PRELIMINARY RESULTS OF A LOW-FREQUENCY 3D-SAR APPROACH FOR GLACIER VOLUME MAPPING

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ABSTRACT

First experimental results with a low-frequency, ultra wideband (UWB) radar for estimating the height of glacier beds are illustrated. We use a 3-dimensional Time-Domain Back-Projection (TDBP) algorithm which incorporates the influence of the refractivity of ice to reconstruct the glacier bed of the Aletsch Glacier in the Swiss Alps using several CARABAS data sets. As the results indicate, the proposed method underlines the ability of low-frequency Synthetic Aperture Radar (SAR) to penetrate into glacier ice and thus, to map glacier volumes on a large scale even with only few, suboptimal data acquisitions.

Index Terms— Synthetic aperture radar, Ultrawideband radar, VHF radar, Ice

1. INTRODUCTION

In this paper we demonstrate first results of a three dimensional SAR processing method to generate height profiles of glaciers with the CARABAS UWB sensor. Several algorithms exist to extract height information in SAR data, ranging from interferometric approaches (for CARABAS e.g. [1]) and cross correlation in circular tracks [2] to tomographic processing of dual-pol data [3, 4].

In the context of global warming and planetary change the estimation of glacier ice volume becomes increasingly important for questions concerning sea-level rise or water resource management. To estimate the ice thickness a possible solution is based on mass conservation and principles of ice flow dynamics ([5]). In this paper, we propose a 3D SAR processing approach of CARABAS data to calculate the height of the maximal backscattering response in the glacier ice and thus approximate its volume. 3D SAR is an interesting application for estimating glacier height profiles and volumes since the low-frequency radar waves penetrate into ice and thus approximate the profile of the glacier bed up to a certain depth. During a CARABAS campaign conducted in 2003, the Aletsch Glacier, Switzerland, was recorded over several flight tracks. Due to the large antenna necessary for UWB SAR only HH polarization can be recorded in monostatic mode. Unfortunately, because of air space restrictions, the flown tracks are suboptimal for generating a 3D profile of the Aletsch Glacier bed. Nevertheless, some promising results were generated by an extended TDBP processor incorporating refractivity, which is capable of extracting 3D information from few, arbitrary flight tracks illuminating the area of interest.

2. METHOD

To generate a 3D profile, first a three dimensional reconstruction grid is initialized with the digital surface model values at the top layer in z-direction. Then for each flight track the 3D back-projection algorithm calculates for each voxel an intensity value as the 2D standard back-projection algorithm in an analogous way for each pixel. Since for a coherent summing of the resulting 3D-matrices too few flight tracks are available and additionally the flight configuration is suboptimal for coherent summing, we use instead the absolute values (incoherent) and multiply them for each flight track as a reasonable approximation to merge the single track results to one voxel image. Height information up to a certain depth of the glacier bed can be approximated by finding the position in z-direction with the maximum value. Hence, the position with the strongest backscattering response is assumed to be the height of the glacier bed. However, it still has to be investigated whether the backscattering maxima is indeed caused by the bedrock or by other factors like a significant amount of moraine material, an unfavorable combination of crevasses, processing artifacts or poor signal-to-noise ratio. Finally, we apply a low-pass filter to suppress noise effects and get a smooth, more realistic estimate of the height of backscattering maxima. In our calculations we also consider the refractivity of the ice. That implies an additional processing step within the TDBP algorithm in which the points of entry at the glacier surface have to be calculated. We make use of the spatial and temporal interrelationship between adjusted pixels. Thus we only have to initialize the refractivity calculations for the first time step and can update
the points of entry iteratively and time efficiently for each slightly shifted airplane position for the new echo pulse. However, some imprecision is unavoidable due to the inhomogeneity of the glacier ice and the partially craggy surface features.

3. RESULTS

We applied the method described in Section 2 to a 5x5 km² test site in the Swiss Alps (Konkordiaplatz, Aletsch Glacier). The result for a part of the 3D grid matrix after the merging step is illustrated in Fig. 1. While for the snow and ice free surface (e.g. mountain tops) the highest backscattering response can be found in the top layers, in the glacier ice the low-frequency radar waves penetrate into the ice. At the border of the glacier ice a line is observable that seems to indicate the shape of the glacier bed; this line then becomes indistinct as the influence of undefined volume scattering increases. The height information can be derived by maximum value assignment as mentioned in Section 2. The results are illustrated in Fig. 2. In the 3D-plot the capability of penetrating into the glacier ice can be clearly observed. The results are restricted to a depth of 450m below surface height by finding a compromise between computation time as well as horizontal and vertical resolution. We used a horizontal resolution of 5m for a 5x5 km² area and a vertical resolution of 15m for a 450m vertical depth, subdivided into 30 uniformly spaced layers. That fact may lead to some artifacts in areas where the true glacier depth exceeds 450m (at Konkordiaplatz the glacier depth can reach up to 800m at the deepest areas, see also [5]). In Fig. 3 a glacier mask is used to visualize the structures of the glacier itself. In the SAR tomographic height some interesting structures can be seen, which maybe indicate anomalies within the glacier ice that are often aligned along the flow direction and thus lead to a backscattering response in higher layers; they also provide additional evidence for the “visibility” of rocky material in glacier ice due to the penetration capability of the low-frequency radar waves. However, the results are only a first step towards mapping glacier volumes with low-frequency UWB SAR and they are not to be seen as a “final” mapping of glacier beds. Nevertheless, it illustrates the potential of this technology for future projects with additional, more suitable flight tracks for the problem of glacier mapping. As an example, Fig. 4 shows a cross section through the glacier. The blue line in the graph, indicating the maximum backscattering height estimated with the SAR-based approach, is suitable for a rough estimate but is in detail somewhat noisy, mainly due to the uncertainties in the composition of the ice (enclosed air and water, internal structures, …), which heavily influence the refractive index. Also, the unfavorable flight pattern was not originally planned for glacier volume mapping, and could be better adapted for this purpose.
Fig. 2: Surface maps.
Left, top: Glacier surface generated using conventional surface mapping techniques (optical data and X-band InSAR).
Left, bottom: Height of maximal backscattering derived from CARABAS 3D processing.
Right: Combined 3D-plot of both height maps. The influence of the glacier volume can clearly be seen.

Fig. 3: Left: digital surface model height; right: Height of maximum backscattering derived by tomographic processing of CARABAS data.
4. CONCLUSION

The methods and results introduced in this paper demonstrate the capability of low-frequency UWB SAR sensors to generate glacier height profiles and thus give a rough estimate of glacier volume. Further campaigns with a flight track selection optimized for the problem of 3D glacier mapping, and more research including ground truth validation, has to be done to verify the results. These ground truth validations are especially relevant to the question of how accurate the estimated height of the maximal backscattering response is and how it is influenced by simplified physical assumptions and estimated processing parameters. These include uncertainties about which materials and structures within the ice are responsible for a high backscattering response, imprecise knowledge about the ice composition and therefore the refractive index, possible processing artifacts or the number and choice of the flight tracks. Furthermore, the maximum processing depth has to be extended in some areas to suppress artifacts caused by the limited processing depth of 450m. Nevertheless, the proposed method can potentially be used to map the volume of alpine glaciers on a large scale and thus to provide information about their condition and behavior.

5. REFERENCES


