929) with relaxation time τ to account for frequency dependent losses. The model is similar to the one described in (Ciarletti et al., 2003). Material properties are assumed to be constant in time but can depend on location. The model is summarized by the following system of partial differential equations:

$$\varepsilon_0 \frac{\partial^2 E(t,x)}{\partial t^2} + \sigma(x)\frac{\partial E(t,x)}{\partial t} + \frac{\partial^2 P(t,x)}{\partial t^2} - \frac{1}{\mu_0}\frac{\partial^2 E(t,x)}{\partial x^2} = 0,$$

$$\tau(x)\frac{\partial P(t,x)}{\partial t} + P(t,x) = \varepsilon_0(\varepsilon_r(x)-1))E(t,x),$$

with E the electrical field, P the polarization, $\varepsilon_0 = 8.85 \times 10^{-12}\text{F/m}$ and $\mu_0 = 4\pi \times 10^{-7}\text{H/m}$. The equations are discretized with a fourth order finite difference approximation for the spatial derivatives and a leap-frog method for the time stepping (Ascher, 2008). At the simulation boundaries we use perfectly matched layers (Berenger, 1994). A grid spacing of 10cm and a time step of 0.15ns was used and found to be accurate enough for frequencies up to 100MHz. The size of the absorbing boundaries were 400m on the top and 200m on the bottom. The emitted pulse of the modeled system was measured in air as a time domain trace. It is about 200ns long and contains frequency components from $1-70\text{MHz}$ with significant peaks at 3, 20, 30, and 65MHz (Doel et al., 2014). Spatial spreading losses are taken into account by post-processing the resulting computed traces by the appropriate $1/r$ factor for 3D propagation. We consider a stratified earth model with resistive permafrost ($R = 50k\Omega$) down to depth D at which we place a conductive layer with $R = 1\Omega$, Following (van den Doel and Stove, 2018), we model irregularities causing backscatter by small random variations $\Delta\varepsilon_r$ on top of the background relative permittivity of 7 with a Gaussian distribution with standard deviation 0.25 at random spatial intervals Δx which are taken from an exponential distribution with mean 5m. We add Gaussian noise to the simulated measured reflections, and quantify the noise level as the ratio of the RMS background noise (which would be recorded with transmitter Tx turned off) to the maximum field strength recorded when the pulse enters the ground, as illustrated in Fig. 1.

Simulation results

The simulations were performed with reflectors at depths of $D = 415\text{m}$, 830m, 1245m, and 1660m with varying noise levels, resulting in synthetic radar traces. The traces were analyzed using the "stacked correlation" method (van den Doel and Stove, 2018; van den Doel, 2017) which allows identification of

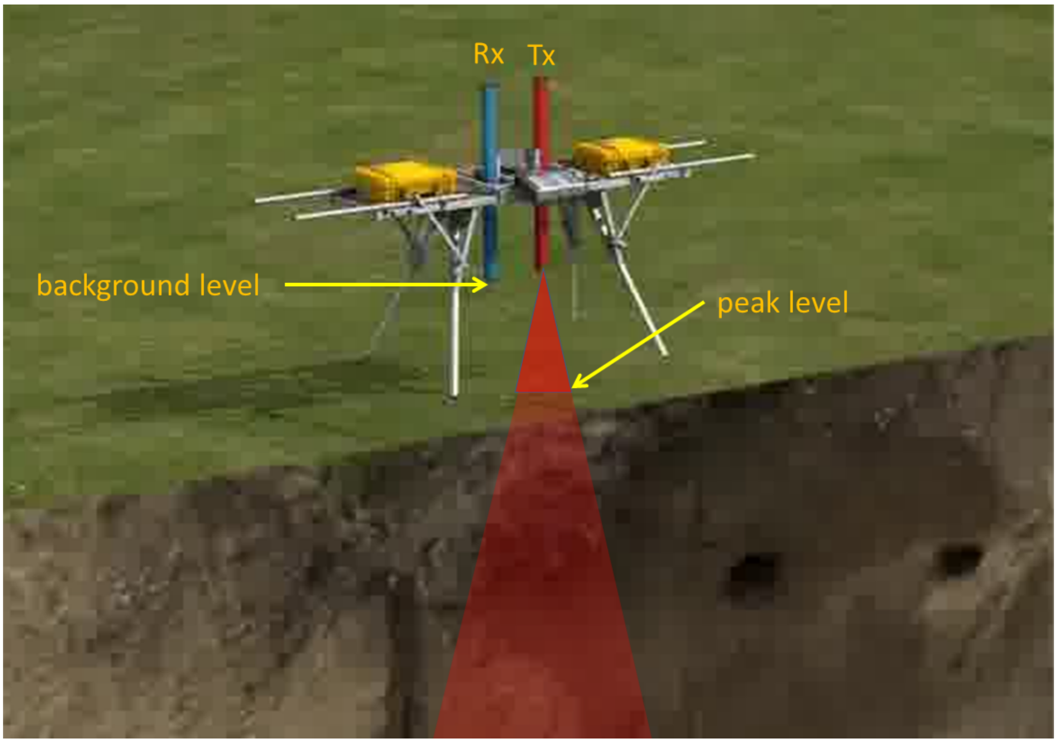

Figure 1 *The radar pulse emitted by Tx enters the ground and subsurface reflections are recorded at the receiver Rx. Noise level is defined as the ratio of the background noise at the receiver and the peak signal when entering the ground.*

reflectors from peaks in mean correlation (and dips in standard deviation). The reflector was considered detected if 10 replica experiments with independently generated noise resulted in the correct peak at depth D for all. Noise levels were gradually reduced to determine the maximum noise level tolerated. The process is illustrated in Figs. 2 - 4 which shows how the results change when the noise level is decreased.

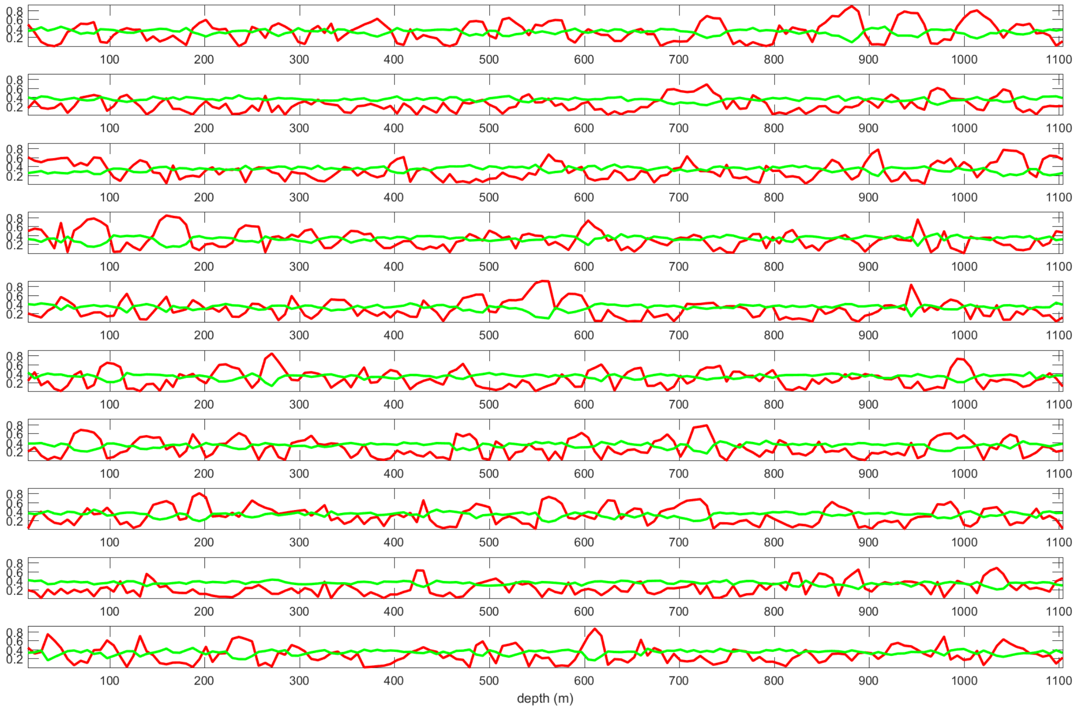

Figure 2 *Correlation results for a reflector at* 850*m with* 5% *noise, yielding a negative result.*

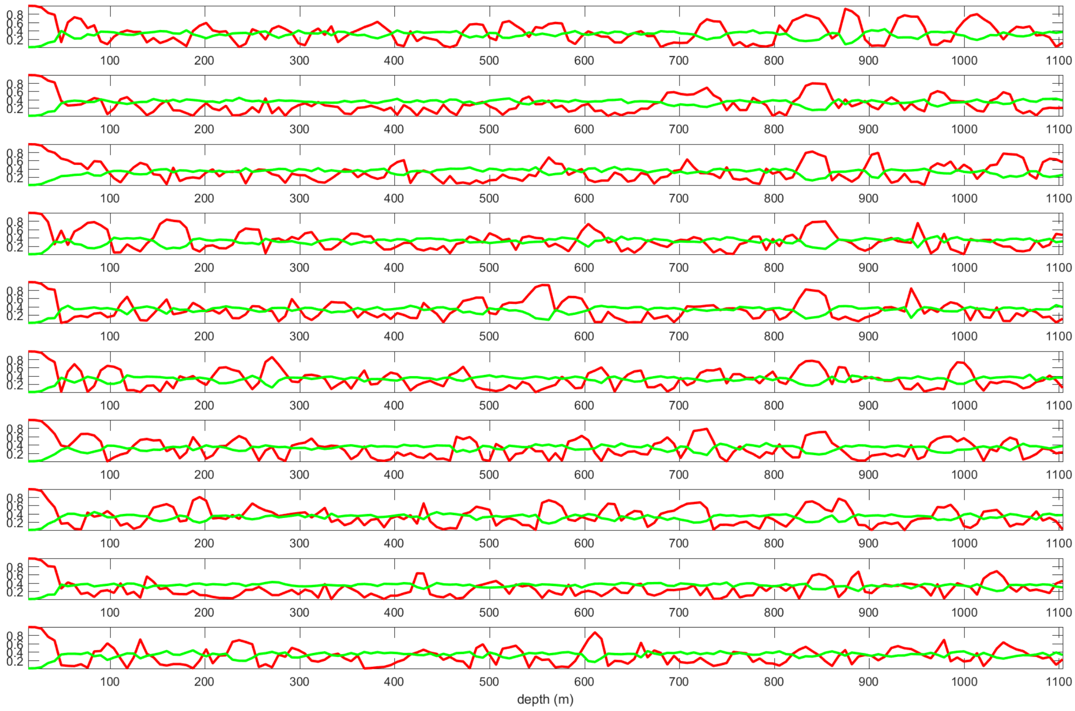

Figure 3 *Correlation results for a reflector at* 850*m with* 0.5% *noise. Most but not all traces have a peak at* 850*m so this is just above acceptable threshold.*

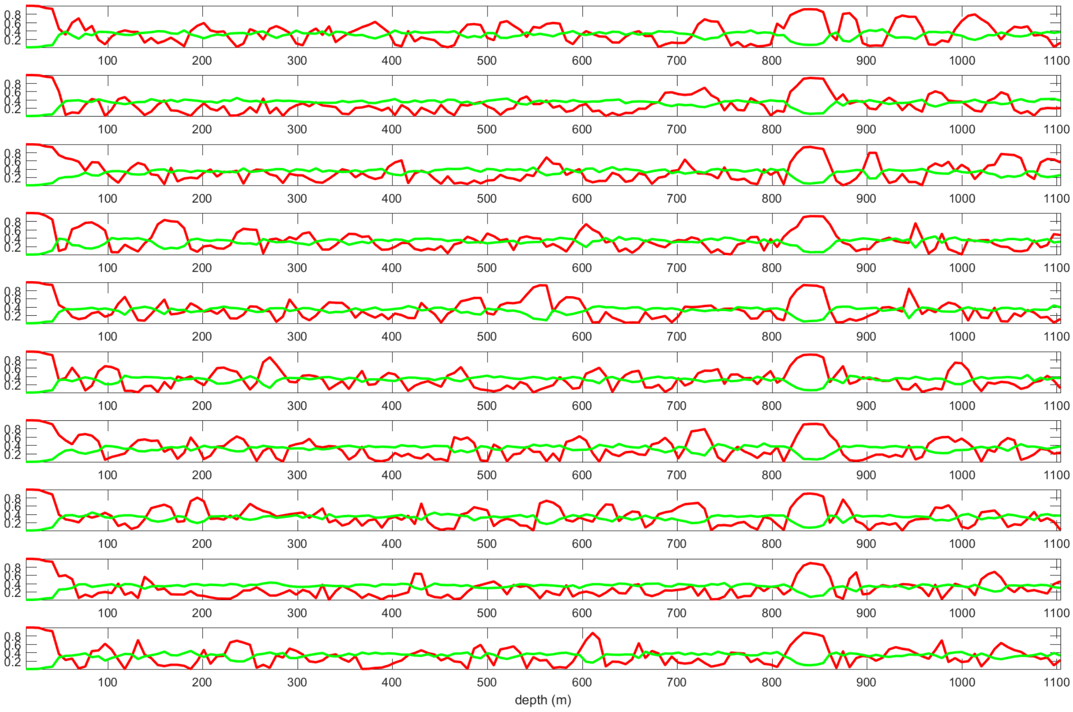

Figure 4 *Correlation results for a reflector at* 850*m with* 0.25% *noise, with acceptable noise level as all* 10 *scans have a peak at* 850*m.*

Applying this procedure for the depths considered yields the results given in Table 1. A good fit to the data is

$$\text{Max noise(D)} = 10e^{-D/250}\%.$$

Depth (m)	Noise level (%)
415	2.0
830	0.25
1245	0.04
1660	0.01

***Table 1** Maximum acceptable noise levels to detect the target as a function of target depth.*

Conclusions

Simulation results have been presented for the remote sensing of conductive sulfide lenses in permafrost host rock at depths up to 1660m, using radar reflection scans with a low frequency pulsed radar system. The sulfide layers are highly reflective due to their high conductivity whereas the host rock is mostly transparent to radio waves. Results were used to estimate the maximum noise levels tolerated to detect such a reflector at various depths. Noise level was quantified as the ratio of the RMS value of the background signal to the peak signal level entering the ground. These results can guide experimental design for such a detection scheme. Provided the background noise is not correlated with the measurements this allows the amount of stacking required to detect to a given depth to be estimated.

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