Geophysical Research Abstracts
Vol. 16, EGU2014-13197, 2014
EGU General Assembly 2014

Simulation of snow stratigraphy using full-waveform inversion applied to data from an upward-looking radar system

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Snow stratigraphy is a key contributing factor for assessing avalanche danger, but so far only destructive methods can provide this kind of information. Furthermore, continuous monitoring of the temporal evolution of the snowpack is not possible with destructive methods. Radar technology provides information on the snowpack non-destructively and allows deriving internal snow properties from its signal response. In our previous work, we demonstrated that it is feasible to quantitatively derive snowpack properties relevant for avalanche formation and monitor their evolution in time using an upward-looking ground penetrating radar system (upGPR) that was buried in a wooden box underneath the snow. Reliable results could only be obtained for the time when the snow cover was dry. In addition, to determine some properties, we still needed additional information such as independently measured snow height or modeled snow density. Hence, the system was not yet able to provide information from avalanche starting zones, since this type of information is generally not available in avalanche-prone terrain. To fully exploit the information content of upGPR data, and thus to at least partially compensate for the lack of information, we applied full-waveform inversion (FWI) techniques. We refined the model of the snowpack by repeated forward modeling the waveforms and updating the model parameters to match it with recorded data. The forward model took into account both the effect of the snow density on the velocity of the electromagnetic wave, as well as the influence of snow wetness on the attenuation. This allowed the density and the liquid water content for each layer in the snowpack to be determined. As we conducted a measurement every 3 hours (every 30 minutes as soon as the snowpack became wet), we could also simulate the temporal evolution of the density and the liquid water profiles. The method worked without assumptions or external measurements, even when the snow cover was wet.