EUROPEAN SCIENCE FOUNDATION

Research Networking Programmes

Science Meeting – Scientific Report

The scientific report (WORD or PDF file - maximum of seven A4 pages) should be submitted online within two months of the event. It will be published on the ESF website.

Proposal Title: *Workshop on Microstructure in Snow Microwave Radiative Transfer*

Application Reference N°: 5538

1) Summary (up to one page)

The first day of the MicroSnow workshop concentrated on reviewing historic observations and theory, the current state of microwave emission and scattering models, and new techniques to quantify the microstructure of snow. On the first evening, a model clinic was held where microwave scattering models were made available to workshop participants, and the people who developed those models were on hand to assist with any questions. The second day concentrated on uncertainties in model inputs, evaluation and intercomparison of microwave models. On the third day, the morning session covered applications of those models to satellite retrievals, and was followed by an afternoon discussion as to the future of theory and applications, and collaborative efforts within the community.

Significant progress has been made in understanding how to quantify the snow microstructure, and in defining the steps needed to allow full microstructural information to be used in microwave scattering models. Microstructure evolution within snowpack models needs further development, but will require more micro-CT and field observations. This approach will move the community away from subjective or empirical corrections to microstructure quantification, towards a fully objective and physics-based interpretation that will be consistent between microwave models. Stratigraphy, representation of soil and melt-freeze processes and vegetation effects are also areas of significant research activities, which will contribute to the overall remote sensing of snow.

There is a strong need and desire for a satellite mission to measure snowpack properties, and our improved understanding and representation of the microstructure is at the core of this. The community is co-ordinated and planning to collect a gold-standard dataset for validation of snow remote sensing retrieval systems. We will reconvene in 2015 at MicroSnow2.

2) Description of the scientific content of and discussions at the event (up to four pages)

Snow microstructure is a key uncertainty in interpretation of satellite observations at microwave frequencies as scattering of electromagnetic radiation is hugely sensitive to the size of the scatters. This workshop focussed on how to quantify the snow microstructure, and use that information in electromagnetic scattering models for new techniques to observe global snow mass.

The workshop opened with a keynote presentation from Martin Schneebeli, who gave a summary of new techniques to quantify the microstructure of snow, and presented results from a field experiment to compare the specific surface area (SSA) of the same samples of snow observed with a range of instruments. These included micro-CT observations, traditional observations, image analysis, spectral and single wavelength reflectance, BET gas adsorption and snow micropenetrometer measurements. It was shown that micro-CT, BET and reflectance methods agreed to within 2 m^2 kg^{-1} for snow SSA in the range 5-30 m^2 kg^{-1}. The dataset from this experiment will be made publicly available in 2015.

Christian Mätzler gave the second keynote presentation with an historical overview of research in snow microwave observations and modelling, which spans over 36 years of his own experience. This presentation included observations of wet snow, ice lenses, snow on sea ice and impact of layering, and highlighted soil and roughness effects as areas where future research activities are needed.

Ghislain Picard gave the third and final keynote presentation, which focussed on the role of microstructure in radiative transfer. There were several thought provoking points raised: that there is no one perfect model for all applications, that the single length scale to parameterise the snow microstructure captures some, but not all of the scattering behaviour and that empirical parameterisations such as ‘stickiness’ or scaling of the grain size really compensates for the need for multiple microstructure length scales in the model. In addition, the scattering models that are based on assumptions of spherical scattering work well when the scatterers are genuinely spherical i.e. air bubbles in ice.

In the first afternoon, the technical details of 4 different microwave scattering models were presented. These were the Helsinki University of Technology emission model (HUT), the Microwave Emission Model of Layered Snowpacks model (MEMLS), the Dense Media Radiative Transfer Multi-Layer emission model (DMRT-ML) and the Bicontinuous and Quasi-Crystalline Approximation (QCA) flavours of the active DMRT model. Each of these models use a different quantification of the snow microstructure. HUT has an effective diameter, which was derived from observations of the maximum grain extent. MEMLS uses correlation length, which is one length scale derived from the autocorrelation function. DMRT-ML and DMRT-QCA active uses effective diameter and a ‘stickiness’ parameter, although DMRT-QCA active can also use effective diameter and standard deviation of particle sizes. The bicontinuous representation of snow uses a series of stochastic waves to represent the snow microstructure. Although this appears to give a realistic distribution of snow in comparison with snow thin section images, the model parameters required to represent the snow do not translate easily to snow observations. All presentations on the first day gave a good basis for the evening activities: a model clinic to distribute microwave scattering model code and discuss details of the model assumptions and get assistance in installing and using the code as well as adapt their own data to use in the models.

On the second day, the first session discussed quantification of the necessary parameters to drive the snow radiative transfer models. Henning Löwe investigated the relationship between the Improved Born Approximation (a two-point correlation function) and QCA with coherent potential (QCA-CP) (a pair correlation function) assumptions. He then used micro-CT data to derive necessary parameters for a sticky hard sphere microstructure representation, which require a grain scale factor to be consistent with observations. Martin Proksch presented snow micropenetrometer field observations of a 50m transect with 2-D measurements of snow microstructure and stratigraphy, and related those to the spatial variability in brightness temperature simulated with the MEMLS model. Clearly one profile of snow observations is not sufficient to represent the snow stratigraphy, and techniques such as this can be used to define field measurement protocols for satellite ground truth data collection. Ice lenses within the snow have a strong impact on microwave brightness temperature so introduce uncertainty in simulations, as shown by Tom Watts, but have been modelled in the past either as solid ice layers, or as high density snow layers. Tom presented a new field method of measuring ice lens density by immersing samples in mineral spirits and measuring the change in volume and mass. Measured ice lens density was 885 kg m^{-3}, and gave improved simulations compared with assumptions of pure ice but poorer simulations compared with lower assumed density values. Overall, caution was advised not to use ice lens density to tune the simulations, and that other aspects of the models should be examined.

The model evaluation session covered airborne radar measurements in the Canadian Tundra with coincident trench and pit observations, presented by Josh King. As the underlying topography controls both depth and fraction of larger depth hoar crystals within the snowpack, interpretation of the signal is complicated. Large-scale evaluation of satellite data requires careful consideration of ground-truth site locations and capability. Ali Arslan discussed a plan for community efforts to harmonize field observations and retrieval techniques, as well as plan for future measurement and validation strategies. Ed Kim highlighted a novel technique to retrieve snow depth from GPS receivers, using interferometric techniques. As GPS receivers are widespread, these could partially fill in measurement gaps in existing measurement network sites that have elevation biases. As the parameterisation of the soil was considered by the workshop participants to be one area where more research was needed, Simone Bircher gave an impromptu talk on laboratory and field measurements of soil dielectric constant at L-band frequencies. This work needs to be extended to higher frequencies for snow applications.

Building on Martin Schneebeli's presentation of the different measurements of snow microstructure, Nick Rutter showed the impact of source of the microstructure information on the simulation of microwave brightness temperature. Although two of the seven available datasets had retrieval errors that have since been understood, the spread in brightness temperature from the seven measurements ranged from 6K (with three measurements excluded) to 82K. Marion Leduc-Leballeur presented a comparison between brightness temperature simulated with the MEMLS model and data from the Soil Moisture Ocean Salinity (SMOS) mission at L-band frequencies. With the longer wavelength, the penetration depth is much greater, so SMOS is sensitive to snow and ice properties deep within ice sheets. Noise in the density profile was required to reproduce the angular dependence of SMOS observations, which led to the development of a wave model and opens up the possibility of using L-band observations to retrieve internal ice sheet properties and climate information. Jinmei Pan gave the final presentation of the session and looked at conceptual differences between the HUT and MEMLS models. MEMLS is a 6-flux model and accounts for downwelling radiation explicitly whereas HUT is a simplified 2-flux model with the assumption that 96% of radiation is scattered in the forward direction, and both have different representations of the scattering coefficient based on different microstructure parameters. From the MEMLS simulations, the proportion of radiation scattered in a forward direction is not as strong as assumed in the HUT model, which leads to large errors in brightness temperature simulations for deep snow.

Posters concluded the second day and were well attended, with vibrant discussion surrounding them. Ludovic Brucker demonstrated the potential of using snowpack evolution models based on physics to provide the necessary parameters to drive microwave scattering models, but noted that the simulation of larger snow grains needed to be improved. Nicolas Champollion inverted brightness temperatures to show a decrease in surface snow density from 2002 to 2011, which indicates changes in the meteorological conditions. Ensemble simulations of snowpack properties and brightness temperature were demonstrated by Ian Davenport, who showed that melt-freeze events at the start of the snow season had an impact on brightness temperatures throughout the season. Maria Hörhold used the fact that densification and grain growth are part of the same metamorphic process to reconstruct snow specific area profiles from 5 micro-CT observations and high resolution Gamma-absorption derived density profiles. Incorporation of increased variability in snow SSA in MEMLS and DMRT-ML improved seasonal simulations of satellite brightness temperature at Kohnen Station, Antarctica.

An overview of the ECMWF snow analysis was presented by Heather Lawrence, who also demonstrated the need for accurate understanding of the surface emissivity (governed by the snow microstructure) to be able to use atmospheric sounding data in their data assimilation scheme. Leena Leppänen compared traditional, optical, effective (from inversion of microwave observations with the HUT model) grain sizes and correlation length measured with a snow micropenetrometer. Although the traditional grain measurement gave the best agreement with the effective grain diameter, the variability of the optical measurements explained the temporal variation in effective grain diameter the most. Results from the first Arctic Snow Microstructure Experiment (ASMEx) were presented by William Maslanka. Brightness temperature of slabs of snow were measured at multiple frequencies and incidence angles, followed by destructive sampling of the snow to measure microstructural parameters including extraction of samples for micro-CT analysis. These measurements will allow the microwave scattering coefficient to be determined as a function of the snow microstructure, which will govern future model developments.

On the final day, presentations demonstrated how a better understanding of snow microstructure may be used for future remote sensing products. Wolfgang Dierking demonstrated the potential of radar to retrieve ice sheet accumulation rates, as large accumulation rates are linked to small snow grain sizes and thick layers, whereas low accumulation rates result in larger grain sizes and thinner layers. A consideration of the surface and internal layer roughnesses was also presented, as the radar intensity depends on the azimuth, and the need for an understanding of snow microstructure anisotropy was also highlighted. Juha Lemmetyinen presented retrievals of the effective grain diameter from satellite, NoSREx airborne and ground-based radiometer observations. The effective grain diameter gave reasonable agreement with traditional grain size observations (maximum extent of grains), with differences occurring because the effective grain diameter incorporates land cover effects. In order to retrievals to be made that reflect spatial variability in snow microstructure, model deficiencies must be resolved and appropriate inputs used.

Richard Kelly presenting on behalf of Nastaran Saberi introduced a prototype retrieval system to derive snow water equivalent from the new AMSR-2 measurements. Comparisons between observations and forward modelling of brightness temperature with the DMRT-ML model (driven by depth observations and climatological grain size and density values) showed a good level of agreement. Saberi notes that the retrieval system will be a balance between data integration and stand alone physics-based approach, and that both observation and modelling errors need proper characterisation. Mike Durand built on this by presenting the results of a SAST-MEMLS data assimilation retrieval system applied over the Kern River basin in California, USA. Snow microstructure evolution was represented with the SNTHERM grain growth rate, where the growth parameter was calibrated to seasonal AMSR-E observations. The presentation raised the question about which microstructural evolution models should be used, and whether those that retained a link to the physical grain size is better. Alain Royer gave the final presentation of the meeting and the only presentation to consider vegetation effects explicitly. Forward simulations of brightness temperature were presented from the CLASS land surface model, coupled with the snow SSA evolution model of Taillandier et al. (2007), DMRT-ML and the tau-omega vegetation model, and the brightness temperature was shown to have a low sensitivity to SWE in dense boreal forests. Highlighted areas for improvement were the representation of the forest effects, soil permittivity characterisation, representation of layering within the snow and an understanding of the snow microstructure (particularly the stickiness parameter).

It is clear that the international community has made significant progress over the last decade in direct and indirect quantitative snow grain measurements, and is well co-ordinated in determining the spread in snow grain measurement methods although large faceted grains require more investigation. There is also a rich heritage of microwave measurements and emission modelling of terrestrial snow cover but no central data repository. In addition, classic experiments are being revisited with new microstructure observations.

Ongoing challenges include the inconsistency between microstructure characterization within microwave scattering models, understanding the microwave permittivity of soils (particularly organic soils), how to use field observations of snow microstructure in the microwave models, spatial variability in snow microstructure and macrostructure, and whether current observations and models are sufficient to achieve the ultimate goal of snow water equivalent retrievals.

Assessment of the results and impact of the event on the future directions of the field (up to two pages)

The MicroSnow workshop was a unique opportunity to bring together researchers from groups traditionally focussed on snow microstructure observations and modelling with researchers for whom snow microstructure is a crucial variable for remote sensing retrievals. Significant progress has been made over the last year, in terms of understanding why empirical scaling factors or 'stickiness' parameters are required to use objective measurements of optical snow grain diameter in microwave scattering models, even though both are based on assumptions of spherical scatterers. The answer became apparent during the meeting, through the presentations of Picard and Löwe: that the scattering of microwave radiation is sensitive to a range of length scales, and empirical correction factors compensate for the representation of only one length scale in the models. The next step for the community, therefore, is to redefine the microwave scattering models for the range of scales in the model. The bicontinuous representation of the snow in DMRT does this, but the parameters do not have a physical equivalent. New micro-CT observations can be used to quantify the full microstructure of the snow. There are sample size limitations, but these can be used to quantify the autocorrelation function. Scattering coefficients dependent on the autocorrelation function should give a much better representation of the microwave behaviour, without the need for empirical corrections. This is a fundamental step change in how we approach microstructure and radiative transfer theory.

With that in mind, the next step from the snowpack modelling community is the need for a snowpack evolution model capable of simulation of the autocorrelation function. A limitation at present is the lack of a range of datasets to do this. In general, it was agreed that community efforts should be focussed on producing a 'gold standard' dataset for testing snowpack evolution models linked to microwave scattering models in order to test retrieval systems. This will be a combination of high quality meteorological data, snow microstructure and macrostructure profile measurements with consideration of spatial variability, and passive and active microwave observations at multiple frequencies throughout the season and in multiple locations. The trade-off between multiple sites, multiple years and multiple scales was discussed heavily, but depends on future remote sensing activities.

There is a clear need and desire for a snow satellite mission to measure snow properties, made more feasible through the work presented in the MicroSnow workshop and the collaborations enhanced or developed as a result. Much of the final discussion focussed on co-ordination of activities through IACS, Global Cryosphere Watch and COST Action, and various space agency pathways to make this happen. The need for a follow-up meeting was agreed. 'MicroSnow2' will be held in North America in summer 2015, where plans for a gold standard field campaign and snow mission approach will be outlined.

Annex 4a: Programme of the meeting

Programme: 6 August 2014

0815	Registration	*Meadow Suite*
0845	Welcome and Housekeeping	*Mel Sandells*
0900	SESSION (INVITED): CURRENT STATE OF THEORY	*Chair: Mel Sandells*
0900	Lessons learned and recommendations from the Snow Grain Size Workshop	*Martin Schneebeli*
1000	Measuring and Modelling the Interaction of Microwaves with Snow	*Christian Mätzler*
1100	Coffee break	
1130	Snow microstructure to microwave modelling	*Ghislain Picard*
1230	Discussion	
1300	Lunch	
1400	SESSION (INVITED): MICROWAVE RADIATIVE TRANSFER MODELS	*Chair: Ian Davenport*
1400	Application of HUT snow emission model for practical retrieval of snow cover parameters	*Juha Lemmetyinen*
1430	Using the Microwave Emission Model of Layered Snowpacks (MEMLS)	*Mike Durand*
1500	The DMRT-ML model: numerical simulations of the microwave emission of snowpacks based on the Dense Media Radiative Transfer theory	*Ludovic Brucker*
1530	Coffee break	
1600	Active and Passive Microwave Remote Sensing of Terrestrial Snow Based on Bicontinuous/ DMRT and QCA/DMRT Models	*Leung Tsang*
1700	Discussion	
1830	MICROWAVE MODEL CLINIC AND BUFFET	*Chair: Maria Hörhold*

Programme: 7 August 2014

0900	SESSION: QUANTIFYING MODEL INPUT	*Chair: Nick Rutter*
0900	Sticky hard spheres as snow microstructure model: Tomography-based parameter estimation and the relation between MEMLS and DMRT	*Henning Löwe*
0930	The influence of spatial variability of polar firn on microwave emission	*Martin Proksch*
1000	Improved measurement of ice lens densities in snow microwave emission models	*Tom Watts*
1030	Coffee break	
1100	SESSION: MODEL EVALUATION	*Chair: Stefanie Linow*
1100	SnowSAR in Canada: An evaluation of basin scale dual-frequency (17.2 and 9.6 GHz) snow property retrieval in a tundra environment (Invited)	*Josh King*
1130	Cost Action On A European Network For A Harmonised Monitoring Of Snow For The Benefit Of Climate Change Scenarios, Hydrology And Numerical Weather Prediction	*Ali Arslan*
1200	GPS L-band interferometry offers new validation option for snow product evaluation (Invited)	*Ed Kim*
1230	Discussion	
1300	Lunch	
1400	SESSION: MODEL COMPARISON	*Chair: Ed Kim*
1400	Sensitivity of simulated brightness temperatures to multiple grain size measurement techniques of snow microstructure	*Nick Rutter*
1430	Modeling L-band brightness temperature at Dome C, Antarctica and comparison with SMOS observations	*Marion Leduc-Leballeur*
1500	Differences between the multiple-layer HUT and the MEMLS model and their comparisons with in-situ snowpack observations	*Jinmei Pan*
1530	Discussion	

Programme: 7 August 2014 (continued)

1600	SESSION: POSTERS	*Chair: Will Maslanka*
	Simulation of seasonal snow microwave brightness temperature using coupled multi-layered snow evolution and microwave emission models	*Ludovic Brucker*
	Spatial and temporal variations of snow density near the surface on the Antarctica Plateau, from AMSR-E passive microwave observations and ENVISAT radar altimetry measurements	*Nicolas Champollion*
	Towards a Data Assimilation Framework for Snow Microwave Retrieval from Passive Microwave Remote Sensing	*Ian Davenport*
	Accounting for the layering of snow and firn – on the link between density and grain size variability	*Maria Hörhold*
	Developments in the snow analysis at ECMWF and prospects for assimilating more sounder radiances over snow covered surfaces	*Heather Lawrence*
	Comparison of microwave radiometer observations and snow grain size in Sodankylä	*Leena Leppänen*
	Results from Arctic Snow Microstructure Experiments, 2014	*Will Maslanka*
1930	Conference Dinner	

Programme: 8 August 2014

0900	SESSION: MICROWAVE APPLICATIONS	*Chair: Josh King*
0900	Retrieval of Accumulation Rates on the Ice Sheets Using SAR	*Wolfgang Dierking*
0930	Retrieval of a microwave effective grain size for seasonally and spatially varying snow cover	*Juha Lemmetyinen*
1000	Coupling DMRT-ML to Spaceborne Snow Depth Retrieval	*Nastaran Saberi*
1030	Coffee break	
1100	The role of microstructure in forward modeling and data assimilation schemes: a case study in the Kern River, Sierra Nevada, USA	*Mike Durand*
1130	Coupling the Canadian Land Surface Scheme to a microwave model to simulate the snow microwave brightness temperature under boreal forest	*Alain Royer*
1200	Discussion	
1230	Lunch	
1330	Discussion: Future of Snow Microwave Scattering Theory and Applications	*Chair: Nick Rutter*
1500	Close and depart	

Annex 4b: Full list of speakers and participants

First Name	Surname	Institution	Country
Raquel	Alegre	University of Reading	UK
Teruo	Aoki	Meteorological Research Institute	Japan
Ali	**Arslan**	Finnish Meteorological Institute	Finland
Simone	**Bircher**	Centre d'Etudes Spatiales de la BIOsphère	France
Ludovic	**Brucker**	NASA-GSFC	USA
Nicolas	**Champollion**	International Space Science Institute	Switzerland
Debbie	Clifford	University of Reading	UK
Ian	**Davenport**	University of Reading	UK
Wolfgang	**Dierking**	Alfred Wegener Institute	Germany
Mike	**Durand**	Ohio State University	USA
Steven	English	ECMWF	UK
Richard	Essery	University of Edinburgh	UK
Charles	Fierz	WSL Institute for Snow and Avalanche Research SLF	Switzerland
JC	Gallet	Norwegian Polar Institute	Norway
Robert	Gurney	University of Reading	UK
Maria	**Hörhold**	University of Bremen	Germany
Javier	Jimenez	Alcalá University	Spain
Richard	**Kelly**	University of Waterloo	Canada
Michael	Kern	ESA / ESTEC	The Netherlands
Ed	**Kim**	NASA-GSFC	USA
Josh	**King**	Environment Canada	Canada
Alex	Langois	Université de Sherbrooke	Canada
Heather	**Lawrence**	ECMWF	UK
Marion	**Leduc-Leballeur**	Laboratoire de Glaciologie et Géophysique de l'Environnement	France
Juha	**Lemmetyinen**	Finnish Meteorological Institute	Finland
Leena	**Leppänen**	Finnish Meteorological Institute	Finland
Stefanie	Linow	Alfred Wegener Institute	Germany
Henning	**Löwe**	WSL Institute for Snow and Avalanche Research SLF	Switzerland
William	**Maslanka**	University of Reading	UK
Christian	**Mätzler**	Institute of Applied Physics	Switzerland
Samuel	Morin	Centre d'Etudes de la Neige, Météo France	France
Liz	Morris	University of Cambridge	UK
Jinmei	**Pan**	Ohio State University	USA
Ghislain	**Picard**	Laboratoire de Glaciologie et Géophysique de l'Environnement	France
Martin	**Proksch**	WSL Institute for Snow and Avalanche Research SLF	Switzerland
Alain	**Royer**	Université de Sherbrooke	Canada
Nick	**Rutter**	Northumbria University	UK
Mel	Sandells	University of Reading	UK
Martin	**Schneebeli**	WSL Institute for Snow and Avalanche Research SLF	Switzerland
Leung	**Tsang**	University of Washington	USA
Tom	**Watts**	Northumbria University	UK
Satoru	Yamaguchi	Snow and Ice Research Center	Japan

The names of presenters are given in bold