Summary Final Report

Support to Microwave Scatterometer Measurements during MOSAiC

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Table of Contents

1. Summary of Achievements

The scientific goal of the multi-frequency microwave scatterometer deployment as a part of the MOSAiC remote sensing program was to evaluate current and future satellite missions such as SARAL/AltiKa (Ka-band), CryoSat-2, Sentinel-3 and CRISTAL (Ku-band), TerraSAR-X and COSMO SkyMed (X-band), RADARSAT Constellation Mission (RCM) and Sentinel-1 (C-band), ALOS-2 PALSAR-2, SAOCOM and ROSE-L (L-band) with high-resolution, ground-based microwave remote sensing measurements.

During the year-long MOSAiC expedition, a unique and benchmark dataset of Ka-, Ku-, X-, C- and L-band multi-frequency in situ radar measurements of winter, summer, and thin sea ice during freeze-up were acquired between October 2019 and October 2020, collected once per hour (whenever operational).

Overall, combined, 8000+ scans were collected from all scatterometers during the MOSAiC campaign, with a combined raw data volume of 255 GB.

Supporting meteorological observations around the scatterometer systems included 20+ meteorological and radiation parameters (sampled every second).

Coincident geophysical measurements included snow depth from magnaprobe and rulers, sea ice thickness from GEM and drill holes, snow/sea ice geophysical property observations of snow density, snow/sea ice salinity, snow/sea ice temperature and snow grain microstructure characterization.

Helicopter laser scans, terrestrial lidar scans and snow pits provide surface roughness at various resolutions covering Ka- to L-band microwave frequencies.

The multi-frequency aspect of the scatterometer measurements proposed is unique, as the MOSAiC expedition provided us with the opportunity to characterize a diverse range of snow and sea ice conditions found in the Arctic.

Overall, the MOSAiC campaign was a success, and the datasets are very important to understand multi-frequency microwave signals over snow-covered sea ice.

2. Objectives

Satellite remote sensing is the ideal tool to obtain regional- and hemispherical-scale, short- and long-term observations of snow-covered Arctic sea ice, lying within the ocean and atmosphere interfaces. Remote sensing datasets can be used to extend observations collected from the MOSAiC Floe (with diverse snow covers and a variety of sea ice types) to a larger scale and set them in context of a warming Arctic. MOSAiC expedition provided the ideal conditions for validation of satellite remote sensing observations: (a) as a unique case to observe the complete, annual seasonal thermodynamic cycle of sea ice growth, formation, and decay. Especially, winter observations from the central Arctic are basically absent and (b) the concept of MOSAiC that covered not only the MOSAiC floe, but also a distributed grid of measurements that covered satellite footprint scales, to make meaningful spatiotemporal comparisons feasible.

The year-long MOSAiC expedition provided us with the unique opportunity to acquire and interpret a benchmark dataset involving coherent in situ and multi-frequency microwave satellite data. This unique data will allow scientific community to better illustrate how diverse snow/sea ice geophysical and thermodynamic properties, from different sea ice types, influence microwave interactions (i.e., backscatter, penetration etc.) of Ka-, Ku-, X-, C- and L-band microwave frequencies. In particular, for the first time, with the data collected from MOSAiC, it will be possible to evaluate the seasonal evolution of multi-frequency microwave backscatter and penetration depth through snow-covered sea ice over different sea ice regimes, from first-year (sea ice greater than a few cm) through to multi-year sea ice. In addition, the MOSAiC expedition showcased the joint deployment and measurements of coincident active and passive microwave observations from the multi-frequency microwave scatterometers and passive microwave radiometers (operational from 0.5 GHz to 6 GHz). The expedition also provided the opportunity for year-round observations of snow and sea ice geophysical properties that will now allow for a rigorous development, improvement and assessment of retrieval methods of snow and ice properties from forward radiative transfer and microwave scattering models. As a fundamental requisite to develop and validate such models, joint ground-based scatterometer measurements with coincident in-situ measurements of all relevant variables are needed. These experiments with collection of a suite of unique multi-frequency scatterometer data with coincident in situ geophysical property data are needed for current and future EUMETSAT/EU Copernicus/ESA satellite missions, if we are to improve satellite retrievals of critical snow/sea ice state variables such as snow depth, sea ice thickness, detection of snow/sea ice thermodynamic timings such as freeze-up, melt- and pond-onset, quantifying melt pond fraction etc.

3. Questions to answer from MOSAiC Observations

One scientific goal of MOSAiC for remote sensing is the ground validation of various satellite products and to develop novel retrieval methods for critical snow and sea ice state variables from satellites. The data collected from MOSAiC will help us answer the following questions:

1) How well do satellite data-derived algorithms work in the Central Arctic when older and thicker multi-year ice is replaced by younger and thinner first-year ice for parameters such as snow depth, sea ice thickness distribution, freeze-up and melt-onset timings, sea ice type, floe sizes, ice concentration, and ice drift and deformation?

2) Would it be possible for co-located in situ sea ice/snow and multi-frequency microwave measurements help to develop improved satellite retrieval methods of parameters mentioned in 1) and lead to better understanding and forward models of the snow/sea ice microwave scattering and emission and scattering processes?

3) How can present and forthcoming EUMETSAT/EU Copernicus Candidate Missions such as CryoSat-2, Sentinels, CRISTAL and ROSE-L extend our sea ice observation capabilities in the future?

4. Scatterometer Data Analysis: First Results

All final data and metadata of all scatterometer measurements will be stored at the MOSAiC Central Storage (MCS) and at PANGAEA (World Data Center PANGAEA Data Publisher for Earth & Environmental Science (www.pangaea.de) after post-processing and quality control. Storage and release of data follow the MOSAiC data policy (https://mosaic-expedition.org/wp-content/uploads/2020/12/mosaic_datapolicy.pdf). All data and metadata are handled, documented, archived and published following the MOSAiC data policy. Scatterometer instrument PI permission is required to access, analyse and publish data before 1st January 2023. Data will be freely and publicly available on 1st Jan 2023 abiding by MOSAiC Data Policy. From this date, there are no restrictions on data usage. However, users are encouraged to communicate with the PI, during access, analyses, interpretation and publishing of data. The status of individual scatterometer data processing is as follows:

- All Ka- and Ku-band (KuKa radar) data has been processed and quality controlled. The raw and processed data in netcdf format are stored in the UK's NERC repository (https://doi.org/10.5285/5fb5fbde-7797-44fa-afa6-4553b122fdef).

- All C- and X-band (C-Scat and X-Scat) data have been processed and quality controlled. Since no external calibration was conducted for these instruments during MOSAiC, data processing is carried out using an internal calibration routine proposed and tested by the instrument manufacturer ProSensing Inc. Additional external calibration files from the instruments conducted from previous field campaigns are available for data quality comparison. Once data processing is complete (expected by mid-December 2022), the raw and processed data (in .txt format) will be made available in a EUMETSAT server.

- The L-band (L-Scat) data is presently undergoing data pre-processing quality checks by the instrument manufacturer ProSensing Inc. and the instrument PI. The quality checks include investigating data from October 2019 to March 2020 at higher incidence angles where L-Scat underwent wind-induced movement of the system during data acquisition. In March 2020, the instrument suffered a major technical failure that was refurbished in July 2020. Data collected after refurbishment are undergoing tests for signal quality (e.g. noise levels, shift in range power at select incidence angles, etc.). Once quality checks and data processing are complete (date to be confirmed), the raw and processed data (in .txt format) will be made available on a EUMETSAT server.

Multi-frequency scatterometer measurements acquired from Ka-, Ku-, X-, C- and L-band frequencies allows us to better determine the influence of different microwave scattering mechanisms from the snow-covered sea ice media on the measured signal. **Figure 1** illustrates the first-ever, high-resolution multi-frequency microwave measurements of a daily-averaged Ka-, Ku-, X-, C- and L-band VV-polarized backscatter dataset (as a function of incidence angle), acquired from the remote sensing site on the MOSAiC floe on different days during polar winters in January and February 2020. The scatterplot clearly demonstrates strong frequency-dependent backscatter separability between Ka- and L-bands as a function of penetration depth. Higher backscatter at Ka-band suggests dominant backscatter from the air/snow interface, while much lower backscatter from the lower frequency L-band suggests backscatter originating from the sea ice volume. Also to note is the classical decline of backscatter across incidence angle, strongly demonstrating the shift of microwave scattering from surface scattering (at steep incidence angles) to volume scattering (at shallow incidence angles); both suggesting the sensitivity of microwaves to snow/sea ice geophysical properties to changes in microwave parameters such as frequency and incidence angle.

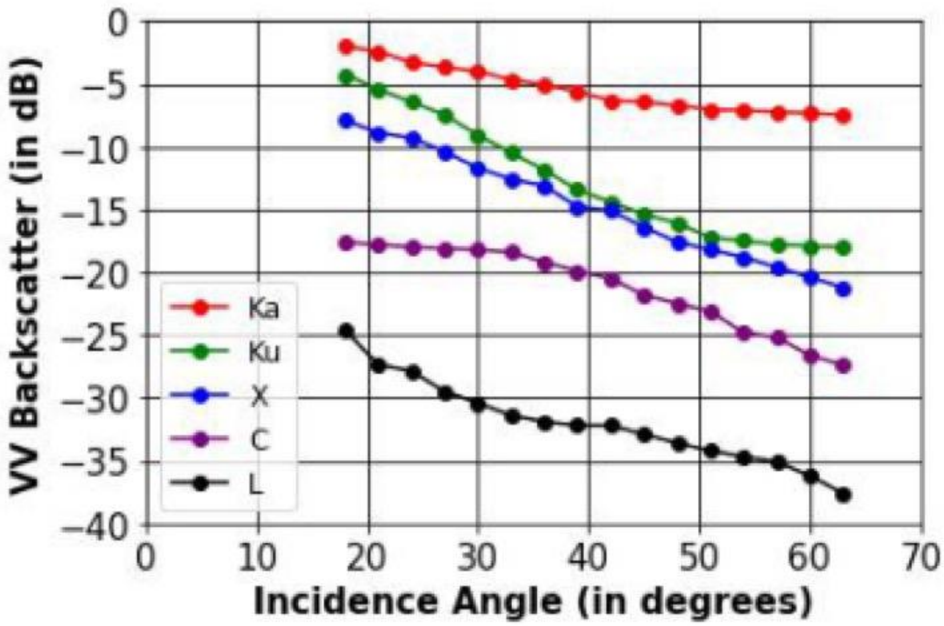

Figure 1: Scatterplot of daily averaged Ka-, Ku-, X-, C- and L-band VV-polarized backscatter (y-axis) against incidence angle (x-axis) from MOSAiC Winter Leg 2 Phase. Ka- and Ku-band (KuKa Radar) and L-band (L-Scat) observations are from 8 January 2020. C-band data (C-Scat) is from 17 January 2020. X-band (X-Scat) observations are from 6 February 2020. **Note:** Ka-, Ku-, and L-band data are calibrated. Markers represent the daily mean backscatter and cubic spline interpolated.

5. Moving Forward

During the MOSAiC expedition, a unique dataset of multi-frequency (Ka-, Ku-, X-, C- and L-band) in situ radar measurements was collected between October 2019 and October 2020 and is now analysis-ready. Listed below are five topics that merit investigation using the dataset:

a) Evaluation of first-ever, multi-frequency microwave backscatter characterization of Arctic sea ice from Ka-, Ku-, X-, C- and L-band frequencies. The overarching research objective would be to quantify and differentiate the dominant scattering horizons (peak power location within air/snow/sea ice interface and/or volumes), penetration depths and diverse scattering mechanisms from snow-covered sea ice, throughout the snow/sea ice annual thermodynamic regime (i.e., from freeze-up to advanced melt) for different sea ice types. Scatterometer observations will be supported by snow/sea ice geophysical properties and meteorological measurements that will help resolve the scattering horizons and mechanisms from the snow/sea ice media.

   Status: Work is in progress and is led by Dr. Randy Scharien (U. Victoria) and Dr. Vishnu Nandan. Data from January and February 2020 are being used for the analysis when all scatterometers operated coincidently during this period. Ka-, Ku- and C-band data processing and quality control is complete. Since C-band corner reflector calibration was not conducted during MOSAiC, the internal calibration routine is used to calibrate the data files. Additionally, only polarimetric data files are selected while corrupted files are filtered and removed from the analysis. X- and L-band data processing is half-way. Due to strong wind effects on L-band scatterometer system at higher incidence angles, only select data from stable incidence angles will be used in the analysis.

Work Priority: High. Preliminary data analysis is in progress, and an update will be provided in mid-December 2022.

b) Investigation of how diurnal meteorological and geophysical property cycling during spring, warm winter storms and unusual precipitation events such as rain-on-snow and freezing rain events impact temporary/permanent change in snow/sea ice geophysical properties (e.g. melt/refreeze cycles, formation of surface crusts and/or ice layers in snow) and its resultant effect on radar signals at multiple frequencies. Supported by meteorological and snow/sea ice geophysical property measurements collected coincident to these events, the scatterometer measurements will provide us a process-scale understanding how these environmental-driven changes affect microwave backscatter at plot-scales and will further allow comparisons with potential changes observed from satellite measurements.

Status: The impact of warm winter storms and summer rain-on-snow events on Ka- and Ku-band radar signatures (from KuKa radar) is in its manuscript publication phase. Two papers are already in review in journal The Cryosphere. The rain-on-snow paper has been published (see: https://tc.copernicus.org/articles/16/4223/2022/) and the KuKa wind paper first review is complete with positive reviews, and the revision due to be submitted by 25 November.

Forthcoming Study: The KuKa radar analysis team discovered a strong melt/refreeze cycling event that occurred in July 2020 impacting Ka- and Ku-band radar signatures. L-band measurements were also collected coincident to KuKa radar measurements. A joint Ka-, Ku- and L-band multi-frequency investigation is planned as a follow-up study to the Ka- and Ku-band rain-on-snow study. Although KuKa radar processing is complete and quality controlled, L-band scatterometer data is presently undergoing quality checks due to technical issues during July 2020 timeframe.

Work Priority: Medium (dependent on L-band scatterometer data quality). An independent Ka- and Ku-band study will be conducted if L-band data is deemed unusable. The Ka- and Ku-band data is analysis-ready and could start in January 2023.

c) Development and improvement of microwave radiative transfer models such as MEMLS-A, SMRT, and others to retrieve critical snow/sea ice state variables. High resolution snow/sea ice geophysical and thermodynamic properties would be utilized to simulate microwave backscatter and penetration depth at multiple microwave frequencies. The plan would be to compare and correlate modeled vs observed microwave backscatter and report the model uncertainties and biases.

Status: SMRT model setup is ready for snow/sea ice parameter ingestion for model runs. All necessary snow/sea ice geophysical parameters are compiled, and quality controlled for model runs. The remaining task is to select model input data timeframes from winter and summer seasons to compare SMRT modeled backscatter vs observed scatterometer data. Although modeled vs observed analysis can be conducted for the winter period from January and February 2020 when all scatterometers operated coincidentally, summer analysis will be limited to only Ka-, Ku- and L-band data since X- and C-scats were not operational.

Work Priority: Medium. SMRT model performance for different snow and sea ice property types could start in February 2023 as there is a need to initiate collaboration with the snow team to get all the data for the modeling study.

d) Investigation of the potential of combining active and passive microwave measurements from MOSAiC to quantify the joint impact of snow geophysical and thermodynamic properties on snow depth, sea ice thickness and concentration. The focus of the study would involve using C-band backscatter from C-Scat and brightness temperature measurements from HUTRAD, collected during mid-winter season, prior to melt-onset where snow/sea ice medium underwent critical diurnal cycling of snow properties (e.g. snow temperature, density and salinity effect on brine volume).

Status: C-band scatterometer along with HUTRAD passive microwave radiometer data collected high-resolution datasets during the April 2020 mid-winter thermodynamic warming event that significantly affected the MOSAiC floe. A joint study combining C-Scat and HUTRAD, with coincident meteorological data and snow/sea ice geophysical property measurements has already started. The study is in collaboration with the University of Bremen and AWI, Germany. The study already has access to snow/sea ice geophysical datasets collected by SLF, Switzerland. C-Scat and HUTRAD data processing is complete and analysis-ready.

Work Priority: High. Data analysis could start anytime and the first round of analysis could be completed by early December 2022. The HUTRAD data has been received from the University of Bremen and the C-Scat processing is also complete.

e) Assessing scaling (upscaling) effects from X-, C- and L-band scatterometer data to satellite-based SAR TerraSAR-X, RCM and ALOS-2 PALSAR-2 measurements. This study will provide us detailed and in depth understanding of how snow/sea ice geophysical and thermodynamic process at plot-scales can be effectively utilized to interpret satellite SAR signatures, towards retrieving critical snow/sea ice physical parameters such as freeze-up and melt-onset timings, sea ice types, surface roughness etc.

Status: The study requires extensive review of methods as methodological approaches needs to be devised that will enable to upscale the scatterometer data to SAR data, and thereby establish meaningful relationships between the scaled data and underlying snow/sea ice geophysical processes.

Work Priority: High. Satellite SAR data compilation and review of methods could start in mid to late February 2023.

f) Development of a generic open-access python workflow to process datasets collected from all scatterometer systems during MOSAiC. We propose to extend this package applicable for all scatterometer data for all frequencies.

Status: The python workflow has been successfully implemented for Ka- and Ku-band (KuKa radar) system and the python package KuKaPy is publicly available. C-Scat python package is half-complete and is undergoing tests. X- and L-band workflow translation will start once C-band workflow is complete.

Work Priority: Low. Operational IDL scripts are already being used for X- and L-band data processing.