Theoretical Modeling of Multi-frequency Tomography Radar Observations of Snow Stratigraphy

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***Abstract*—Traditionally, a snow stratigraphy is characterized through a snow pit study. It only represents a snapshot view of the snow vertical properties and cannot capture the continually evolving snow process. This type of study is also destructive and time-consuming. Recent studies show that by using multi-baseline SAR configuration, the tomographic processing can provide the vertical image of the snowpack and monitor temporal variability. In this study, the full wave solution of the forward model will be used to reconstruct the tomograms and relate snow properties with the images.**

Keywords*—*tomography, snow, FMCW radar, SWE

I. Introduction

The understanding of the seasonal snowpacks is critical for effective water resource management, weather/climate prediction and natural hazard forecasts [1]. The stratigraphy of an alpine snowpack is important for estimating the water availability from snowmelt, flooding prediction, estimating the snowpack strength for avalanche applications, and input for atmospheric and hydrological models. The snow stratigraphy describes the physical properties and behavior of the snow layers. The individual snow layers result from the various precipitation and snow drift events. The surface of the snow cover is constantly modified by the local weather, like for example wind, radiation, precipitation and melt processes. Most methods for measuring snow stratigraphy include the digging of a snow pit, a vertical profile wall to the ground, which allows the observer to identify individual layers based on visually and manually observed variations in the snow cover. The detected layers are then characterized based on their snow type, grain size, hardness, density, and temperature [2]. Snow type and grain size (mean greatest extension) are visually estimated on a ruler plate with a magnification lens (10x). Snow hardness is measured using a Rammsonde) or applying the hand test and density is calculated due to the weight of a certain snow volume. One drawback of conventional field measurements is their subjective nature, particularly regarding grain size and hardness assessment. Although international standards exist for such measurements the results strongly depend upon the observer's estimation abilities and experience. Another problem is the low spatial resolution and the one-dimensional character of the mentioned methods. The measurement schedule assumes homogeneous layers, separated by distinct boundaries and therefore it is not possible to detect more subtle vertical changes or lateral variations of the observed features.

Recently, the successful application of multi-baseline SAR tomography in P-band forestry biomass observation [3] enlightens the possibility of using a similar approach of X-/Ku-band SAR tomography of snowpack in extracting snow stratigraphy information remotely [4]. The emerging companion/mirror SAR concept also makes the multi-base line configuration in space possible. The tomographic imaging approach [5-8], however, needs knowledge of the scattering matrix, which contains information on both magnitude and phase of the scattering field. The traditional radiative transfer theory that is based on energy conservation cannot account for the phase term. The full wave method is needed for the tomograms analysis.

II. SAR Tomography Algorithm

The processing chain of the raw data collected from the radar consists of a standard FMCW processor followed by a multi-looking time-domain back-projection processor. After anti-aliasing, downsampling, and leakage subtraction, the raw FMCW samples are range-compressed via an FFT with an appropriate apodization window. Auxiliary information is used to split up the data into sets of 2D scans of 0.6 x 0.6 m. Since vertical cuts through the snow are targeted, each 2D scan is split up into vertical strips 5 cm wide. The tomographic coherent focusing could be achieved by jointly processing multiple the vertical strips acquisitions through time domain back projection [3]. The imaging operator takes the form

$$I(\bar{p}) = \sum_{n=1}^{N} S_n(\bar{p}) e^{-i\phi_n(\bar{p})}$$

where N is the total number of transmitter-receiver pairs (number of baselines), $\bar{p}$ represents a certain point in the ground range and height plane, $S_n(\bar{p})$ is the complex range compressed signal sampled with the transmitter-receiver pair n focused at position $\bar{p}$, $\phi_n(\bar{p})$ is the phase compensation term for the target position $\bar{p}$ considering the location of transmitter and receiver pair n,

$$\phi_n(\bar{p}) = k_c(|r_n^{Tx} - \bar{p}| + |r_n^{Rx} - \bar{p}|)$$

where k_c is the wavenumber at center frequency.

Such a focusing approach provides resolution capabilities consistent with the Rayleigh limit and is suitable for tomographic imaging of distributed media. The resulting vertical resolution ρ_z and height of ambiguity z_{amb} can be approximated as

$$\rho_z = \frac{\lambda}{2A_z}R$$

$$z_{\text{amb}} = \frac{\lambda}{2\Delta z}R$$

where Δz is the vertical spacing between two nearby baselines, $A_z = (N-1)\Delta z$ is the overall vertical extent of the virtual array, R is the distance from the antenna to the target, and λ is the carrier wavelength. In figure 1, the six tomograms plots are preliminary results from SRT3 the day and night measurement at Fraser sites with about 70cm of snow depth from three frequencies. It reveals the various penetration depth of the different frequencies with X-band of more influence of the surface scattering and K-band of more influence of the snow volume scattering. During the daytime, the snow surface becomes wet; more scattering power is generated from the air-snow surface. To better understand the tomograms, the forward model will be used to reconstruct it and relates to the snow properties.

Based on the initial analytical forward modeling analysis, the numerical simulation of the snow scattering method will be adapted to the tomograms calculations. Numerical simulation will also make it possible to better quantify the correlation between tomogram and snowpack stratigraphy. It will help to study the time de-correlation of tomogram due to snow metamorphosis, evaluate the applicability of snow SAR tomography, and greatly facilitate the development of stratigraphy retrieval algorithm from SAR tomograms.

Previously, a similar concept of tomographic coherent focusing is applied to cluster scattering and correlation imaging, where Mie scatters with independent scattering amplitudes are used to calculate the scattering field and compute angular correlation function as well as frequency angular correlation function. In this previous work, focus was on choosing a form of SAR to reduce the cluster effects .

The numerical modeling of SAR tomography of snowpack, however, is challenging. It is built upon the fully coherent scattering matrix of the scene, and thus requires the full wave simulation of the snowpack. The underlying computing efforts are tremendous and will rely on high performance computing. The approach is quite different from the traditional DMRT approach. In DMRT wave coherency are only accounted for within wavelengths in the calculation of phase matrix. In this proposed new approach, wave interactions inside the whole snowpack including boundaries are fully coherent, yielding fully polarimetric and coherent scattering matrices, and the backscattering enhancement effects are also automatically accounted for.

The bicontinuous media will be used to model the snowpack, and apply half-space Green's function. The scattering problem will be solved with discrete dipole approximation (DDA). The location of the transmitter and receiver will be treated carefully to account for the field phase. Nystrom method with higher order basis function will also be applied to improve accuracy.

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