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SNOW CHARACTERIZATION AT KU-BAND WITH A BISTATIC POLARIMETRIC GROUND-BASED RADAR

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ABSTRACT

The Ku-band provides opportunities for investigations of snow morphology through radar observations, since it exhibits a relatively high amount of scattering even from snow layers of limited depth, while maintaining low absorption. Due to technological and practical challenges, the bistatic parameter space of Ku-band radar observations of natural media such as snow, has been relatively unexplored. We present radar measurements of snow cover obtained with KAPRI, a bistatic polarimetric Ku-band radar system. In August 2021 and March 2022, we carried out time series observations of the Aletsch glacier in the Swiss Alps, acquiring a fully-polarimetric interferometric time series of both monostatic and simultaneous bistatic observations of the glacier's accumulation zone. This dataset will serve as a test-bed to investigate new snow parameter inversion methods based on bistatic Ku-band radar data. The bistatic polarimetric measurement configuration, as well as preliminary results of the analysis of radar backscatter, are presented.

***Index Terms*—** Bistatic radar, ground-based radar, polarimetry, seasonal snow

1. INTRODUCTION

The Ku-band of the radio frequency spectrum can serve as a useful tool for investigations of snow layers, owing to a favourable ratio of a relatively long absorption length to a short scattering length. This results in a large contribution of scattering within the snow layer to the total observed backscatter from the observed scene, even for layers of a limited thickness. This makes Ku-band imaging radar – and its modalities such as interferometry, polarimetry, as well as bistatic radar observations (i.e. observations where the transmitter and receiver are spatially separated) – a useful tool for probing of various morphological parameters of snow.

The bistatic parameter space has so far been relatively unexplored due to the increased technical complexity of bistatic acquisitions as opposed to the simpler monostatic imaging. However, recently there's been a rising interest in bistatic systems and observation methods, due to their promise in terms of single-pass interferometric capabilities, and also possible access to scattering processes which are not observable with the monostatic imaging modality. This is also reflected in the proposals of bistatic spaceborne radar missions such as Harmony [1] and ROSE-L [2]. Nevertheless, bistatic radar datasets still remain relatively rare, especially when additional properties such as polarimetric information, fast repetition time, or particular bistatic angles are required.

KAPRI is a Ku-band ground-based radar system capable of bistatic, fully-polarimetric and interferometric acquisitions. These capabilities, together with its flexibility in terms of bistatic acquisition geometry, and capability of acquisitions of long time series with fine temporal resolution, make it a useful tool to investigate sensitivity of Ku-band radar to snow morphology in the relatively unexplored bistatic parameter space. Details about the system's configuration and context of the state of the art of bistatic radar can be found in [3].

2. ACCESS TO SNOW PROPERTIES WITH BISTATIC KU-BAND RADAR

The upper radar frequency ranges (i.e. X-band and up) are often used for probing of snow layers [4]. This is due to their relatively short penetration depth, which allow a large fraction of the incident radio waves to interact with the snow volume even with limited layer thickness, thus providing opportunities for probing of the layer's physical parameters. The parameters of interest include, among others, the snow water equivalent (SWE), grain size and autocorrelation length [5], snow anisotropy [6, 7], or firn depth [8].

Bistatic radar provides an opportunity to expand the observed parameter space, through variation of the bistatic angle β. This provides access e.g. to a larger number of polarimetric parameters (such as the 4th Pauli scattering term which is zero by definition in the monostatic case due to the reciprocity principle). It's been indicated that bistatic configurations can provide enhnanced sensitivity to certain physical properties of the observed scene, such as soil moisture [9]. Modeling research is ongoing for the medium on snow, which has so far focused primarily on passive and monostatic active radar observations [4, 10].

In the first application to cryospheric investigations, bistatic KAPRI was deployed in February 2021 to investigate the coherent backscatter opposition effect (CBOE) [11] in a layer of seasonal snow on top of the peak Rinerhorn in Davos, Switzerland [12]. The observations were used to retrieve the scattering and absorption lengths of the snow layer.

3. BISTATIC RADAR INVESTIGATIONS OF THE GREAT ALETSCH GLACIER

In August 2021 and March 2022, KAPRI was deployed at the High Altitude Research Station Jungfraujoch, observing the Jungfraufirn area of the Great Aletsch Glacier.

The measurements in August 2021 were performed at time of year when the snow cover was experiencing daily melt-freeze cycles. This opens possibilities for exploration of the effect of varying penetration depth of the radio waves over the course of the day. A follow-up campaign was carried out in March 2022, complementing the dataset with observations of fresh, frozen snow cover, long time series (up to 30 hours in duration), as well as in-situ measurements of snow properties (vertical profiles of snow grain size, density, and temperature).

3.1. Observation parameters

The primary and secondary KAPRI devices are shown in Figs. 1 and 2 respectively. The devices operated simultaneously – the primary device operated as a transmitter-receiver, acquiring a monostatic dataset ($\beta = 0°$), while the secondary device operated as a receiver only, acquiring an additional bistatic dataset ($\beta = 20°$ to $60°$). Fig. 3 shows a map of the bistatic observation geometry.

The acquired dataset includes full-polarimetric interferometric time series (span of 8-30 hours, time step 2-3 minutes), allowing analysis of glacier flow through differential interferometry, and investigation of possible changes in polarimetric scattering properties of the snow cover over the course of the daily melt-freeze cycle. Comparison of data between the summer and winter campaigns can also provide insights into the yearly cycle of the properties of the snow cover.

3.2. Preliminary results

In a preliminary analysis, the radar data was processed into first-order polarimetric parameters (lexigographic and pauli scattering vectors) and second-order polarimetric parameters (entropy, anisotropy, alpha angle). Fig. 4 shows the polarimetric alpha angle observed by the monostatic device, the low value of which suggests that the predominant scattering process is single scattering. Fig. 5 shows bistatic polarimetric data in the lexicographic RGB basis. Fig. 6 shows a differential interferogram acquired with the primary device with a temporal baseline of 1.5 hours. Map underlay data source for Figs. 4–6: swissALTI3D, swisstopo.

Fig. 1. The primary KAPRI instrument (P) placed on the terrace of the High Altitude Research Station Jungfraujoch, observing the Jungfraufirn area. The rotating tower performs azimuthal sweeps of the scene, acquiring a monostatic, full-polarimetric, single-pass interferometric dataset during each acquisition.

4. DISCUSSION

The characterization of the CBOE using KAPRI [12] demonstrates its capabilities for experimental acquisitions and exploration of previously inaccessible imaging configurations. Furthermore, the Davos experiment demonstrates the benefits of performing exploratory smaller-scale acquisitions with ground-based systems to better understand the investigated effects, before moving on to larger scale airborne and spaceborne campaigns. The results can help better understand scattering processes within snow, and can improve accuracy of methods that depend on precise knowledge of penetration bias, such as ice thickness monitoring.

The measurement campaign using KAPRI in the bistatic configuration at the Jungfraujoch High Altitude Research station aims to provide a comprehensive dataset for investigations of the Ku-band monostatic and bistatic backscatter of snow. Combined monostatic and bistatic phase information can be used for precise mapping of the glacier's displacement magnitude as well as direction. Furthermore, as shown in the preliminary analysis, fully-polarimetric information can be used to provide insights into the scattering processes occurring within the snow layers. When combined with in-situ measurements and fresh snow observations, this dataset aims to serve as a test-bed for development and validation

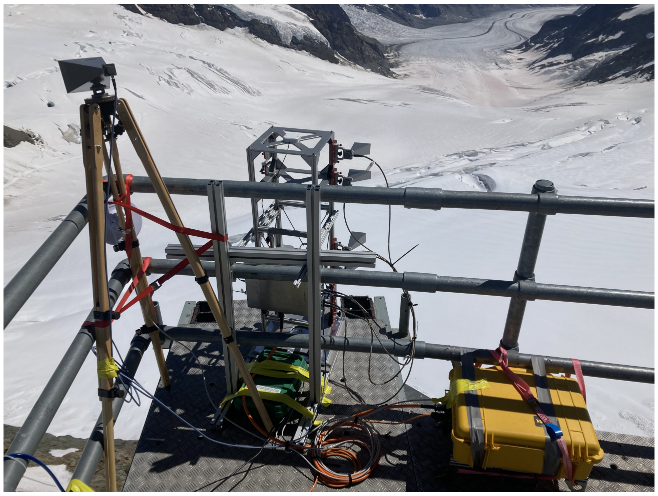

Fig. 2. The secondary KAPRI receiver (S) placed on the terrace of the East Ridge building of the Jungfraujoch complex. The fixed horn antennas with half power beam width of 12° observe the snow cover at a variety of bistatic angles β (as the range distance changes). The retrieved dataset is full-polarimetric and single-pass interferometric.

of new snow parameter inversion methods which incorporate Ku-band bistatic radar data.

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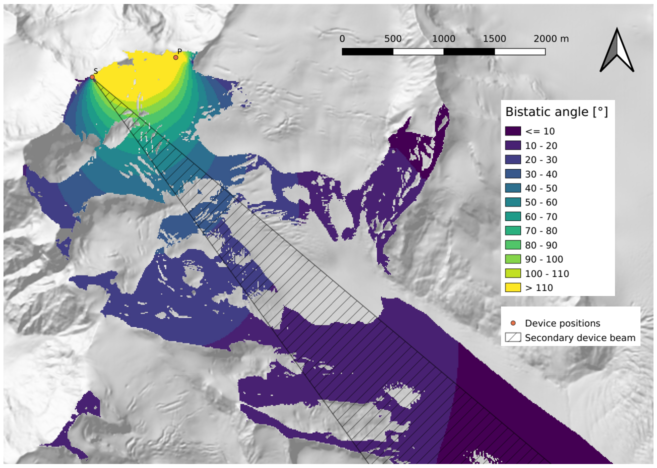

Fig. 3. Geometrical configuration of the bistatic acquisitions of the Jungfraufirn area. The positions of the primary (P) and secondary (S) device are marked in the upper left corner. The colored map shows the area visible from the location of the primary device, which can be imaged. Due to the local topography, certain areas of the glacier cannot be imaged from the devices' positions, however the exact coverage slightly varies depending on the height of the snow cover. The color indicates the value of the bistatic angle β between the P and S device. The triangular patterned area shows the beam of the secondary devices' receiver antennas. Bistatic imaging is performed in the area covered by this beam, and spans a range of bistatic angles.

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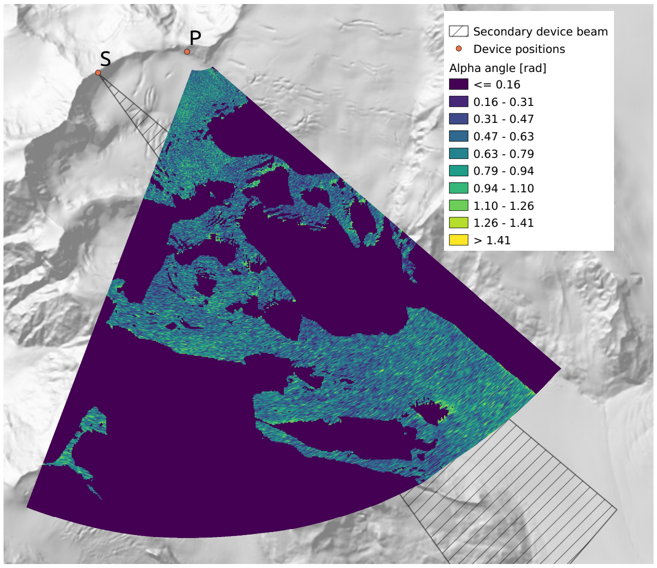

Fig. 4. Monostatic polarimetric alpha angle observed by the primary device. The low value of the alpha angle indicates that the predominant scattering process is a single-scattering type process. *Preliminary results.*

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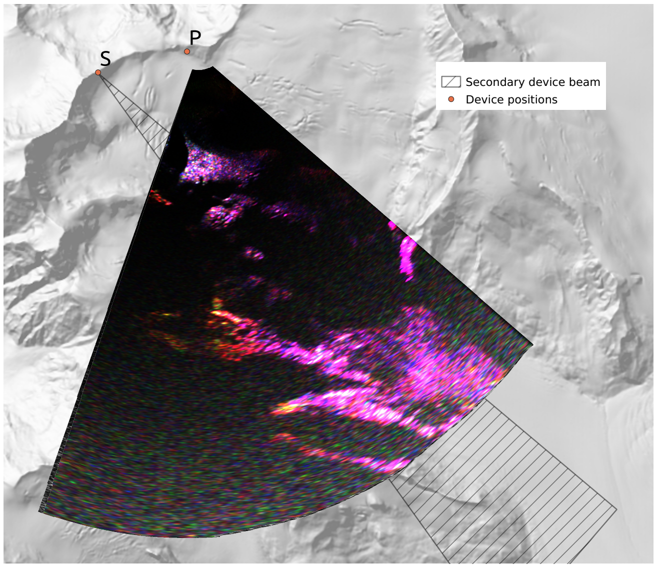

Fig. 5. Bistatic polarimetric image acquired by the secondary device in the lexicographic basis (R: HH, G: HV, B: VV). Only areas within the secondary device's beam return a strong signal. The purple color of the majority of the areas indicates that the HH and VV channels are equal in strength, while the HV channel is comparatively much weaker. This suggests a high contribution of surface scattering, similarly to monostatic data. This can be explained by presence of melt-freeze crusts close to the surface. *Preliminary results.*

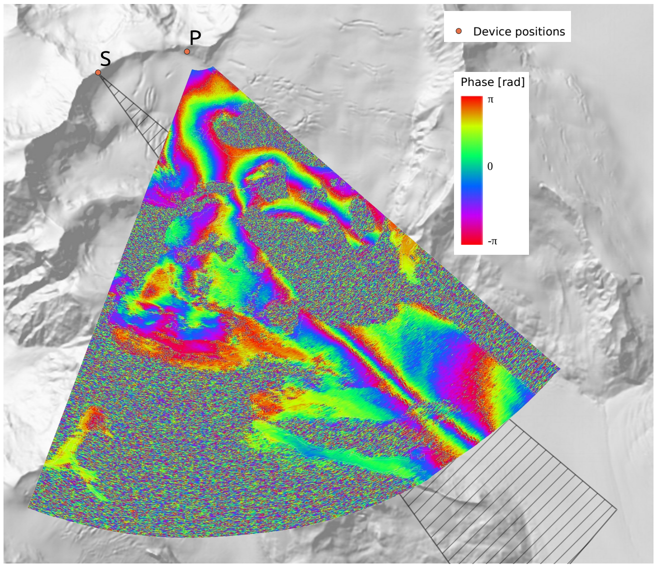

Fig. 6. Monostatic differential interferogram with temporal baseline of 1.5 hours and zero spatial baseline. The fringe pattern is caused by glacier motion – each wrap of the interferometric phase corresponds to displacement along the line of sight of $\lambda/2 \approx 8.2\,\mathrm{mm}$. At Ku-band, the 1.5-hour temporal baseline is already exhibiting ambiguities due to phase wrapping, and thus shorter temporal baselines (on the order of minutes) are beneficial for resolving these ambiguities through unwrapping of the phase history. *Preliminary results.*