SPACE MISSION CONCEPTS FOR THE RETRIEVAL OF ACCUMULATION RATES IN POLAR REGIONS

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ABSTRACT

In this short note we present an overview about different methods to retrieve accumulation rates over the ice sheets using data from different satellite sensors (passive microwave radiometers, radar) and applying different retrieval algorithms. We demonstrate that a mission concept for the task of accumulation rate retrieval in the Polar Regions requires linking various components which comprise satellite data acquisitions, field measurements, and techniques for retrieval of snow/firn properties.

INTRODUCTION

In the public, space missions are usually recognized as exciting satellite technology optimized for a given goal such as acquiring data for monitoring Earth's environment. Exploratory and accompanying activities regarding technical details, data processing, or mission control – to name a few examples – are rarely appreciated in the same manner. This is also valid for efforts that are required to define the scientific goal of a mission and to maximize its outcome. In environmental studies and related Earth Observation (EO) activities, there is often a need to use data not only from a single satellite mission but from different missions, and to link them with field measurements and computer simulations of environmental processes. For deriving accumulation rates over the ice sheets, which is the topic of this note, it is essential to combine different observation technologies and retrieval methods.

The accumulation of snow on the ice areas of Greenland and Antarctica is linked to the mass balance of the ice sheets, i. e. the difference between mass gain due to precipitation and mass loss due to melting processes and iceberg calving. The interest in the mass balance of the polar ice sheets arises from the fact that their annual mass loss has been increasing during the past years. Hence, their contribution to sea level rise becomes more and more important. If the observed trend in mass loss continues, the ice sheets will become the major contributors to sea level rise during the 21st century [35]. The rate of snow accumulation needs to be known to quantify the mass gain of the polar ice sheets, as it is one of the parameters to deduce whether the mass balance of an ice sheet is positive or negative.

In this note we sketch approaches for accumulation rate retrieval, considering different satellite sensors, related fieldwork, and algorithms for the retrieval of snow/firn properties. Our conclusion is that a successful mission for the retrieval of accumulation rates consists of various components, which we discuss in the summary at the end of this note.

MEASUREMENTS AND RETRIEVAL OF ACCUMULATION RATES

The term "accumulation rate" refers to the net mass gain due to snow deposition at a given location for a defined time interval. It is the result of precipitation, sublimation and wind redistribution. The accumulation rate, and also the diurnal /annual temperature cycle, depends on the environmental conditions which constantly change the microstructure of the deposited snow. Large snow grain sizes and thin annual layers in the snow/firn[1] volume are associated with low accumulation, while small grains deposited in thicker layers are typical for high accumulation [31].

In the field, accumulation is quantified by measuring snow/firn layer thickness and density variations in snow pits or by using stakes, ultrasonic sounders or ground-penetrating radar [12]. Another possibility is to analyze chemical profiles of snow/firn cores [17] [27]. Ground measurements serve also as calibration and validation for other methods of accumulation rate retrieval [17].

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[1] Firn is the transition stage between snow and glacial ice with densities between 400 and 830 kg/m^3.

Regions of coarse-grained snow/firn have a higher radar backscattering intensity and a lower microwave brightness temperature than regions of fine-grained firn. The links between layer thickness and grain size, on the one hand, and the amount of snow accumulation, on the other hand, are the basis for algorithms developed to retrieve accumulation rates for the dry snow zone[2] from microwave data. On large spatial scales, accumulation rates were determined using data from passive (radiometer) or active (radar) microwave sensors [2] [10] [13] [14] [28]. Satellite data from sensors with large spatial coverage and high temporal sampling rate (such as passive microwave radiometers, PMR) were used to interpolate between locations of field measurements [13]. Synthetic aperture radar (SAR) was applied to derive snow accumulation rates on regional and local scales [8]. It is also expected that space-borne radar altimetry can be used for accumulation retrieval [20] [32]. The proposed methods for altimetry rely on the possibility to identify single annual layers in the firn. In the percolation zone, the snow/firn volume structure changes due to summer melt, related metamorphosis of the snow, and formation of ice lenses, crusts, and pipes. Therefore it is only possible to derive the current annual winter accumulation from satellite altimeters or scatterometers.

WHICH SATELLITE SENSORS CAN BE USED FOR ACCUMULATION RATE RETRIEVAL?

As there is a large variety of different satellite sensor types operating in the microwave frequency range, the instruments suitable for accumulation rate retrieval are briefly introduced here. *Table 1* gives an overview of some available sensors.

- ***Radiometers:*** Passive microwave brightness temperatures (T_B) are obtained from radiometers measuring the Earth's radiation. Those instruments typically have spatial resolution on the order of kilometers, but provide data at a high temporal rate. Brightness temperatures measured by space-borne radiometers at frequencies <7 GHz depend significantly on the layering structure of the firn [42]. The numerical simulation of microwave emission is less complex compared to the case of active remote sensing [33].
- ***Scatterometers:*** These radar instruments have spatial resolutions comparable to PMRs. Scatterometer data were used to develop empirical relationships for the retrieval of snow accumulation rates in the dry snow zone [10] and to delimit the dry snow zone on the ice sheets [5] [10]. By employing data from QuikSCAT, it was also possible to derive accumulation rates in the percolation zone [30].
- ***SAR***: This type of radar is an imaging instrument with high spatial resolution (between a few to several tens of meters) but mostly narrow swath widths (between 15 and 500 km). SAR is highly valuable for detailed comparisons between backscattering intensity (or other radar parameters) and accumulation rates measured in the field [11] [26]. Until now, investigations focused on the use of C-band SAR (5.3 GHz), but recently, also the application of X-band (9.6 GHz) and L-band (1.27 GHz) data was studied [6] [9].
- ***Radar Altimeters:*** Airborne measurements using a radar altimeter operated at 13.5 GHz in preparation of the Cryosat mission showed that individual reflecting horizons can be identified in the upper firn volume of the dry snow zone. These horizons can be correlated with annual layering of snow [32]. On the basis of the airborne measurements it is expected that the Cryosat-2 altimeter can be used for accumulation retrieval over areas of high accumulation rates. Over the percolation zone, it may be possible to determine the winter accumulation rate [20].

Table 1: Example of sensor types / data suitable for accumulation rate retrieval

Sensor type	***Sensor***	***Frequency***	***Operation period***
Passive microwave radiometer	SSM/I	4 bands: 19.35 – 85.5 GHz	1987 –
	AMSR-E AMSR-2	6 bands: 6.9 – 98 GHz	2002 – 2011 2009 –
Scatterometer	Seawinds / QuikSCAT	13.4 GHz	1999 – 2009
	ASCAT (MetOP-A and -B)	5.3 GHz	A: 2006 – B: 2012 –
Synthetic aperture radar (SAR)	Envisat ASAR	5.3 GHz	2002 – 2012
	Radarsat-2	5.3 GHz	2007 –
	TerraSAR-X	9.6 GHz	2007 –
	Sentinel-1	5.4 GHz	2014-
Radar altimeter	Cryosat-2	13.5 GHz	2010 –

[2] The dry snow zone is the region of an ice sheet not affected by melt. This means that melt-induced inclusions, such as ice lenses / pipes, do not affect the scattered or emitted microwave signal.

METHODS OF ACCUMULATION RATE RETRIEVAL

Empirical approach (EA): The most basic possibility for deriving accumulation rates from satellite data is an empirical approach. In this case, retrieval algorithms are established on the basis of relatively simple relationships, which are derived from comparisons of accumulation rates measured in the field and corresponding microwave signatures [30] [36]. However, the robustness of such relationships depends on the quality of the field data [17] [27]. Dependent on the spatial resolution of the satellite sensor, the effect of spatial heterogeneities and temporal changes of the firn properties have also to be taken into account [34].

Stratification approach (STA): Firn density stratification is strongly linked to accumulation rate. The stratification approach makes use of the sensitivity of brightness temperatures (T_B) to the reflections from firn density layering [42] [43]. This method requires T_B measurements at relatively low frequencies (< 7GHz) , where the influence of scattering from the snow grains is negligible. If both H and V polarization are analyzed, the polarization ratio of brightness temperatures reveals sensitivity to accumulation rates, which is strongest at lower rates. This method is described in detail in [30]. Internal ice crusts generated by intra-seasonal weathering have also a non-negligible effect on firn emission.

Two-step algorithms (2S): Another class of algorithms explicitly considers the sensitivity of the signal to environmental conditions. Those two-step algorithms explicitly include the scattering/emission properties of snow/firn microstructure [8] [14] [28]. In the first step, the metamorphosis of snow and firn is simulated using theoretical or empirical relationships that describe variations of grain size, density and temperature with depth as functions of accumulation rate and average annual surface temperature. The second step is a simulation of the interaction between microwaves and the snow/firn. Here, microwave brightness temperatures T_B or radar backscattering coefficients σ^0 are calculated from firn profiles generated in step 1. This calculation results in a value of T_B or σ^0 for each firn profile, which means that those values are indirectly given as functions of accumulation rate and average annual surface temperature. In this way, it is possible to generate look-up tables of T_B and σ^0 values versus annual mean surface temperature and accumulation rate (or apply more sophisticated inversion techniques). The accumulation rate can then be retrieved for locations for which satellite data of the brightness temperature or backscattering coefficient are available and the average annual surface temperature is known. The algorithms described in the literature differ both in modeling snow metamorphosis and in calculating the emission / scattering from the firn volume.

Seasonal cycle approach (SC): Air temperature variations and related changes of temperature, snow grain size, and density in the upper snow/firn volume cause a seasonal signal in brightness temperatures and radar backscatter intensities. The amplitude of this seasonal variation is large at a brightness temperature of 37 GHz, moderate at 19 GHz, and low for the radar backscattering coefficient at 13.4 GHz (all measured at vertical polarization) [13]. The respective sinusoidal curves show a relative phase shift to the temperature maximum, dependent on penetration depth of the microwave radiation into the snow/firn. While the seasonal cycle approach described in [13] could not reproduce the measured absolute level of brightness temperature/backscattering intensity because of a comparatively simple approach to model volume scattering, the seasonal variation corresponds to the observations with sufficient accuracy. The inversion of accumulation rates from the measured radiometer and radar data is hence based on an inversion scheme in which theoretically derived seasonal curves of T_B and σ^0 are fitted to the seasonal cycle measured by PMRs or scatterometers (including modeling snow metamorphism – in this sense it is an extended 2S approach). The theoretical seasonal curves are determined by varying annual layer thickness, grain size, and density within realistic ranges.

Altimeter approach (ALTA): In early fall, depth hoar layers can form in the dry snow zone. The altimeter approach uses the distance between interfaces created by stratigraphically distinctive hoar layers in the firn volume to estimate the annual accumulation. To this end, the travel times between radar reflections at those interfaces are determined. Calculation of the distance, which the radar signal travelled, requires the knowledge of the refractive index of snow, which in the dry snow zone is directly related to snow density. The latter can be laterally interpolated between vertical in-situ density profile data [32] [43]. In the studies described in [19] and [32], it was demonstrated that it is possible to identify the uppermost annual snow/firn layers in airborne radar altimeter data, and it was speculated that this will also be possible using Cryosat-2 data – at least for higher accumulation rates of several tens of centimetres. This is complementary to the use of PMRs, scatterometers, and SARs, since T_B or σ^0 reveal a low sensitivity for retrieval of accumulation rates larger than 0.2 m/a.

MAPPING OF THE POLAR ICE SHEETS

Accumulation rates: Many of the methods described above were used to generate maps of accumulation rates over the dry snow zones of Greenland and Antarctica. Examples are [10] (Greenland, based on empirical relationship between the gradient of the backscattered intensity and accumulation rates measured on the ground, using 13.4 GHz scatterometer data), [28] (Greenland, 2S, 5.3 GHz SAR), [13] (Greenland, SC, radiometer and scatterometer data), and

[2] (Antarctica, stratification approach, 6.6 GHz radiometer channel). Annual accumulation in terms of snow depth over the percolation zone was derived from QuikSCAT data (13.4 GHz) [30].

Complementary data: It has to be taken into account, however, that the penetration depth of the microwave signals depend on the frequency, the air temperature, and on the snow/firn properties. Hence, the derived accumulation rates represent averages over different time periods, revealing differences not only between sensors but also between different locations on the ice sheets. In the process of mapping, known "disturbances" have to be considered and to be indicated in the results, or provided as supplementary maps. One example is the influence of the surface topography, which is the reason for variations of brightness temperature / radar intensity as a function of sensor look direction, as described below. Areas of low-accumulation wind-glaze are another example, since they affect radar intensities on spatial scales of hundred kilometers (observed at C-band [38]). Such areas are characterized by very sparse low-relief sastrugi and intense subsurface recrystallization (recognized as increase of snow grain size).

Snow/firn properties: Another type of information is the supply of complementary data as input for retrieval algorithms or for judging the results of the retrieval. One example are maps of surface snow grain size such as the ones derived from MODIS data [39] or from microwave emissivities [5][13] . It is important to note that those maps differ relative to one another, which is attributed to the different penetration depths between the microwave range and the solar spectrum [5]. A second example are maps of snow facies over the ice sheets derived from radar altimeter and microwave radiometer [41] or scatterometer and SAR [36]. These maps provide indications of the snow pack structure (surface morphology, grain size, stratification, melt events) on larger spatial scales and are hence useful to develop retrieval algorithms adapted to different facies.

INFLUENCE OF THE ICE SHEET SURFACE

Most of the retrieval methods focus on the interactions between the microwaves and the snow/firn volume. In addition, however, the influence of the ice sheet surface needs to be considered. Scatterometer and radiometer data provide evidence of azimuthal modulations of T_B and σ^0, which are correlated with surface undulations in the range of several decimeters to a few hundred meters. These features – called sastrugi – are often generated under the influence of katabatic winds. Snow dunes creating surface slope variations on kilometer-scale also contribute to the azimuthal modulations but to a lesser extent. Azimuthal variations of the radar backscattering coefficient / brightness temperature are a function of the look direction and incidence angle and are dependent on the geographic location [3] [26] [36]. The amplitude of the azimuthal modulation is strongly associated with the frequency of occurrence of sastrugi. It is smaller when there are proportionally fewer larger sastrugi with more variable orientations present on the surface [16].

INSAR AND POLARIMETRY

INSAR: When using interferometric SAR data, the gain compared to conventional SAR imaging is the availability of another observation parameter that can be used for accumulation rate retrieval, namely the interferometric correlation. It is obtained from the combination of two SAR images acquired from slightly different positions. C-band data from the ERS1/ERS2 tandem mission were used for a study over the dry snow zone of Greenland [31]. The authors also use a 2S approach, assuming that the interfaces between coarse-grained hoar and the fine-grained snow act as additional scattering sources, hence both interface and volume contributions have to be considered. At depths of about 5 m, hoar layers collapse because of the weight of the overlying snow. It is not clear whether the occurrence of depth hoar is more a localized or a wide-spread phenomenon, i. e. whether an approach such as used by [31] is generally valid. In its present version, their backscatter model requires corrections. In another study, L-band INSAR data (from ALOS PALSAR) were employed [6]. At L-band one needs to consider that ionospheric effects influence the received radar signal. Compared to C-band, the temporal correlation is higher, and the penetration depth much larger (by a factor of 6-7). Surface/interface effects can be neglected. At the present stage of the retrieval algorithm presented in [6], the consistency between accumulation rates retrieved from L-band INSAR data and in-situ measurements is still relatively low.

Polarimetry: A retrieval algorithm based on radar or passive microwave polarimetry has not been presented yet. Polarimetric radar parameters (co- and cross-polarization ratios, phase differences between differently polarized channels) are useful for characterizing snow/firn properties and detecting their changes [9] [15]. They may help to develop more robust retrieval algorithms. However, surface slopes in the radar azimuth direction affect the relative magnitude and phase of all terms of the covariance matrix, which characterizes the radar response of a target [22]. The compensation of this effect can be carried out even if a DEM is not available. In this case, the correction is derived directly from the polarimetric data, preferably at low frequencies (L- or P-band). At higher frequencies the influence of topography is overlaid by effects related to smaller scatterers in the radar resolution cell [22]. Passive polarimetric microwave signatures are represented by the third and fourth Stokes parameters U and V, respectively, which are the real and imaginary components of the cross-correlation between V- and H-polarized emission. Seasonal variations of U and V from WindSat (stronger at 10.7 GHz and less at 37GHz) observed over Antarctica are caused by varying snow deposition rate and morphological properties of the snow/firn, e. g. [29].

USING DIFFERENT MICROWAVE FREQUENCIES

The SC works best when applied on passive microwave data at frequencies between 18 and 40 GHz. At the lower frequency end, the major fraction (95 percent) of the received radiation comes from firn layers down to a depth of about 7 m. At the high-frequency end, the corresponding depth is 1.5 m [13]. Quikscat radar data (13.4 GHz) are too noisy relative to the seasonal amplitude [13], which may be – at least to a certain degree - a consequence of the larger penetration depth. The STA requires measurements of brightness temperatures at lower frequencies (< 7 GHz) [42] [43]. Model calculations carried out for radar signals acquired at Ku- and C-band revealed that the lower frequency is more sensitive to changes of accumulation rate [9]. This can be attributed to the fact that scattering from larger firn particles is close to or in the Mie regime. The latter effect is even more pronounced at Ka-band, which may reduce the sensitivity even further or generate more complex dependencies between radar intensity and accumulation rate. In addition, the influence of atmospheric water vapor on the received radar signal is stronger but in the polar regions still comparatively low. Scattering simulations for snow on land showed that the radar intensity at 17 GHz is very sensitive to grain size changes for grain radii below 1 mm but almost insensitive for radii > 1 mm. At X-band (9.6 GHz), the sensitivity decreases much slower with increasing radius [11]. Modeled sensitivities at L-band [6, chapt. 5] seem to be slightly weaker compared to the results at C-band presented in [9] but it has to be considered that the simulation models used in the studies [6] and [9] differ. Compared to simulated radar intensities, measured L-band data are considerably more noisy than C-band data [6, chapt. 6], which increases the uncertainty of accumulation rate retrievals.

SCALING

In particular when using scatterometer and passive radiometer data with spatial resolutions of several kilometers, it is not clear whether the retrieved properties are more or less constant over the whole resolution cell or whether they are averages over significant sub-pixel heterogeneities. Ground-based radiometer measurements revealed undulations of brightness temperatures up to 10 K at 37 GHz over lengths of 30-50 m, caused by distinct patches of highly compacted snow [34]. Some studies showed that accumulation rates may show a very high spatial variability on length scales less than a kilometer [1a]. Often, accumulation pattern and surface topography are linked, which indicates that wind-borne redistribution of snow significantly contributes to the spatial variations of accumulation rates [1]. In Antarctic regions covered by megadunes (which are between 2 and 5 km across), snow accumulates on the windward faces of the dune, whereas the leeward faces and troughs experience very low to no snow accumulation due to redistribution by katabatic winds. The leeward faces exhibit a glaze surface during late winter months made up of ice crusts [7]. The snow deposited on the upwind faces is fine-grained, therefore they appear as narrow stripes of low intensity in radar images. The leeward faces and troughs with their very low accumulation rates experience significant metamorphism which causes the snow grains to grow fast, creating a strong radar signal. Hence, the signals received by the sensors with a large footprint such as scatterometers (and passive microwave radiometers) will be a mixture of the contributions from upwind and leeward faces.

VALIDATION AND INPUT DATA FOR RETRIEVAL ALGORITHMS

Reliability of retrievals: Considering the huge extent of the ice sheets, the number of field sites where accumulation rates have been measured in-situ is not sufficient. Sites are located in more accessible regions, and large gaps exist in spatial coverage. Another problem is that not all field data are equally reliable [12] [17] [27]. According to [27], direct measurements from snow stratigraphy or precipitation gauges are deemed unreliable, whereas multi-annual and decadal stake measurements are of sufficient quality. Indirect measurements (such as oxygen and hydrogen isotope ratios, chemical markers, natural radionuclides) are "conditionally accepted" methods, whereas the analysis of anthropogenic radionuclides is classified as "fully accepted". The quality control and related rejection of data sets can have a significant effect on mapping of accumulation rates by interpolating between field data [17]. Profiles of the internal firn structure can be obtained by ground penetrating radar (GPR). Thickness and depth variations of single layers along profiles are related to the spatial and temporal variations of accumulation. For measurements on the Antarctic Plateau, the uncertainty in the derived accumulation rates is given as about 5 per cent [12].

Spatial and temporal variations: Ground-based measurements reveal large variations of local annual accumulation rates. For example on the Fimbul Ice Shelf the accumulation rate varied between 170 and 620 kg m^{-2} a^{-1} for the time period from 1983-2009 [1]. Hence, the local penetration depth of the satellite sensor and the resulting integration period has to be considered when comparing results of accumulation rate retrievals and ground-based measurements. The issue of scaling lengths is also of importance for validation, since the limited horizontal resolution of some satellite sensors prevents them from resolving any local accumulation anomalies that can be recognized in ground-based point or profile data acquisitions. Special consideration has to be given to the changes of firn properties as a function of depth, e. g. [21]. Strong temperature gradients may influence snow grain growth in the upper 5-10 m. For applications in retrieval algorithms, parameterizations of snow density and grain growth were derived as functions of mean surface temperature and accumulation rate, based on measured profiles from different regions of Greenland and Antarctica [25]. The data base for these parameterizations has to be extended.

Snow grain size measurements: Since higher-frequency microwave radiation is sensitive to snow grain sizes it is an essential parameter in a number of retrieval algorithms. However, grain size is difficult to measure in the field and laboratory, and is in addition impaired by the coexistence of inconsistent definitions. Several instruments and methods that are based on very different physical principles (optical, gas adsorption, tomography, stereology) have been developed in the last decade. In many retrieval algorithms, the grains are approximated as spheres. Hence the question arises what the appropriate "effective" radius of these spheres is which reproduces the scattering and absorption of the real snow grains as realistically as possible. (In some approaches the correlation length of the snow/firn medium, which is related to the particle size, is required as input, and it may be a better parameter to characterize snow microwstructure).). One solution is to represent a cluster of non-spherical particles by spheres having the same total surface area and the same total volume [18]. A related parameter commonly used is the specific surface area (SSA), i. e. the surface area per unit mass [37]. For application in emission and scattering models, the SSA needs to be related to the effective radius. Unfortunately, sensitivity studies seem to indicate that the effective radius is dependent on the spectral range (optical, microwave) and specific application (firn, snow on land or sea ice) [33] [37]. Investigations concerning this item are still ongoing.

SUMMARY

The main conclusion based on various publications related directly or indirectly to the accumulation retrieval over the ice sheets is that no single sensor and retrieval approach can be regarded as optimal. There is a need to combine data of different sensors and results of different algorithms, to collect and archive quality-controlled data of field measurements, and to use different scattering models for studying interactions between microwaves and firn as well as sensitivities to variations of snow pack properties. Hence we interpret the term "mission concept" in a very broad sense (which is in agreement with the European "Copernicus" programme).

How could a mission concept for the retrieval of accumulation rates look like?

- *Archive of ground data*: For validation, a database of in-situ accumulation rates and snow-pack properties has to be systematically established and continuously be supplemented, considering clearly defined criterions for quality control. Ground-based measurements of accumulation rates serve in the validation of satellite-based retrievals. They are also required in the development for retrieval algorithms, as are measurements of vertical profiles of snow pack properties such as density, grain size, layer thickness, or occurrence of ice crusts and other ice bodies.
- *Choice of sensors and retrieval methods*: The percolation and dry snow zones have to be treated separately. On the former, only the current winter accumulation can be determined by means of radar altimetry or from scatterometer data. The percolation zone can be delimited from the dry snow zone using radar data at higher frequencies (proven for Ku-band). For the dry snow zone, sensors and retrieval algorithms need to be selected based on a rough separation of regions of low, moderate, and high accumulation rates. This can be achieved by generating *maps of snow facies*. In the case of low accumulation ($\leq$ 0.2 m water equivalent per year), measurements of radar intensities seem to be most promising, applying a 2S algorithm. Another alternative are PMR data at lower frequencies ($<$7 GHz) with an STA retrieval. PMR data in the frequency interval 18-40 GHz in combination with SC-methods have also shown encouraging results but it has to be checked whether this approach is also suitable for higher accumulation rates. High accumulation rates ($\geq$ 0.3 w.e. /a) are optimally measured by means of radar altimetry.
- *Provision of additional data:* An important point is to provide *maps of the penetration depth* as a function of microwave frequency and environmental conditions (in particular mean annual air temperature, but also snow pack properties). The penetration depth determines the time span for which the retrieved average accumulation rate is valid. Also required are maps providing locations of additional snow pack features known for affecting the retrieval of accumulation rates (*"disturbance" maps*), such as sastrugi, or patches of wind glaze or compacted snow.

What is still missing?

- Further investigations into the potential of polarimetry and interferometry are required. For the correction of polarimetric signals in the presence of azimuthal slopes, a DEM is needed (generated, for example, from Ka-band formation flying-SAR satellites). If the topography is unknown, L-band polarimetric SAR data can be used for correction.

- A joint analysis of high and coarse spatial resolution data is necessary to study the effect of lateral heterogeneities on the results of accumulation rate retrievals.
- Forward scattering models used in the 2S and SC approaches should be developed further. Key words are dense medium (and in this context particle "stickiness", grain size versus correlation length of snow microstructure), firn layering, and azimuth anisotropy of σ^0 and T_B. New in-situ data have to be considered for improving parameterizations of snow metamorphism (e. g. depth profiles of density and grain size) and for extending retrieval algorithms.
- Because of the observed anisotropy of the received radiometer/radar signals it is necessary to combine microwave measurements from different azimuth angles and to continue the efforts of establishing/improving parameterizations of the azimuthal modulation at different frequencies for Antarctica and Greenland.
- Accumulation rate retrievals would benefit from the development of spaceborne PMRs and scatterometers with better spatial resolutions.

REFERENCES

[1] H. Anschütz, O. Eisen, H. Oerter, D. Steinhage, M. Scheinert, "Investigating small-scale variations of the recent accumulation rate in coastal Dronning Maud Land, East Antarctica," *Annals of Glaciology*, vol. 46, pp. 14-21, 2007.

[2] R. J. Arthern, D. P. Winebrenner, and D. G. Vaughan, "Antarctic snow accumulation mapped using polarization of 4.3 cm wavelenght microwave emission," *J. Geophys. Res.,* vol. 111, D06107, 2006.

[3] I. S. Ashcraft and D. G. Long, "Relating microwave backscatter azimuthal modulation to surface properties of the Greenland ice sheet," *J. Glaciology*, vol. 52, no. 177, pp. 257-266, 2006.

[4] A. W. Bingham and M. R. Drinkwater, "Recent changes in the microwave scattering properties of the Antarctic ice sheet," I*EEE Trans. Geosci. Rem. Sens.*, vol. 38, no. 4, pp. 1810-1820, 2000.

[5] L. Brucker, G. Picard, and M. Fily, "Snow grain-size profiles deduced from microwave snow emissivities in Antarctica," *J. Glaciology*, vol. 56, pp. 514–526, 2010.

[6] A. C. Chen, "L-Band INSAR estimates of Greenland ice sheet accumulation rates," dissertation, Stanford University, USA, December 2013.

[7] Z. R. Courville, M. R. Albert, M. A. Fahnestock, L. M. Cathles IV, and C. A. Shuman, "Impacts of an accumulation hiatus on the physical properties of firn at a low-accumulation polar site," *J. Geophys. Res.*, vol. 112, F02030, doi:10.1029/2005JF000429, 2007.

[8] W. Dierking, S. Linow, and W. Rack, "Towards a robust retrieval of snow accumulation over the Antarctic ice sheet using satellite radar," *J. Geophys. Res.*, vol. 117, D09110, doi:10.1029/2011 JD017227, 2012.

[9] W. Dierking, S. Linow, C. Wesche, W. Rack, M. Hoppmann, and S. Willmes, "TSX-data for studies of snow on ice sheets and sea ice – preliminary results," 5. TerraSAR-X / 4. Tandem-X Science Team Meeting, 2013

[10] M. Drinkwater, D. G. Long, and A. Bingham, "Greenland snow accumulation estimates from satellite radar scatterometer data," *J. Geophys Res.*, vol. 106 no. D24, pp. 33935–33950, 2001.

[11] J. Du, J. Shi, and H. Rott, "Comparison between a multi-scattering and multi-layer snow scattering model and its parameterized snow backscattering model," *Rem. Sens. Env.*, vol. 114, pp. 1089-1098, 2010.

[12] O. Eisen, and 15 co-authors, "Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica," *Rev. Geophys.*, vol. 46, RG2001, doi:10.1029/2006RG000218, 2008.

[13] J. D. Flach, K. C. Partington, C. Ruiz, E. Jeansou, and M. R. Drinkwater, "Inversion of the surface properties of ice sheets from satellite microwave data," *IEEE Trans. Geosci. Rem. Sens.*, vol. 43, no. 4, pp 743-75, 2005.

[14] R. Forster, K. Jezek, J. Bolzan, and F. Baumgartner, "Relationships between radar backscatter and accumulation rates on the Greenland ice sheet," *Int. J. Remote Sensing*, vol. 20, no 15&16, pp. 3131–3147, 1999.

[15] M. C. Fuller, T. Geldsetzer, and J. J. Yackel, "Surface-based polarimetric C-band microwave scatterometer measurements of snow during a Chinook event," *IEEE Trans. Geosc. Rem. Sens.*, vol. 47, no. 6, 2009.

[16] T. Furukawa and N. W. Young, "Comparison of microwave backsatter measurements with observed roughness of the snow surface in east Queen Maud Land, Antarctica," 3rd ERS-Symposium, Florence, 1997.

[17] C. Genthon, O. Magand, G. Krinner, and M. Fily, "Do climate models underestimate snow accumulation on the Antarctic plateau? A re-evaluation of/from in situ observations in East Wilkes and Victoria Lands," *Annals of Glaciology*, vol. 50, pp. 61-65, doi:10.3189/172756409787769735, 2009.

[18] T. C. Grenfell and S. G. Warren, "Representation of a nonspherical ice particle by a collection of indpendent spheres for scattering and absorption of radiation," *J. Geophys. Res.*, vol. 104, no. D24, pp. 31697-31709, 1999.

[19] R. L. Hawley, E. M. Morris, R. Cullen, U. Nixdorf, A. P. Shepherd, and D. J. Wingham, "ASIRAS airborne radar resolves internal annual layers in the dry-snow zone of Greenland," *Geophys. Res. Letters*, vol. 33, L04502, doi:10.1029/2005GL025147, 2006.

[20] V. Helm, W. Rack, R. Cullen, P. Nienow, D. Mair, V. Parry, and D. J. Wingham, "Winter accumulation in the percolation zone of Greenland measured by airborne radar altimeter," *Geophys. Res. Letters*, vol. 33, L06501, doi:10.1029/2006GL029185, 2007.

[21] M. W. Hörhold, S. Kipfstuhl, F. Wilhelms, J. Freitag, A. Frenzel, "The densification of layered polar firn," *J. Geophys. Res.*, vol. 116, 2011.

[22] J. S. Lee, D. L. Schuler, and T. L. Ainsworth, "Polarimetric SAR data compensation for terrain azimuth slope variation," *IEEE Trans. Geosc. Rem. Sens.*, vol. 38, no. 5, pp. 2153-2163, 2000.

[23] J. T. M. Lenaerts, M. R. van den Broeke, W. J. van de Berg, E. van Meijgaard, and P. Kuipers Munneke, "A new, high resolution surface mass balance map of Antarctica (1979-2010) based on regional atmospheric climate modeling," *Geophys. Res. Letters*, vol. 39, L04501, doi:10.1029/2011GL050713, 2012.

[24] S. Linow, "Deriving snow accumulation rates of Greenland and the Antarctic ice sheet from microwave remote sensing data," PhD Thesis, University of Bremen, http://elib.suub.uni-bremen.de/peid=D00102235, 2011.

[25] S. Linow, M. W. Hörhold, and J. Freitag, "Grain-size evolution of polar firn: a new empirical grain growth parameterization based on X-ray microcomputer tomography measurements," *J. Glaciology*, vol. 58, no. 212, pp. 1245-1252, doi:10.3189/2012JoG11J256, 2012.

[26] D. G. Long and M. R. Drinkwater, "Azimuth variation in microwave scatterometer and radiometer data over Antarctica," *IEEE. Trans. Geosci. Rem. Sensing*, vol. 38, no. 4, pp. 1857-1870, 2000

[27] O. Magand, C. Genthon, M. Fily, G. Krinner, G. Picard, M. Frezotti, and A. A. Ekaykin, "An up-to-date quality-controlled surface mass balance data set for the 90°-180°E Antarctica sector and 1950-2005 period," *J. Geophys. Res.*, vol. 112, D12106, doi:10.1029/2006JD007691, 2007.

[28] J. Munk, K. C. Jezek, R. R. Forster, and S. P. Gogineni, "An accumulation map for the Greenland dry-snow facies derived from spaceborne radar," *J. Geophys. Res.*, vol. 108, no. D9, doi:10.1029/2002JD002481, 2008.

[29] P. S. Narvekar, G. Heygster, T. J. Jackson, R. Bindlish, G. Macelloni, and J. Notholt, "Passive polarimetric microwave signatures observed over Antarctica," *IEEE Trans. Geosci. Rem. Sens.*, vol. 48, no. 3, pp. 1059–1075, 2010.

[30] S. V. Nghiem, K. Steffen, G. Neumann, and R. Huff, "Mapping of ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet," *J. Geophys. Res.*, vol. 110, F02017, doi:10.1029/2004JF000234, 2005.

[31] S. Oveisgharan and H. A. Zebker, "Estimating snow accumulation from INSAR," *IEEE Trans. Geosc. Rem. Sens.,* vol. 45, no. 1, pp. 10-20, doi 10.1109/TGRS.2006.886196, 2007.

[32] S. de la Peña, and 9 co-authors, "Spatially extensive estimates of annual accumulation in the dry snow zone of the Greenland Ice Sheet determined from radar altimetry," *The Cryosphere,* vol. 4, pp. 467-474, doi:10.5194/tc-4-467-2010, 2010.

[33] G. Picard, L. Brucker, A. Roy, F. Dupont, M. Fily, A. Royer, and C. Harlow, "Simulation of the microwave emission of multi-layered snowpacks using the Dense Media Radiative transfer theory: the DMRT-ML model," *Geosci. Model Dev.*, vol. 6, pp. 1061-1078, doi:10.519/gmd-6-1061/2013, 2013.

[34] G. Picard, A. Royer, L. Arnaud, and M. Fily, "Influence of meter-scale wind-formed features on the variability of the microwave brightness temperature around Dome C in Antarctica," *The Cryosphere*, vol. 8, pp. 1105-1119, 2014.

[35] E. Rignot, I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. T. M. Lenaerts, "Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise," *Geophys. Res. Lett.*, vol. 38, L05503, doi:10.1029/2011GL046583, 2011.

[36] G. Rotschky, W. Rack, W. Dierking, H. Oerter, "Retrieving snow pack properties and accumulation estimates from a combination of SAR and scatterometer measurements," *IEEE Trans. Geosci. Rem. Sens.*, vol. 44, pp. 943–956, 2006.

[37] A. Roy and 7 co-authors, "Brightness temperature simulations of the Canadian seasonal snowpack driven by measurements of the snow specific surface area," *IEEE Trans. Geosci. Rem. Sens.*, vol. 51, no. 9, pp. 4692-4704, 2008.

[38] T. A. Scambos, T. M. Haran, M. A. Fahnestock, T. H. Painter, and J. Bohlander, "MODIS-based mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size," *Rem. Sens. Env.*, vol. 111, pp. 242-257, 2007.

[39] T. A. Scambos and 12 co-authors, "Extent of low-accumulation wind glaze areas on the East Antarctic plateau: implications for continental ice mass balance," *J. Glaciology*, vol. 58 no. 210, pp. 612-647, 2012.

[40] A. Sinisalo, and 12 co-authors, "Surface mass balance on Fimbul ice shelf, East Antarctica: Comparison of field measurements and large-scale studies," *J. Geophys. Res. Atmospheres*, vol. 118, pp 11625-11635, doi:10.1002/jgrd.50875, 2013.

[41] N. Tran, F. Remy, H. Feng, and P. Femenias, "Snow facies over ice sheets derived from Envisat active and passive observations," *IEEE Trans. Geosci. Rem. Sens.*, vol. 46, no. 11, pp. 3694-3708, 2008.

[42] R. D. West, D. P. Winebrenner, L. Tsang, and H. Rott, "Microwave emission from density-stratified Antarctic firn at 6 cm wavelength,“ *J. Glaciology,* vol. 42, no. 140, pp. 63-76, 1996.

[43] D. P. Winebrenner, R. J. Arthern, and C. A. Shuman, "Mapping Greenland accumulation rates using observations of thermal emission at 4.5-cm wavelength," *J. Geophys. Res.*, vol. 106, no. D24, pp. 33919-33934, 2001.