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Resolution enhancement of SMOS brightness temperatures: application to melt detection on the Antarctic and Greenland ice sheets

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Abstract

A large part of the surface of the Greenland Ice Sheet (GrIS) and the margins of Antarctica are melting every summer, affecting their surface mass balance. Wet/dry snow status has been detected for decades using the peaks of brightness temperature at 19 GHz, and more recently at L-band (1.4 GHz) using both the SMOS and SMAP missions. SMOS owns a longer time series than SMAP with data since 2010, but the 52.5° incidence bin in the Level 3 (L3) product from Centre Aval de Traitement des Données SMOS (CATDS) that was previously used to detect melt suffers from a coarse spatial resolution. For this reason, we developed a new SMOS enhanced resolution brightness temperature (T_B) product building on the radiometer version of the Scatterometer Image Reconstruction (rSIR) algorithm. We also exploited the SMOS L1C observations near 40° incidence angle instead of 52.5° as the native spatial resolution of SMOS is better at low incidence. The new product is posted on a 12.5 km polar stereographic grid and covers all the GrIS and Antarctica for 2010-2024 with twice-daily morning and afternoon acquisitions. The **effective** spatial resolution was evaluated to ~ 30 km, a 30 % enhancement compared to the SMOS L3TB at 40° and almost a 50 % enhancement compared to the SMOS L3TB at 52.5°. Then, we applied a melt detection algorithm to both the enhanced resolution product at 40° and the L3TB product at 52.5° which is used in the literature. The spatial resolution enhancement results not only in the detection of smaller melt regions but also in a widespread increase in the annual number of melt days. This increase is larger than 30 days per year in the GrIS percolation area and on multiple Antarctic ice shelves. This is primarily due to the mix of dry and wet snow regions near the ice shelves grounding line, resulting in lower brightness temperature peaks in the SMOS L3TB product due to a large power spread. These findings highlight the dependence of melt detection in particular, and geophysical applications in general, on the spatial resolution of passive microwave observations. This study provides a new open dataset suitable to monitor melt at the surface and at depth on the two main ice-sheets.

Keywords: SMOS, melt, Antarctica, Greenland, resolution enhancement, rSIR

1. Introduction

Surface melt occurs each summer over a large part of the Greenland Ice Sheet (GrIS) and over the margins of the Antarctic Ice Sheet (AIS) (Picard & Fily, 2006; Mote, 2007). It contributes to the ice sheet mass balance both directly through the reduction of surface mass balance (SMB) and indirectly through the enhancement of ice

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33 dynamics (Otosaka et al., 2023). Over the GrIS, the widespread surface melt in summer drives the negative SMB
34 accounting for 34% to 50% of the total mass loss (Mouginot et al., 2019; IMBIE, 2020), with an increasing trend
35 in meltwater runoff since the 1990s (Fettweis et al., 2017; IMBIE, 2020). On the contrary, the colder and drier
36 AIS experiences melt only over the margins and the mass loss primarily comes from ice dynamics (IMBIE, 2018;
37 Rignot et al., 2019). Most of the meltwater produced in the AIS percolates in the snowpack or forms ponds at
38 the surface of ice shelves (Kingslake et al., 2017; Stokes et al., 2019), while runoff to the ocean is very low. When
39 refreezing, meltwater creates impermeable ice layers which foster again the formation of supraglacial lakes.
40 Melt ponds play a role in hydrofracturing, potentially leading to the destabilization of ice shelves (Scambos
41 et al., 2000), and are known to have triggered the collapses of the Larsen A and B ice shelves in 1995 and 2002
42 (Rott et al., 1996; Scambos et al., 2004; Banwell et al., 2013) and of the Wilkins ice shelf in 2008 (Scambos et al.,
43 2009). An important consequence is the acceleration of outlet glaciers that are not anymore buttressed by their
44 downstream ice shelves (Rott et al., 2002; Scambos et al., 2004). The monitoring of surface melt and liquid water
45 percolation is therefore essential to understand and predict runoff and ice dynamics on the ice sheets.

46 Remote sensing is a suitable tool for detecting the presence of liquid water in the snowpack at large scale. Mi-
47 crowave radiometers have provided a near twice-daily coverage of polar regions since 1988 and every other days
48 since 1979, combining the Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave
49 Imager (SSM/I), Special Sensor Microwave Imager Sounder (SSMIS) and Advanced Microwave Scanning Ra-
50 diometer (AMSR-E and AMSR2) sensors. The time series of 19 GHz and 37 GHz brightness temperatures (T_B)
51 were used to detect wet snow occurrence and compute trends and anomalies for up to four decades (Zwally &
52 Fiegles, 1994; Abdalati & Steffen, 1995; Torinesi et al., 2003; Liu et al., 2006; Picard & Fily, 2006; Picard et al., 2007;
53 Tedesco, 2007; Tedesco & Fettweis, 2020). Active microwave sensors are also suitable for wet snow detection,
54 with Synthetic Aperture Radars (SAR) such as Sentinel-1 at C-band (Liang et al., 2021), and scatterometers such
55 as the Quik Scatterometer (QuikSCAT) at Ku-band (Ashcraft & Long, 2006; Trusel et al., 2012) and the Advanced
56 Scatterometer (ASCAT) at C-band (Bevan et al., 2018; Kuipers Munneke et al., 2018). Lastly, optical sensors can
57 detect the accumulation of meltwater at the surface when it forms slush, ponds and streams (Yang & Smith,
58 2013; Bell et al., 2017; Williamson et al., 2018; Banwell et al., 2019).

59 The difference between the imaginary part of the permittivity of ice and water (related to absorption) is
60 responsible for a large increase in the T_B at any microwave frequency when liquid water appears in snow (Zwally,
61 1977; Picard et al., 2022). Multiple algorithms have been proposed in the past 30 years for detecting melt using
62 microwave radiometers, with most of them being based on simple thresholding methods (Zwally & Fiegles,
63 1994; Abdalati & Steffen, 1995; Ramage & Isacks, 2002; Torinesi et al., 2003; Picard & Fily, 2006; Tedesco, 2007).
64 All these algorithms use the 19 GHz and 37 GHz signals to detect liquid water in the first meter of the snowpack
65 (Picard et al., 2022). However, lower frequencies (e.g. L-band) can provide additional insights on the presence of
66 meltwater at great depths (Colliander et al., 2022, 2023).

67 The European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS, Kerr et al. (2001)) and the Na-

68 tional Aeronautics and Space Administration (NASA) Soil Moisture Active and Passive (SMAP, Entekhabi et al.
69 (2010)) satellites have provided T_B at L-band (1.4 GHz) since 2010 and 2015, respectively. Both have been recently
70 used to detect melt (Leduc-Leballeur et al., 2020; Mousavi et al., 2022) and can be used in synergy with higher
71 frequency sensors such as SSMIS or AMSR2 (Colliander et al., 2022, 2023). Both sensors are mostly limited by a
72 coarse instrumental spatial resolution. For SMOS, the spatial resolution varies within the field of view from ~ 30
73 km to ~ 60 km depending on the incidence angle, with an average resolution of 43 km (Kerr et al., 2010). SMAP
74 antenna achieves a comparable resolution with an instantaneous field of view of $39 \text{ km} \times 47 \text{ km}$ (Piepmeier
75 et al., 2017). For both sensors, the resolution of conventional gridded T_B products is slightly worse than the in-
76 strumental resolution due to the averaging of multiple observations with varying geometry in one pixel (Al Bitar
77 et al., 2017; Long et al., 2023). The coarse spatial resolution of these products is therefore not sufficient to capture
78 small-scale melt patterns observed for instance on the Shackleton (Saunderson et al., 2022) and Larsen C (Luck-
79 man et al., 2014) ice shelves. The melt detection algorithm for SMOS presented in Leduc-Leballeur et al. (2020)
80 is indeed based on the SMOS Level 3 T_B (L3TB) product at 52.5° incidence angle with a 25 km grid sampling,
81 but its effective spatial resolution is coarser than 50 km. As a consequence, it is necessary to assess whether
82 the detected melt is resolution-dependent or not, *i.e.*, whether an improvement in spatial resolution leads to an
83 increase of the melt signal detected by SMOS. For this purpose, a SMOS enhanced resolution gridded T_B dataset
84 needs to be first developed.

85 The reconstruction of radiometer images with enhanced resolution exploits the overlap of multiple obser-
86 vations before their averaging into gridded products. It has been mostly performed using two algorithms: the
87 Backus-Gilbert (BG) inversion technique (Backus & Gilbert, 1967, 1968; Stogryn, 1978), and the radiometer ver-
88 sion of the Scatterometer Image Reconstruction (rSIR) algorithm (Long & Daum, 1998). None of these algorithms
89 have been previously applied to interferometric radiometers like SMOS. For conventional radiometers, the pre-
90 vious works from Long & Daum (1998) and Long & Brodzik (2016) indicated that the BG and rSIR algorithms
91 produce output images with an equivalent resolution. However, both the noise and the computation time are
92 significantly higher using BG compared to rSIR. Based on these evaluations, they have been using rSIR to pro-
93 duce enhanced resolution brightness temperature datasets for SSM/I, AMSR-E (Long & Brodzik, 2016) and SMAP
94 (Long et al., 2019).

95 This study presents the first resolution enhancement of SMOS brightness temperatures and its application
96 to detect melt on the Antarctic and Greenland Ice Sheets. Given the large amount of SMOS data to process,
97 computation time is critical. For this reason, we applied the rSIR algorithm rather than BG to the SMOS Level
98 1C (L1C) data. Furthermore, we have taken advantage of SMOS multi-incidence capabilities to reconstruct
99 three distinct products. The first one is the *Single-incidence Enhanced Resolution* dataset at 52.5° (SiER_{52.5}), and
100 uses the measurements in the $50^\circ - 55^\circ$ incidence bin to compare with the L3TB at 52.5° . The second one is a
101 similar dataset computed using the $37.5^\circ - 42.5^\circ$ incidence bin (SiER₄₀), at SMAP looking angle, where the native
102 spatial resolution of SMOS observations is better. The third dataset, called *Multi-incidence Enhanced Resolution*

103 (MiER), uses all the measurements with an incidence angle lower than 40° to exploit the observations with the
104 best native spatial resolution near nadir. For each of these new datasets, we first evaluated the effective spatial
105 resolution and then we applied the melt detection algorithm from Leduc-Leballeur et al. (2020). Comparisons
106 are performed against the L3 T_B and melt products to highlight the major changes due to spatial resolution
107 enhancement.

108 Section 2 presents the different datasets used as input and for validation, Section 3 presents the whole
109 methodology, Section 4 presents the results for the spatial resolution improvement and melt detection, and
110 finally Section 5 discusses the limitations and perspectives to this work.

111 2. Data

112 2.1. SMOS Level 1C product

113 The Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) instrument onboard SMOS is an in-
114 terferometric radiometer operating at 1.4 GHz (Kerr et al., 2010). It is composed of 69 Lightweight Cost-Effective
115 Front-end (LICEF) receivers which are equally distributed over a central structure and three deployable arms.
116 The signal acquired by each LICEF receiver for one SMOS snapshot is transmitted to a central processing unit
117 that performs cross-correlation to deliver the observables. In full polarization mode, MIRAS furnishes co- and
118 cross-polarized T_B in the XY antenna frame with a 1.2 s integration time (Wu et al., 2013). Co-polarized snap-
119 shots provide real T_B^{XX} or T_B^{YY} measurements while cross-polarized snapshots provide complex measurements
120 $T_B^{XY} = Re(T_B^{XY}) + Im(T_B^{XY})$. All the values of T_B^{XX} , T_B^{YY} , $Re(T_B^{XY})$ and $Im(T_B^{XY})$ are estimated at fixed positions
121 sampled every ~ 15 km in the equal-area Discrete Global Grid (DGG, Sahr et al. (2003)). Hereafter, a DGG refers
122 to the location of these low-level SMOS measurements.

123 The SMOS L1C T_B , version 724 distributed by ESA is the single input our processing chain requires. The
124 L1C data are distributed by half orbit, 29 per day (both ascending and descending). L1C data blocks include
125 the T_B^{XX} , T_B^{YY} , $Re(T_B^{XY})$ and $Im(T_B^{XY})$ acquired by MIRAS in full-polarization mode along with the longitude,
126 latitude, altitude and identifier of each DGG, the radiometric accuracy (RA), azimuth and incidence angles, the
127 semi-minor and semi-major axes of an ellipse approximating the -3 dB footprint of a measurement, and L1C
128 flags which are further used in Section 3.1. For the purpose of this study, we downloaded all the L1C files from
129 April 2010 to March 2024 and we extracted the Antarctic and Greenland measurements for each track.

130 2.2. SMOS CATDS Level 3 Brightness Temperatures

131 The Centre Aval de Traitement des Données SMOS (CATDS) produces twice-daily, horizontal and vertical-
132 polarized T_B maps from SMOS posted on the EASE-2 Grid at 25 km, for each 5° incidence angle bin ranging
133 from 0° to 65° (Al Bitar et al., 2017). The SMOS L3TB product is obtained by averaging the L1C T_B in all the grid
134 pixels for each incidence bin. The averaging of multiple measurements with varying footprints and independent
135 noise results in both a lower spatial resolution and a lower radiometric noise than the L1C T_B . SMOS L3TB

136 has been used in cryospheric studies in particular using the near-Brewster angle (50-55°) (Macelloni et al., 2019;
137 Leduc-Leballeur et al., 2020; Houtz et al., 2021). In this study, the L3TB version 331 at bins 50-55° and 37.5-42.5°
138 are merged on a daily basis to compare with the outputs of our processing chain (Section 3).

139 2.3. SMAP rSIR-Enhanced Brightness Temperatures

140 For the purpose of comparison with our new products, and especially for assessing the effective spatial
141 resolution, we used the SMAP Radiometer Twice-Daily rSIR-Enhanced EASE-Grid 2.0 Brightness Temperatures
142 Version 2 dataset (Long et al., 2019; Brodzik et al., 2021) distributed at the National Snow and Ice Data Center
143 (NSIDC). This product contains morning and evening SMAP T_B posted on EASE-2 grids with a pixel spacing of
144 3 km, 3.125 km, 9 km, 25 km, and 36 km. The resolution of SMAP instrument is still unchanged (~ 40 km) for all
145 these datasets. The resolution enhancement is based on the same rSIR algorithm that we used in this study for
146 SMOS and that was previously applied to SSM/I, SSMIS and AMSR data (Long & Daum, 1998; Long & Brodzik,
147 2016). Only the number of iterations differs. We downloaded the SMAP rSIR-enhanced, Version 2 3.125 km T_B
148 maps for two particular events lasting three days each where the spatial resolution is evaluated (Section 3.4). A
149 single 12.5 km SMOS L1C rSIR-enhanced pixel therefore contains 16 SMAP rSIR-enhanced pixels.

150 2.4. Sentinel-1 images

151 We used images from the ESA Sentinel-1 SAR Ground Range Detected (GRD) product in the process of
152 quantifying the effective spatial resolution of the SMOS enhanced-resolution maps. Two sets of images were
153 chosen: the first one is over Anvers Island (-64.5° latitude, -63.5° longitude) in the Antarctic Peninsula (AP) on the
154 26th of January 2019, and the second one is over West ice-shelf (-66.5° latitude, 83° longitude) in East Antarctica
155 on the 8th of February 2019. We preprocessed and downloaded HV backscatter images using the Google Earth
156 Engine (GEE) code editor. Preprocessing steps include the thermal noise removal, radiometric calibration and
157 terrain correction as implemented in the Sentinel-1 toolbox.

158 3. Methods

159 The methodology is depicted in Figure 1 and the steps are presented in the following sections.

160 3.1. Conversion of T_B to the surface frame and preprocessing

161 The preprocessing applied to SMOS L1C data consists in four steps: i) conversion of the T_B from the (XY)
162 antenna frame to the (HV) surface frame, ii) removal of the low-quality and flagged L1C data, iii) incidence
163 angle binning and selection, and iv) solar time calculation.

164 The first step provides linearly polarized T_B defined in the surface frame with its vertical and horizontal
165 components. These are used by most geophysical applications over the ice sheets, such as the melt detection
166 and ice sheet temperature estimation algorithms based on the horizontal and vertical polarization, respectively
167 (Leduc-Leballeur et al., 2020; Macelloni et al., 2019). Hence, the sequences of T_B^{XX} , T_B^{YY} , $Re(T_B^{XY})$ and $Im(T_B^{XY})$

168 measurements given in L1C data are first converted to (T_B^H, T_B^V) pairs. The conversion from the HV surface
 169 frame to the XY antenna frame is a simple rotation that requires as input the geometrical and Faraday angles,
 170 and the inverse operation needed here converts a sequence of measurements $[T_B^{XX}, T_B^{YY}, Re(T_B^{XY}), Im(T_B^{XY})]$ to
 171 the fully-polarized $[T_B^H, T_B^V, 3^{rd}$ and 4^{th} Stokes components]. We first construct the vector $[T_B^{XX}, T_B^{YY}, Re(T_B^{XY}),$
 172 $Im(T_B^{XY})]$ for each snapshot, with one exact value and three values obtained through the interpolation of a
 173 sequence of close measurements with limited incidence angle variations. The T_B^H and T_B^V in surface frame are
 174 then obtained through inversion of the rotation matrix.

175 In the second step, we discarded the data affected by sun aliases, radio frequency interferences (RFI) and
 176 the observations located in the aliased area of a snapshot, as the image reconstruction algorithm is particularly
 177 sensitive to noise. For this, we discarded data with the L1C flags (ESA, 2021): *sun point*, *sun glint area*, *alias-free*
 178 *field of view*, *border field of view*, *RFI*, *RFI tails* and *RFI amplitude*. As we noticed additional noise in Greenland
 179 that may be due to an incorrect RFI filtering, we also discarded all the observations with a non-physical TB
 180 higher than 280 K.

181 In the third step, we selected different ranges of incidence angle to compute three SMOS enhanced-resolution
 182 datasets. The motivation is the large dependence of SMOS L1C spatial resolution on the incidence angle (Fig-
 183 ure 2a). The ellipse approximating the -3 dB footprint is larger and more eccentric at higher incidences. The
 184 semi-major axis is <20 km for an incidence angle <20° while it is ~40 km at 52.5° and reaches 90 km near 70°. A
 185 careful selection of the L1C data is therefore necessary to obtain an optimum spatial resolution. The first two
 186 enhanced-resolution datasets use the observations in a short range of incidences (5°) centered at 52.5° (Single-
 187 incidence Enhanced Resolution, SiER_{52.5}) near the Brewster angle, and 40° (SiER₄₀, at SMAP looking angle),
 188 respectively. These incidence bins exist in the L3TB product leading to an easy evaluation of the gain in spatial
 189 resolution. The third dataset uses all the observations with an incidence angle lower than 40° (Multi-incidence
 190 Enhanced Resolution, MiER). It is designed to exploit the near-nadir observations owing the best native spatial
 191 resolution. The low-incidence measurements (<40°) correspond to the dark blue dots and the red contour in
 192 Figure 2.

193 Figure 2c shows the variations of the radiometric accuracy in H pol (RA_H) within a SMOS snapshot (~1500

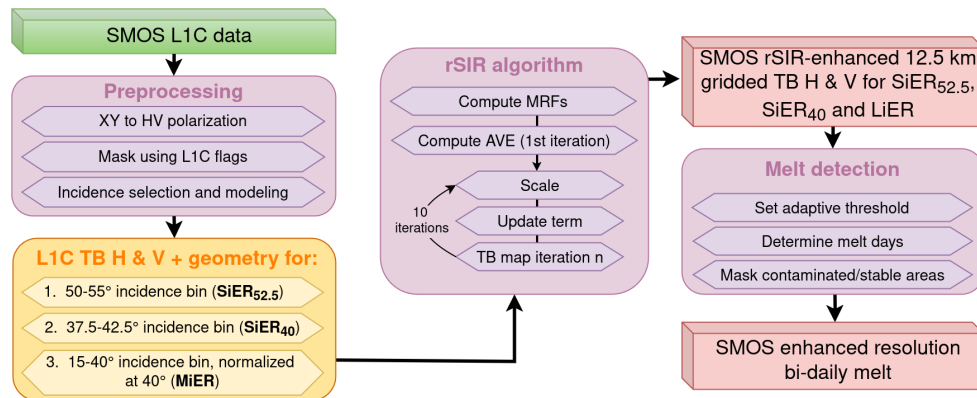


Figure 1: Flowchart of the SMOS resolution-enhancement and melt detection algorithms. The output datasets are highlighted in red boxes.

194 $\times 1500 \text{ km}^2$). RA_H is around 2 K at boresight and is degraded up to 8-9 K along the margins of the snapshot,
 195 especially in the cross-track direction. The RA_H is low in the entire area covered once the flagged observations
 196 have been discarded, that is in medium blue in Figure 2b, and also after the 40° incidence angle selection (red
 197 contour in Figure 2b). The selected observations therefore have a low noise to facilitate the image reconstruction
 198 process.

199 Finally, we separated the morning (before 12 A.M.) and afternoon measurements according to their local
 200 solar time which is calculated as $t_{\text{solar}} = t_{\text{UTC}} + \text{longitude}/15$. Morning and afternoon measurements correspond
 201 broadly to the ascending and descending passes, respectively.

202 3.2. Modeling the incidence angle variations

203 To accommodate the large range of incidence angles in the MiER product, we devised a normalization pro-
 204 cedure of the T_B to a common equivalent angle, chosen at 40° by convention and for comparability with SMAP.
 205 For this, we first modeled the angular variations through a semi-physical approach and then applied this model
 206 to scale the T_B at 40° incidence. The Multi-Fresnel Thermal Emission (MFTE) model described in detail in Ap-
 207 pendix A computes the upwelling radiation emanating from a stack of snow layers with uniform temperature
 208 and alternating density values. Given the permittivities ϵ_1 and ϵ_2 of the alternating layers computed from the
 209 density values, the model calculates the reflection coefficients in H and V polarizations (R_H , R_V). The modeled
 210 brightness temperatures $T_{B,\text{model}}^H$ and $T_{B,\text{model}}^V$ are then calculated as:

$$211 \quad T_{B,\text{model}}^H = T(1 - R_H) \quad (1)$$

$$212 \quad T_{B,\text{model}}^V = T(1 - R_V) \quad (2)$$

212 After a first evaluation, we found that this simple physical model does not perfectly reproduce SMOS inci-
 213 dence diagrams. As an example, Figure 3 presents the morning and afternoon T_B^H and T_B^V acquired around Dome

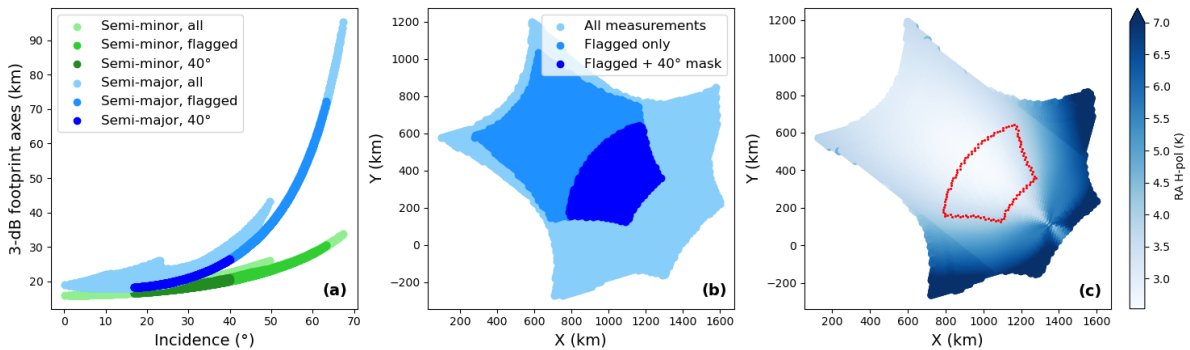


Figure 2: Overview of the L1C flags, radiometric accuracy (RA_H) and spatial resolution variations for one SMOS snapshot on the 19th of January, 2019. (a) Scatterplot of the semi-minor and semi-major axes of the -3 dB antenna footprint against the incidence angle. The light blue and green curves represent all the observations. The medium blue and green curves show the remaining observations once the flagged L1C data have been discarded. The dark blue and green curves show the observations with an incidence angle $<40^\circ$. (b) Location of the non-flagged (remaining) data and the observations with incidence angle $<40^\circ$ within the snapshot, and (c) Spatial distribution of RA_H within the snapshot with the contour of the $<40^\circ$ measurements in red.

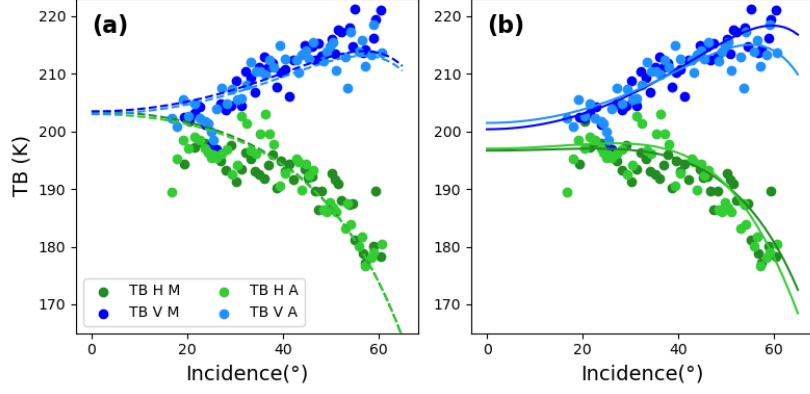


Figure 3: Observed and modeled brightness temperatures as a function of the incidence angle over the DGG n°7144462 close to Dome C on the 19th of January, 2019 for the morning (M) and afternoon (A) passes. In (a) the physical multilayer model was fitted to H and V polarized T_B . (b) is the same for the semi-physical model that includes a linear correction term at H polarization.

214 C in Antarctica for a single day, as a function of the incidence angle. The dashed lines in Figure 3 were obtained
 215 using the MFTE model after fitting both density values. For physical reasons, the modeled T_B are constrained
 216 in such a way that $T_{B,model}^H(0^\circ) = T_{B,model}^V(0^\circ)$. On the contrary, SMOS features significantly lower T_B^H values at
 217 low incidence and a steeper variation in T_B^V than the physical model does. To add flexibility in the model, we
 218 added an empirical linear term to Equation (1), giving:

$$T_{B,model}^H = T(1 - R_H)(\beta + \alpha(1 - \cos\theta)) \quad (3)$$

219 where the coefficients α and β are unknown. In this case, five unknown parameters need to be estimated: ϵ_1
 220 and ϵ_2 (used to determine R_H and R_V), T , α and β . Note that the physical model is obtained for $\alpha = 0$ and
 221 $\beta = 1$. The solid curves in Figure 3 represent the incidence diagrams in Dome C that were computed using the
 222 semi-physical model. The constraint at 0° incidence angle is relaxed which allows the model to represent the
 223 incidence diagram without bias. We assessed the robustness of this semi-physical model by visual inspections
 224 in numerous cases, including over ice shelves in both winter and summer. Because our purpose is to normalize
 225 SMOS L1C T_B without introducing a bias, which was the case using the physical model only, we adopted the
 226 semi-physical approach to compute the MiER product.

227 Finally, the normalization of SMOS brightness temperatures for the MiER product was performed as follows:

$$T_B^p(40^\circ) = T_B^p \frac{T_{B,model}^p(40^\circ)}{T_{B,model}^p} \quad (4)$$

228 where p is the polarization. For convenience, the reference angle is set to 40° , to facilitate the comparison with
 229 SMAP which has a fixed incidence angle of 40° .

230 3.3. rSIR algorithm

231 To retrieve SMOS enhanced resolution T_B , we applied the radiometer version of the Scatterometer Image
 232 Reconstruction (rSIR) algorithm following Long & Daum (1998) with a few adaptations. This algorithm has been

233 widely used within the framework of the National Aeronautics and Space Administration (NASA) Making Earth
 234 System Data Records for Use in Research Environments (MEaSUREs) program to compute enhanced resolution
 235 T_B products from SSM/I, SSMIS, AMSR and SMAP on equal-area grids (Long & Brodzik, 2016; Long et al., 2019).

236 First, the algorithm requires an approximation of the spatial Measurement Response Function (MRF) which
 237 represents the smeared antenna gain pattern projected on Earth's surface for every single measurement. Fol-
 238 lowing previous literature (Long & Brodzik, 2016; Brodzik & Long, 2018) and assuming the response is a two-
 239 dimensional Gaussian where a half-power point corresponds to the -3 dB footprint contour, the discrete MRF
 240 (in dB) of an observation T_i is computed in each pixel $p(x, y)$ as:

$$\text{MRF}_i(x, y) = \ln\left(\frac{1}{2}\right) \exp\left(\left(\frac{2D_x}{a}\right)^2 + \left(\frac{2D_y}{b}\right)^2\right) \quad (5)$$

241 where a is the semi-major axis and b the semi-minor axis of an ellipse approximating the 3-dB antenna footprint.
 242 D_x and D_y are the relative distances from the footprint center to each pixel taken along and across the orienta-
 243 tion of the ellipse, respectively. This model was found to be adequate for reconstructing conventional radiometer
 244 images (Long, 2015). We investigated this approximation and found it was also valid for SMOS. In the L1 image
 245 reconstruction process, a Blackman apodization window is applied to MIRAS synthetic antenna gain to smear
 246 the side lobes at the expense of a slightly degraded resolution. This Blackman window can be fitted with good
 247 accuracy using a relatively simple centro-symmetric function, as demonstrated for soil moisture inversion in the
 248 SMOS L2SM retrieval algorithm (ESA, 2019). If the Gaussian approximation from Long (2015) was used instead,
 249 it would have been almost equivalent to the L2SM Blackman within the -3 dB footprint. We therefore assume
 250 that Equation (5) correctly represents the MRF of SMOS L1C data.

251 For each polarization p , we consider a measurement T_i^p as the sum of the brightness temperature T_B^p sampled
 252 on the Earth's surface weighted by the MRF:

$$T_i^p = \iint \text{MRF}_i(x, y) T_B^p(x, y) dx dy \quad (6)$$

253 The image reconstruction approach in rSIR algorithm aims to estimate the discrete $T_B^p(x, y)$ image from a set of
 254 radiometer measurements T_i^p using the modeled MRF_i . Let a_j be the estimated $T_B^p(x_j, y_j)$ of the row-scanned
 255 j -th pixel. The initialization of the algorithm is performed as a weighted average called AVE:

$$\text{AVE} = a_j^0 = \frac{\sum_i \text{MRF}_{ij} T_i^p}{\sum_i \text{MRF}_{ij}} \quad (7)$$

256 Then, for every iteration k the algorithm determines the estimated brightness temperature a_j^{k+1} as:

$$f_i^k = \frac{\sum_n \text{MRF}_{in} a_n^k}{\sum_n \text{MRF}_{in}} \quad (8)$$

257

$$d_i^k = \sqrt{T_i/f_i^k} \quad (9)$$

258

$$u_{ij}^k = \begin{cases} \left[\frac{1}{2f_i^k} \left(1 - \frac{1}{d_i^k} \right) + \frac{1}{a_j^k d_i^k} \right]^{-1}, & d_i^k \geq 1 \\ \left[\frac{1}{2} f_i^k \left(1 - d_i^k \right) + a_j^k d_i^k \right], & d_i^k < 1 \end{cases} \quad (10)$$

259

$$a_j^{k+1} = \frac{\sum_i \text{MRF}_{ij} u_{ij}^k}{\sum_i \text{MRF}_{ij}} \quad (11)$$

260 where f_i^k is called the forward projection, d_i^k is the scale factor and u_{ij}^k is the update term (Long & Daum, 1998).

261 This process is iterated K times. Long & Daum (1998); Long & Brodzik (2016) noticed that both the recon-
 262 struction accuracy and the noise level increase while iterating. K was set to 10 iterations in our algorithm as this
 263 value permits a good tradeoff between noise and reconstruction accuracy. It is lower than the 20 iterations used
 264 for SSM/I in Long & Brodzik (2016) to account for the higher noise in the interferometric MIRAS measurements
 265 compared to conventional radiometers, ~ 2 K vs < 1 K for SMAP (Piepmeier et al., 2017) and AMSR C, X, K and Ka
 266 bands (Imaoka et al., 2010). After 10 iterations, the reconstruction accuracy converges towards an asymptotic
 267 value with few changes compared to 15 or 20 iterations (also evaluated), while the noise level increases rapidly.

268 The enhanced-resolution T_B maps were computed the same way for both H and V polarizations and morning
 269 and afternoon passes over the entire 14-year SMOS dataset, for the SiER_{52.5}, SiER₄₀ and MiER products.

270 3.4. Evaluation of the effective spatial resolution

271 We defined a common methodology to evaluate and compare the effective spatial resolution of six datasets:
 272 the three new SMOS rSIR-enhanced datasets based on the L1C data (SiER_{52.5}, SiER₄₀ and MiER), the SMAP
 273 rSIR-enhanced T_B and the SMOS L3TB at both 52.5° and 40° incidence angles. The effective spatial resolution is
 274 defined here as the Full Width at Half Maximum (FWHM) of the Pixel Spatial Response Function (PSRF), which
 275 is modeled as a two-dimensional Gaussian. The FWHM is related to the standard deviation σ of the Gaussian
 276 through:

$$\text{FWHM} = 2 \sqrt{2 \ln(2)} \sigma \approx 2.355\sigma \quad (12)$$

277 To determine the FWHM for each dataset, we adopted a similar procedure as in Long et al. (2023). We first
 278 identified a suitable region with an abrupt and large spatial transition, such as between the ice-sheet and the
 279 ocean. This transition is modeled as a two-dimensional step function. The convolution of 2D Gaussian kernels
 280 of varying FWHM with this step function is compared to the observed T_B to determine the smoothness of
 281 brightness temperature changes. We minimize the Root Mean Square Error (RMSE) between the convoluted
 282 and observed data to find the optimal FWHM corresponding to the estimated spatial resolution. The RMSE was
 283 computed along a transect perpendicular to the coastline instead of the whole image.

284 The step function is defined here using Sentinel-1 HV images to delineate the ice and ocean surfaces which
 285 correspond to the maximum and minimum expected brightness temperatures, respectively (see Figure 4, left

286 column). Two case studies are investigated, over the western Antarctic Peninsula on January 26th, 2019 and over
287 West ice shelf in East Antarctica on February 8th, 2019.

288 3.5. Liquid water detection

289 The presence of liquid water in the snowpack is detected using the adaptive-threshold algorithm published
290 in Leduc-Leballeur et al. (2020) with very few changes. This algorithm for SMOS stems from an earlier algorithm
291 designed for 19 GHz observations acquired by SMMR and SSM/I (Torinesi et al., 2003), and further improved by
292 Picard & Fily (2006) with successful applications to SSMIS, AMSR-E and AMSR2 (e.g. (Saunders et al., 2022)).

293 In brief, the sharp increase in T_B time series caused by the liquid water appearance is detected using a
294 threshold value computed as:

$$T = M + 3 \times \sigma \quad (13)$$

295 where M is the average and σ is the standard deviation of T_B^H calculated in dry snow days only, from the 1st of
296 April to the 31st of March. The problem is circular as the knowledge of melt days is required to exclude them
297 from the computation of M and σ , which are further used to detect melt. This is resolved by first detecting melt
298 using the all-day annual average for M and a fixed value of 15 K for 3σ . The first-guess melt time series is then
299 used to update M and σ . Three iterations are performed to obtain the definitive threshold, used to compute the
300 final melt time-series.

301 Noting that false alarms occur in the interior of the Antarctic ice-sheet where melt is obviously absent, we
302 identified and masked these areas by excluding the pixels where the standard deviation of T_B^V exceeds 2.8 K,
303 following Leduc-Leballeur et al. (2020). As this threshold was optimized for Antarctica, it was reevaluated and
304 set to 5 K on Greenland where we noticed a higher variability in SMOS T_B time series.

305 In Antarctica, coastal pixels also show frequent false alarms due to ocean contamination of the radiometric
306 signal. The higher T_B on sea-ice than on open ocean indeed leads to a large and erroneous detection of winter
307 melt days along the coastlines. Winter melt may occur on multiple Antarctic ice shelves due to foehn wind
308 (Kuipers Munneke et al., 2018) or atmospheric rivers (Wille et al., 2019), but with much lower recurrence. Hence,
309 we computed a contamination mask over Antarctica that filters out the pixels where the winter melt occurrence
310 overpasses 5 % in the entire 14-year melt time series. In Greenland, where winter melt is more frequent, the
311 contamination mask is not needed due to the much lower number of marine-terminating glaciers.

312 4. Results

313 We produced three twice daily SMOS rSIR-enhanced datasets based on the L1C product for the period 2010-
314 2024: the SiER_{52.5}, SiER₄₀ and MiER. The coverage of these datasets and the radiometric comparison against the
315 SMOS L3TB product are first presented. Then, we evaluate the spatial resolution of each product in two case
316 studies. Finally, we apply the melt detection algorithm and analyze the benefit of the resolution enhancement
317 for this application.

Table 1: Average percentage of the AIS pixels revisited in one or two days for the MiER, SiER₄₀ and SiER_{52.5} products. The coverage was evaluated for morning and afternoon tracks separately, and also for the daily average of all the tracks.

| | | rSIR morning | rSIR afternoon | rSIR daily |
|--------------------|----------------------|--------------|----------------|------------|
| 1-day coverage (%) | MiER | 90.1 | 91.1 | 98.0 |
| | SiER ₄₀ | 93.7 | 94.5 | 99.2 |
| | SiER _{52.5} | 92.2 | 93.3 | 98.6 |
| 2-day coverage (%) | MiER | 99.4 | 99.7 | 99.9 |
| | SiER ₄₀ | 99.6 | 99.7 | 100.0 |
| | SiER _{52.5} | 99.3 | 99.6 | 99.7 |

318 4.1. SMOS rSIR-enhanced products

319 Table 1 presents the percentage of Antarctic pixels revisited every day and at least every two days for the
320 SiER_{52.5}, SiER₄₀ and MiER datasets. The revisit was computed for the daily average of all tracks and for morning
321 and afternoon tracks separately throughout one year (2019). For the three evaluated datasets, the morning and
322 afternoon tracks cover each more than 90 % of the AIS within one day and >99 % of the AIS within two days.
323 Hence, the SMOS rSIR-enhanced datasets are suitable to detect daily or sub-daily T_B variations associated to a
324 melt signal.

325 The radiometric quality of the SMOS rSIR-enhanced datasets was evaluated by comparing to the 40° and
326 52.5° incidence bins of the L3TB product. Table 2 presents the mean difference (MD) and the Root Mean Square
327 Deviation (RMSD) computed over Antarctica and Greenland in 2019 for all the pairs of datasets compared. We
328 expect a low MD as an indicator of the consistency of each dataset, and a RMSD very low on the stable areas
329 of the Antarctic plateau but much higher on the periphery of the ice sheet where most of the differences due to
330 the resolution enhancement are concentrated. Compared to the L3TB product at 40°, the results show a higher
331 MD for the MiER (+1.16 K to +1.6 K for H, -0.64 K to -0.97 K for V) than for the SiER₄₀ (<0.75 K). The SiER_{52.5}
332 dataset also shows a low MD compared to the L3TB product at 52.5° (<0.33 K). For all the datasets, we obtain
333 a consistent RMSD between 2 K and 4 K with most of the differences concentrated near the coastlines. Only
334 the MiER shows a systematic high MD in the dry and homogeneous Antarctic plateau. The MD is positive
335 for the horizontal polarization and negative for the vertical polarization, which may indicate a bias caused
336 by issues in the incidence diagram modeling. None of the incidence diagrams inspected show an anomalous
337 pattern, but numerical issues in the least square fit could lead to finding a wrong local minimum. This problem
338 requires further investigation to fully exploit the valuable geophysical information contained in SMOS incidence
339 diagrams.

Table 2: Mean difference (MD) and Root Mean Square Deviation (RMSD) over 1 year (2019) between the SMOS rSIR-enhanced datasets and the SMOS L3TB at both 40° (MiER, SiER₄₀) and 52.5° (SiER_{52.5}) incidence angle over Antarctica and Greenland. All units are in Kelvin (K).

| | | MD H | MD V | RMSD H | RMSD V |
|------------|----------------------|-------|-------|--------|--------|
| Antarctica | MiER | 1.60 | -0.97 | 3.15 | 2.68 |
| | SiER ₄₀ | 0.75 | 0.41 | 2.91 | 2.40 |
| | SiER _{52.5} | -0.07 | 0.08 | 2.23 | 1.71 |
| Greenland | MiER | 1.16 | -0.64 | 3.86 | 3.60 |
| | SiER ₄₀ | 0.41 | 0.31 | 3.90 | 3.42 |
| | SiER _{52.5} | -0.02 | 0.33 | 3.10 | 2.64 |

340 4.2. Evaluation of the effective spatial resolution

341 The effective spatial resolution is evaluated in two case studies presented in Figure 4: the West ice shelf (East
 342 Antarctica, top row) and the Anvers Island (Antarctic Peninsula, bottom row). The first column shows the 2D
 343 land/ocean step function derived from Sentinel-1 and the other columns show four T_B^V maps at 40° incidence:
 344 the SMAP rSIR-enhanced from Long et al. (2019), the SMOS rSIR-enhanced MiER (15-40°) and SiER₄₀ (40°), and
 345 the SMOS L3TB. We normalized the T_B^V maps between 0 and 1 to compare measurements performed by different
 346 sensors. Qualitatively, the spatial resolutions of the SMAP enhanced and the two SMOS enhanced maps look
 347 similar although the grid is four times finer in SMAP (3.125 km against 12.5 km). The SMOS L3TB at 40° shows a
 348 larger land-ocean transition indicating a lower spatial resolution in both case studies. For instance, the local T_B
 349 maximums at the locations of Anvers and Brabant islands as well as the channel separating these islands from
 350 the continent are well identified in all the SMAP rSIR and SMOS rSIR products. These features are smoothed in
 351 the SMOS L3TB where a continuous gradient from ocean to land is rather observed.

352 Quantitatively, the spatial resolution was estimated along two transects (red lines in Figure 4). Figure 5

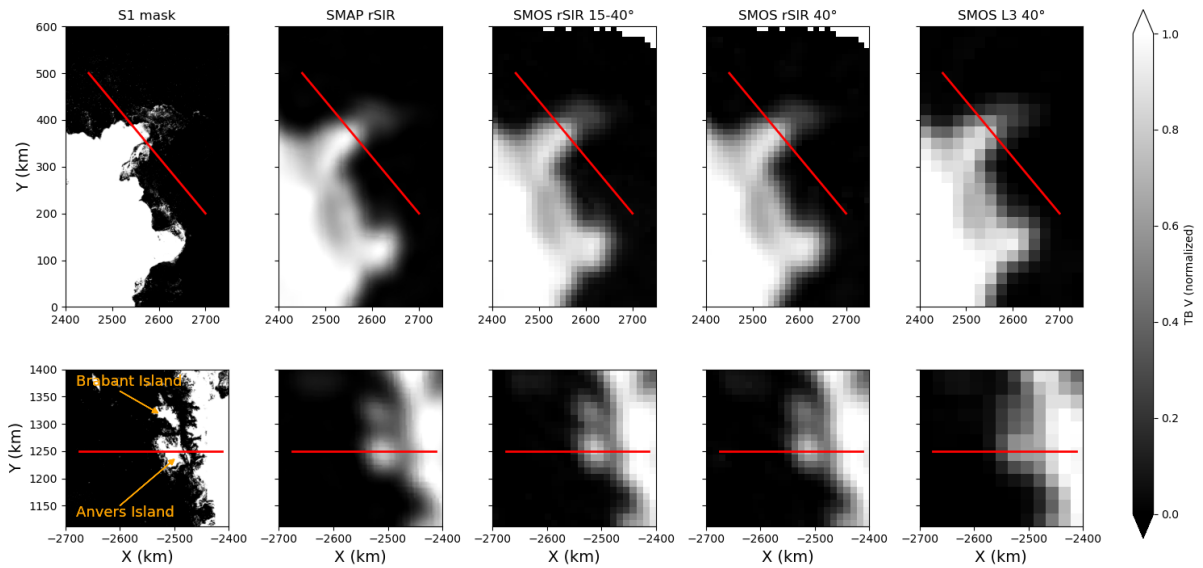


Figure 4: Normalized T_B^V for the ideal S1 mask, SMAP rSIR-enhanced evening tracks, SMOS rSIR-enhanced multi-incidence (15-40°) and single-incidence (40°) afternoon passes and SMOS daily L3TB products over the West ice-shelf on February 7-9th, 2019 (top row) and over Anvers Island on January 25-27th, 2019 (bottom row). The red lines show the transects used to compute the effective spatial resolution of each product in Figure 5.

Table 3: Estimated spatial resolution along two transects over the West ice-shelf and Anvers island, using six datasets: the SMOS L3TB at 52.5° and 40°, the SMOS rSIR-enhanced SiER₄₀, SiER_{52.5} and MiER, and the SMAP rSIR-enhanced at 40°. For each dataset both the H-pol and V-pol spatial resolution were computed.

| Dataset | Spatial resolution (km) | | | |
|------------------|-------------------------|----------|--------|--------|
| | Anvers H | Anvers V | West H | West V |
| SMOS L3TB 52.5° | 55 | 53 | 60 | 58 |
| SMOS L3TB 40° | 47 | 45 | 44 | 42 |
| SMOS rSIR 52.5° | 47 | 45 | 48 | 45 |
| SMOS rSIR 40° | 33 | 32 | 31 | 30 |
| SMOS rSIR 15-40° | 33 | 31 | 33 | 30 |
| SMAP rSIR | 31 | 30 | 28 | 28 |

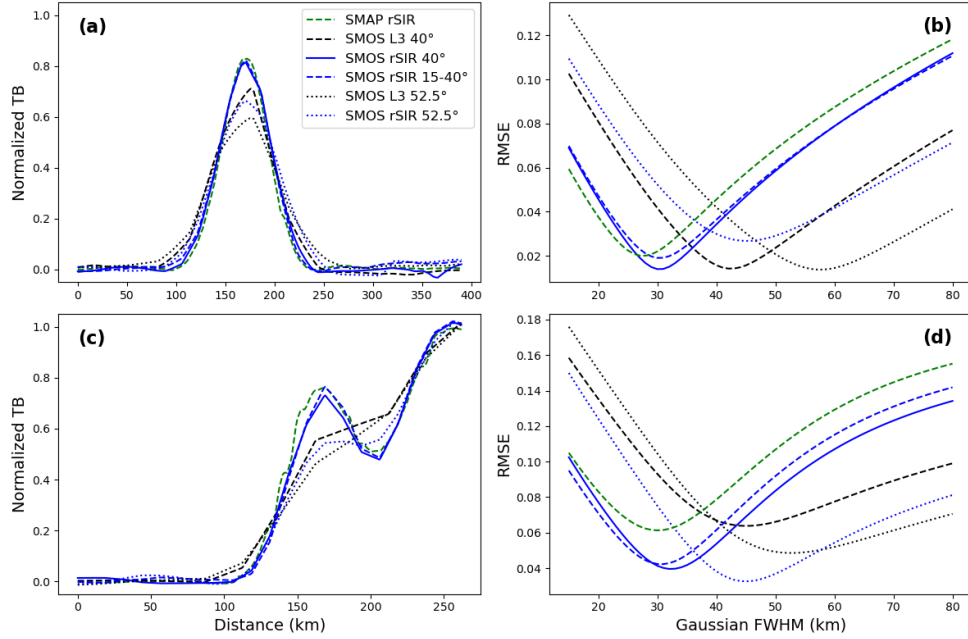


Figure 5: Estimation of the effective spatial resolution along two transects for the West ice shelf (a, b) and Anvers Island (c, d) case studies (see Figure 4 for the locations of these transects). (a, c) T_B plotted along the transects, (b, d) RMSE between the observed and convoluted images plotted against the FWHM of Gaussian kernels used for convolution. The estimated effective spatial resolutions are the FWHM at minimum RMSE for each dataset.

353 presents the normalized T_B^V along these transects (a, c), and the RMSE computed between the observed and
 354 convoluted images as a function of the Gaussian FWHM (b, d). For all the datasets evaluated, the RMSE de-
 355 creases until reaching a minimum where the observed and convoluted maps match the best and then increases
 356 again. The FWHM of the modeled transect at the minimum of RMSE is the estimated effective spatial resolution.
 357 It is reported in Table 3 for all the six datasets and for both case studies in H and V polarizations. The results are
 358 very close for each location and polarization showing the robustness of the estimation. The MiER, SiER₄₀ and
 359 SMAP rSIR-enhanced T_B maps have the finer spatial resolution, around 30 km, while the SMOS L3TB at 40° has
 360 a spatial resolution of 42-47 km. Note that the footprints of native observations used to reconstruct the SiER₄₀
 361 and SMAP rSIR-enhanced datasets are similar (39 × 47 km for SMAP, ~41 × 53 km for SMOS at 40° incidence).
 362 This is a good reason to believe that the rSIR algorithm was correctly implemented and adapted in this study.
 363 At 52.5° incidence, the SiER_{52.5} product has a spatial resolution of 45-48 km and the SMOS L3TB is in the range
 364 of 53-60 km. The SiER₄₀ product therefore improves the spatial resolution by 40-50 % compared to the L3TB at
 365 52.5°, half of the enhancement being due to the reconstruction algorithm (rSIR) while the other half is due to
 366 the lower incidence angle used here. Based on these results, we further used the SiER₄₀ product to assess the
 367 impact of resolution enhancement on melt detection.

368 4.3. Impact of the resolution enhancement on melt detection

369 4.3.1. Ice-sheet wide comparison of melt detection

370 We calculated the 14 year-long (April 2010 - March 2024) time series of melt in Greenland and Antarctica using
 371 the original SMOS L3TB product at 52.5° and the new rSIR-enhanced SiER₄₀ product, using the melt detection

372 algorithm presented in Leduc-Leballeur et al. (2020) and Section 3.5. Note that twice-daily melt was computed
373 from the rSIR-enhanced dataset while the L3TB melt only includes a daily estimation which combines morning
374 and afternoon tracks.

375 The average annual number of melt days according to the enhanced product is shown over Antarctica in
376 Figure 6. It is particularly high over the Antarctic Peninsula, with up to 100 days per year on average on the
377 Wilkins ice shelf. Other regions with a large and recurrent melt signal are located all around Antarctica, on
378 the Riiser-Larsen, Fimbul, Roi Beaudoin, Amery, West, Shackleton and Abbott ice shelves. Additionally, more
379 localized melt patterns with a lower extent and/or less than 30 melt days per year can be distinguished, for
380 example in Wilkes Land.

381 The difference between the average annual number of melt days computed using the SiER₄₀ product and the
382 SMOS L3TB at 52.5° is shown in Figure 7. The pink color represents regions where the enhanced dataset detects
383 more melt than the L3TB, and conversely the green color represents regions with less melt than in the L3TB.
384 The dominant pink color on the map clearly demonstrates that the resolution enhancement makes it possible
385 to capture a longer and wider melt signal over all the Antarctic ice shelves. We found above 30 additional melt
386 days in several regions. This is especially the case near the grounding line (dashed lines in Figure 6 and Figure 7)
387 where the transition from dry to wet snow is sharper in the enhanced resolution dataset. Moreover, the green
388 areas are often very localized on the grounded ice sheet just upstream the grounding line, *e.g.*, for the George VI,
389 Larsen C, Roi Beaudoin and Shackleton ice shelves, suggesting false-positives (*i.e.*, over-estimation) in the L3TB

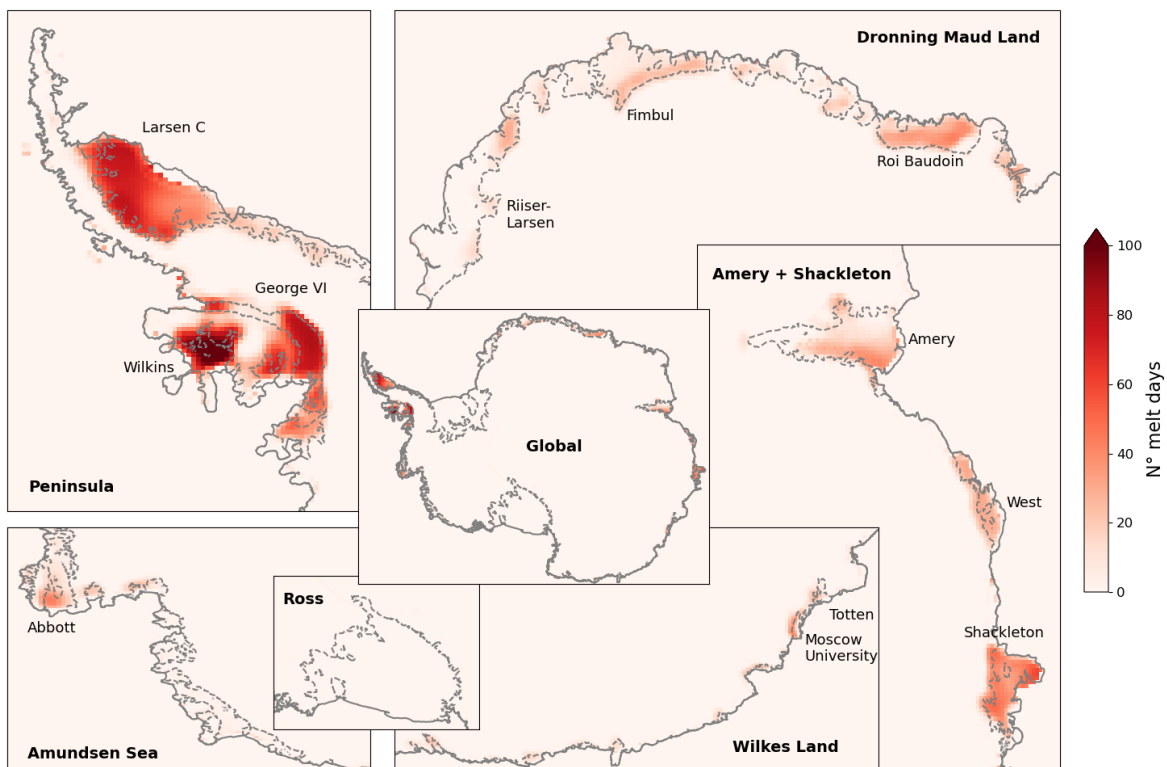


Figure 6: 2010-2024 annual average number of melt days detected using SMOS rSIR-enhanced resolution dataset over Antarctica.

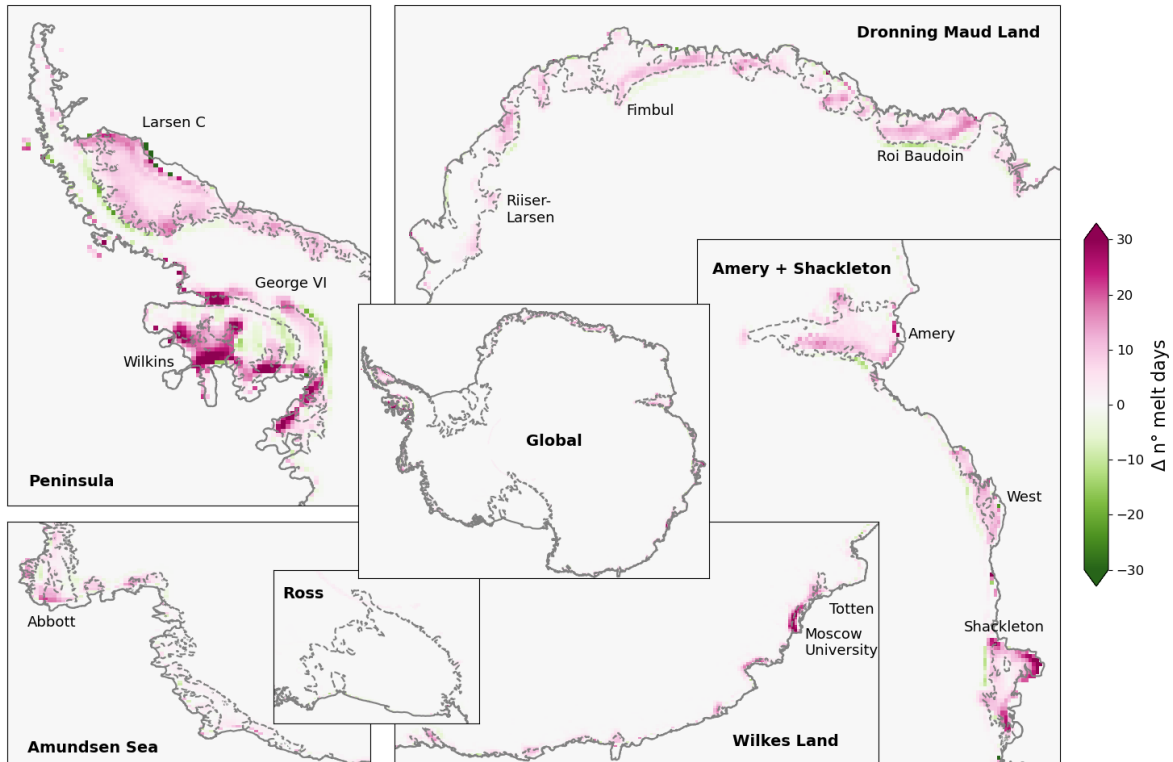


Figure 7: Difference between the 2010-2024 annual average number of melt days detected using SMOS rSIR-enhanced and SMOS L3TB datasets. A higher number of melt days in the enhanced resolution product is shown in pink.

390 due to the spreading of the wet snow signal. We also notice that in some regions the L3TB product indicates no
 391 melt days at all, while the enhanced resolution dataset captures more than 10 melt days per year on average,
 392 such as in Wilkes Land on the Moscow University and Totten ice shelves.

393 The number of melt days detected by the L3TB and SiER₄₀ products over Greenland and their differences are
 394 shown in Figure 8 for each melt year from 2010 to 2023. Several remarks can be inferred. First, when compared
 395 to the L3TB, the SiER₄₀ melt presents similar spatial patterns with intense melt on the contour of the ice-sheet. A
 396 large number of melt days is observed in the southeast and southwest Greenland particularly. This is coherent
 397 with previous studies reporting the presence of perennial firn aquifers and ice slabs in these regions (Koenig
 398 et al., 2014; Miège et al., 2016; Miller et al., 2020, 2022). The interannual variability is well represented with an
 399 exceptional melt season in 2012 which was identified and studied in the literature (Nghiem et al., 2012).

400 Large differences between the L3TB and SiER₄₀ melt in Greenland affect most of the melting areas around
 401 the ice sheet. As in Antarctica, the SiER₄₀ product consistently features a larger number of melt days (about +30)
 402 compared to the L3TB product in many locations and especially along the southeastern coast. On the contrary,
 403 the number of melt days is larger in the L3TB on thin bands located in the upper part of the melting regions.
 404 This localized larger melt signal in the lower resolution L3TB could be due to both the conservative 5 K threshold
 405 on T_B^V used to define the dry snow mask on Greenland for the SiER₄₀ product, and to the mixing of dry and wet
 406 snow regions in the L3TB, as noted in Antarctica around the grounding line. The effect of the conservative
 407 5 K threshold adopted is noticeable elsewhere, for example in 2023 where the baseline product based on the

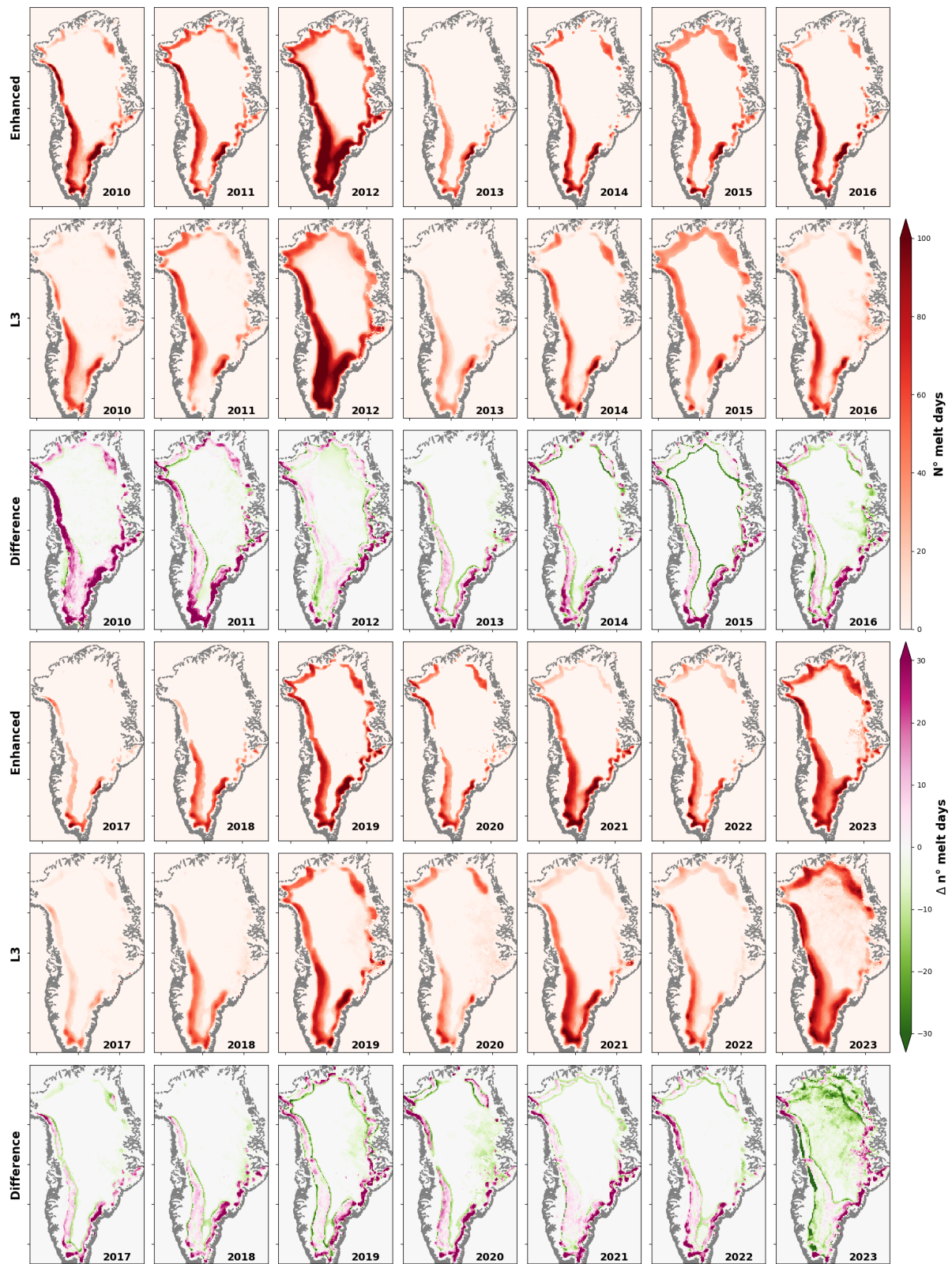


Figure 8: Annual number of melt days detected over Greenland using the SMOS MiER, L3TB and the difference between both products. Fourteen melt years from 2010-2011 to 2023-2024 are presented in the panels.

408 L3TB features many false alarms in the East and Northeast Greenland while these regions are filtered out in the
 409 enhanced resolution product.

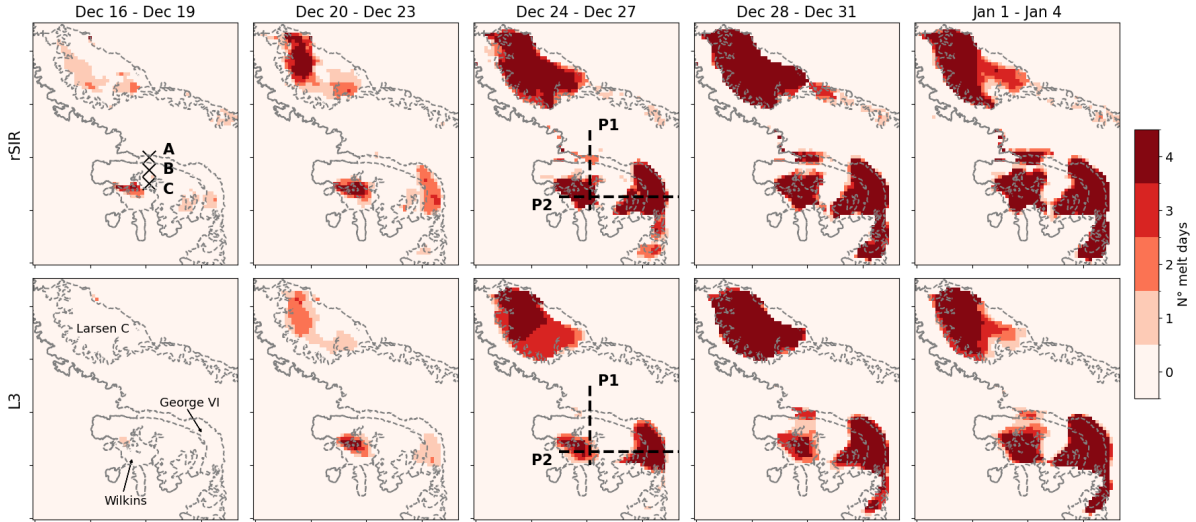


Figure 9: Illustration of the melt onset in the Antarctic Peninsula in 2018-2019. Each map shows the number of melt days over a 4 day period for rSIR (top row) and L3TB (bottom row). Pixels A, B and C correspond to the time series in Figure 11 and P1 and P2 represent the transects shown in Figure 10.

410 4.3.2. Investigation of a melt event in the Antarctic Peninsula

411 To further investigate the reason of the larger number of melt days detected in the SiER₄₀ product, we focus
 412 on a specific melt event. Figure 9 shows the number of melt days on the Antarctic Peninsula in five consecutive
 413 4 day periods from December 16, 2018 to January 4, 2019. Going into the summer, melt propagates rapidly to
 414 the entire Wilkins, George VI and Larsen C ice shelves. Melt is detected earlier and with a wider extent in the
 415 SiER₄₀ product (top row) compared to the L3TB product (bottom row), especially in the northern George VI ice
 416 shelf.

417 Figure 10 presents the difference between the average T_B^H on December 24-27th, 2018 and the average winter
 418 T_B^H (ΔT_B^H) along the transects P1 and P2. P1 crosses the Wilkins and northern George VI ice shelves, while P2
 419 crosses the Wilkins, Bach and Southern George VI ice shelves (see Figure 9). We also show the melt detection
 420 threshold along P1 and P2 for the L3TB and rSIR products to identify areas where ΔT_B^H is larger, corresponding to
 421 melting regions detected by the adaptive threshold algorithm. A large peak in ΔT_B^H is associated to the crossing
 422 of each ice shelf. This peak in summer T_B is also present but smoothed in the L3TB product. This results in
 423 the SiER₄₀ product rising above the melt detection threshold more frequently than the L3TB. On the northern
 424 George VI ice shelf (P1, right peak), the L3TB product does not reach the melt detection threshold while the
 425 SiER₄₀ does. This mainly explains the large increase in annual melt days observed in the northern George VI ice
 426 shelf when using the new enhanced resolution dataset compared to the L3TB (see Figure 7).

427 To explain further the differences observed between the number of melt days detected by the two products,
 428 Figure 11 presents the time series of T_B^H at the locations of pixels A, B and C shown in Figure 9. The melt days
 429 detected by the L3TB product (green bars) and the SiER₄₀ (blue bars) are indicated at the bottom of each plot.
 430 Pixel A is located on the northern George VI ice shelf. Here, the peak in T_B^H is smoothed in the L3TB compared
 431 to the SiER₄₀, and as a consequence the latter indicates more melt (63 days) than the former (48 days). Pixel

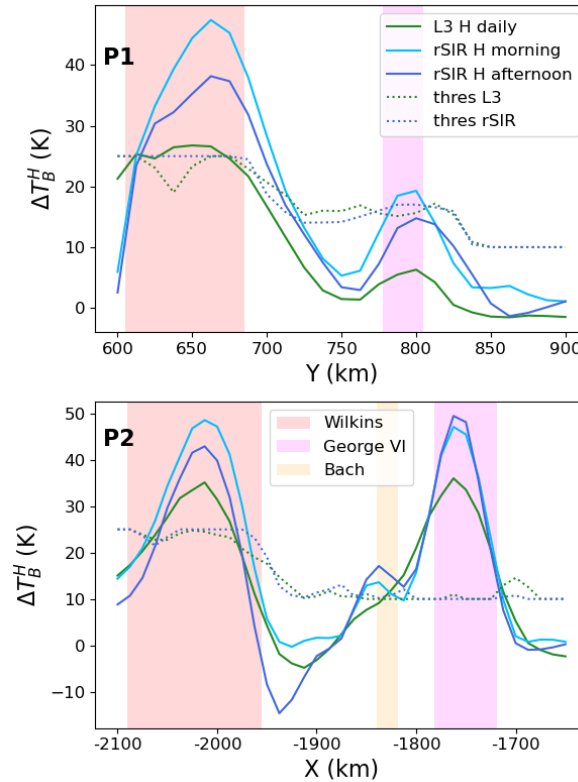


Figure 10: Difference (ΔT_B^H) between the average T_B^H on December 27-30th, 2018 and the average winter T_B^H computed from June 1st to August 31st, 2018, along two transects in Y (P1) and X (P2) crossing the George VI and Wilkins ice shelves. P1 and P2 are identified in Figure 9 which also shows the intensive melt occurring during the 4-day interval on both ice shelves.

432 B is located on the mountain range separating the George VI and Wilkins ice shelves. Here, melt is less likely
 433 due to higher altitude (mountain ranges >1500 m) and results mainly from the contamination of SMOS signal
 434 by surrounding wet snow areas. The amplitude of T_B^H variations in the SiER₄₀ is lower than in the L3TB, which
 435 results in a lower number of melt days (16 instead of 31). Finally, pixel C is located nearby the grounding line
 436 of Wilkins ice shelf in a region with intense melt. Both products show a strong seasonal increase in T_B^H and the
 437 number of melt days detected is slightly higher in the SiER₄₀ (68 days) than in the L3TB (60 days).

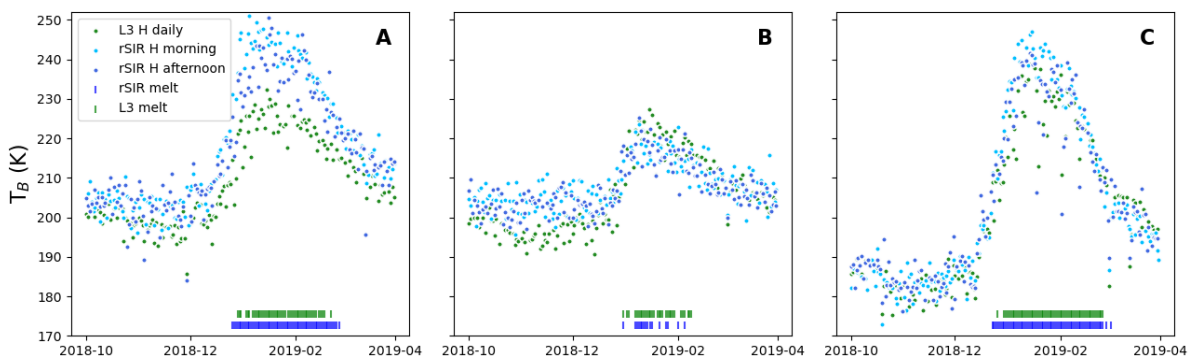


Figure 11: Time series of T_B^H for SMOS L3TB and SiER₄₀ products from April 2018 to March 2019 for the pixels marked at locations A, B and C in Figure 6 and Figure 7 on Antarctic ice shelves. The blue (green, respectively) bars at the bottom of each subplot indicate the days where melt is detected using the SiER₄₀ (L3TB).

438 5. Discussion

439 We have used the SMOS L1C as the unique input of the well-established rSIR algorithm to reconstruct en-
440 hanced resolution T_B maps for SMOS, in order to assess the possible gain in spatial resolution and the impact on
441 melt detection. This process involved several methodological choices and adaptations of the baseline algorithms
442 that are discussed in this section.

443 5.1. Tradeoff between noise, coverage and spatial resolution

444 The application of the rSIR algorithm to SMOS involved several critical choices which were made for a tar-
445 geted application, the melt detection. We discuss here these choices and their influence on the balance between
446 noise level, spatial resolution and coverage, and how they could be adjusted for other applications.

447 A first tradeoff between the noise and the coverage is related to the choices of the poor data rejection criteria.
448 The area within a SMOS snapshot with lowest noise is centered along-track at approximately 35-40° incidence
449 angle, while the noisiest parts are located near nadir and close to the border of the track, as shown in Figure 2c.
450 The selection of the best data only tends to reduce the width of SMOS tracks. Melt detection can accommodate
451 a higher noise as it consists in detecting T_B variations of several tens of Kelvin, while the best possible coverage
452 is required to follow its daily or sub-daily variations. The SiER₄₀ product was therefore computed accepting a
453 high radiometric accuracy threshold of 5 K for a single measurement and it achieves a coverage of 99 % of the
454 Antarctic pixels every day. As a consequence, the average radiometric accuracy is high (<2 K) in the center and
455 lower (~4 K) near the border of the tracks. Other applications requiring higher accuracy should reject more data
456 and deal with a reduced coverage or temporal revisit.

457 A second tradeoff is between noise and spatial resolution, and depends on two settings. Firstly, the measure-
458 ments with lowest radiometric accuracy are located at boresight (32.5° incidence in the along-track direction).
459 Low-incidence observations are likely noisier but also have the highest native spatial resolution (see Figure 2)
460 which led us to select incidence bins at 40° and lower. Low-incidence measurements could be excluded for other
461 applications to ensure a better radiometric accuracy. Secondly, the number of iterations in the image reconstruc-
462 tion process controls the enhancement and the noise of T_B maps. The rSIR algorithm was applied in previous
463 studies to conventional radiometers with low noise (~1 K or lower, (Long & Brodzik, 2016; Long et al., 2019)). In
464 principle, the use of noisier raw data from SMOS logically limits the achievable spatial resolution of the image
465 reconstruction as the iterations must be stopped earlier. For this reason, a threshold of 10 iterations is adopted
466 in this study for SMOS which is lower than the typical 20 iterations threshold of the NSIDC products for SSM/I,
467 SSMIS, AMSR-E and SMAP (Long & Brodzik, 2016; Long et al., 2019). This may explain the slightly reduced
468 effective spatial resolution of the SiER₄₀ compared with the SMAP rSIR-enhanced product (difference ≤ 3 km,
469 Table 3). In practice, the selection of observations with a larger radiometric accuracy (e.g. located on the border
470 of the tracks) does not seem to have a strong impact on the reconstruction of SMOS T_B , as we obtained an
471 equivalent spatial resolution for the range of accuracy 2.8–5 K. We also found that a reconstruction with 15 iter-

472 ations (not shown) provided no significant improvement in spatial resolution, but a higher noise. The potential
473 of further resolution enhancement for SMOS using the rSIR algorithm is therefore likely limited.

474 5.2. Multi-incidence dataset

475 The use of multi-incidence measurements from $\sim 15^\circ$ to 40° in the MiER product aimed to select data with the
476 best native spatial resolution, but it requires to normalize the variations of T_B depending on the incidence angle
477 using the MFTE model. It turns out that the physical model is unable to reproduce SMOS incidence diagrams,
478 especially close to nadir. A similar issue was observed between SMOS incidence diagrams and the in-situ L-band
479 radiometer RADOMEX installed at Dome C in 2010 (see Figure 14 in Macelloni et al. (2013)). We suspect that
480 the conversion of the measurements from the XY antenna frame to the HV surface frame used in geophysics
481 could be responsible for this non-physical behavior. A direct use of XY brightness temperatures in geophysical
482 applications is less common but could prevent this issue. In our approach, we used a more flexible semi-physical
483 model to fit SMOS incidence diagrams as we are only interested in the normalization of all observations to a
484 fixed incidence angle.

485 During the evaluation of the spatial resolution, we observed that the MiER and SiER₄₀ products have almost
486 the same resolution (see Table 3). As our results suggest that the additional complexity and computing cost of the
487 multi-incidence approach are not worth the result, we finally adopted the SiER₄₀ product to detect melt. We have
488 three hypotheses to explain why the inclusion of low-incidence observations does not enhance the resolution.
489 First, the gain in native spatial resolution from 40° to the lowest incidence is relatively small compared to the
490 large improvement between 55° and 40° (Figure 2a). Secondly, SMOS observations near nadir have a small spatial
491 coverage so the reconstructed brightness temperature maps are dominated by data near 40° , especially close to
492 the border of the tracks. Thirdly, the lowest incidence data have a higher radiometric accuracy which could limit
493 the capability of the rSIR algorithm to reconstruct accurate T_B images. Overall, for applications requiring the
494 knowledge of complete SMOS incidence diagrams with an enhanced resolution, a practical solution would be
495 to compute enhanced resolution T_B maps for each incidence bin in the L3TB product.

496 5.3. Limitations and improvements of melt detection

497 The algorithm proposed in Leduc-Leballeur et al. (2020) to detect melt from the L3TB product requires minor
498 modifications to be applicable to the enhanced resolution product. The characteristics of this new product and
499 the necessary technical adjustments may have an impact on the melt detection algorithm in three different
500 ways.

501 First, we had to modify the mask introduced in Leduc-Leballeur et al. (2020) to filter out regions where snow
502 is always dry. In Antarctica, it concerns all the pixels where the standard deviation on T_B^V is lower than 2.8 K.
503 This approach works well in Antarctica, but in Greenland we had to increase the threshold to 5 K to deal with
504 the larger T_B variability. The additional noise in Greenland may be due to an incorrect RFI filtering using L1C
505 flags, as we noticed a bunch of observations with T_B as large as 400 K. These outliers were filtered out using

506 a simple thresholding. All the measurement with a T_B higher than 280 K are considered as non-physical and
507 potentially affected by RFI, which is a fair assumption on the ice sheets. However, some observations with a T_B
508 lower than 280 K could still be affected by RFI and introduce noise in the reconstructed maps.

509 Secondly, the new SiER₄₀ product is noisier than the L3TB at 52.5° (Section 5.1) which is susceptible to disturb
510 the melt detection algorithm. Isolated false alarms may occur due to outliers but this effect is difficult to evaluate,
511 as it is also counterbalanced by the increase of the 3σ melt detection threshold due to higher noise. This higher 3σ
512 threshold can also reduce detection early and late in the season with the enhanced resolution product. However,
513 this effect seems negligible given the otherwise considerable larger number of melt days observed throughout
514 Antarctica and Greenland in the SiER₄₀ compared to the L3TB (see Figure 6 and Figure 7), corresponding to a
515 clear snow wetting with large T_B variations as shown in Figure 10 and Figure 11.

516 Lastly, we used data with an incidence angle of 37.5–42.5° while Leduc-Leballeur et al. (2020) used the 50–55°
517 bin from the L3TB product. T_B^H and T_B^V are respectively higher and lower at low-incidence compared to Brewster
518 angle ($\sim 55^\circ$). Nonetheless, the principle of the melt detection algorithm is based on the large difference observed
519 between winter and summer T_B , that is still largely valid at 40° incidence (Figure 11 gives evidence of it). It is
520 therefore assumed that the radiometric differences between the 40° and 52.5° datasets have a negligible effect
521 on melt detection compared to the stronger effect of the resolution enhancement.

522 To conclude, small adjustments were performed in the melt detection algorithm to cope with the differences
523 in the SiER₄₀ and L3TB products. However, their impact is unnoticeable compared to the main effect of the
524 resolution enhancement.

525 6. Conclusion

526 We applied the state-of-the-art rSIR image reconstruction algorithm to SMOS L1C data to produce for the
527 first time enhanced resolution SMOS T_B maps. Three products were computed and evaluated, using the 50–55°
528 incidence bin only (SiER_{52.5}), the 37.5–42.5° incidence bin only (SiER₄₀), and the observations with an incidence
529 lower than 40° (MiER). The comparisons against the SMOS L3TB product show no systematic bias except for the
530 MiER product that requires a modelisation of incidence diagrams. The spatial resolution of the SiER₄₀ and MiER
531 products is estimated to around 30 km, which is a $\sim 30\%$ improvement (near 50%, respectively) with respect to
532 the L3TB product at 40° (52.5°).

533 We evaluated the impacts of this resolution enhancement for melt detection using the SiER₄₀ product against
534 the L3TB at 52.5° previously used in Leduc-Leballeur et al. (2020). At global scale, there is a widespread in-
535 crease of the annual average number of melt days detected in both the Greenland and Antarctic ice sheets. The
536 largest melt enhancements (>30 days/year) are found in Greenland's percolation areas and on many Antarctic
537 ice shelves, especially near the grounding line. We demonstrated through a case study in the Antarctic Penin-
538 sula that this gain is due to a lesser dilution of the signal produced by localized melt when the surrounding
539 snow areas remain dry. As a consequence, an earlier and sharper increase in T_B is detected as melt in the SiER₄₀

540 product while snow status is still dry in the L3TB. The wet snow detected is also located more accurately on the
541 ice shelves. A sharper T_B decrease in the SiER₄₀ than in the L3TB just above the grounding lines corresponds to
542 the only pixels with more melt days in the L3TB product.

543 These findings and the datasets produced are important for future studies in large-scale hydrology of the ice
544 sheets. First, they could feed L-band and multi-frequency algorithms that aim to detect aquifers, study melt-
545 water percolation and melt/refreeze diurnal cycles. The spatial resolution achieved in the enhanced resolution
546 product (~ 30 km) is comparable for instance to AMSR2 frequency-dependent footprints (~ 41 km at 6.9 GHz
547 to ~ 8 km at 36.5 GHz), and SMOS time series extend to 2010. The enhanced resolution T_B maps are also a
548 valuable input for future algorithms to estimate liquid water content. Finally, for purposes of designing the up-
549 coming passive microwave satellite missions like ESA's Copernicus Imaging Microwave Radiometer (CIMR) and
550 their retrieval algorithms, we demonstrated how important is the spatial resolution when coming to geophysical
551 applications, especially in the cryosphere sciences.

552 **Data availability**

553 Two open access databases contain all the brightness temperature and melt maps on Greenland and Antarc-
554 tica:

- 555 • <https://doi.org/10.57932/f72f9515-3699-4fae-92fc-a350075d042f> for the bright-
556 ness temperature maps,
- 557 • <https://doi.org/10.57932/1970fb7c-cdb4-4ddf-9891-1e6836a46f25> for the melt
558 maps.

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796 **Appendix A. Description of the Multi-Fresnel Thermal Emission model**

797 The model applies to a slab of n horizontal layers $i = 1 \dots n$ with given optical depth τ_i , relative permittivity
 798 ϵ_i and temperature T_i . The model neglects scattering so that the optical depth can be calculated as the product
 799 of the layer thickness d_i and absorption coefficient κ_{ai} .

800 Let $J_i^{t,b}$ and $I_i^{t,b}$ be the upwelling and downwelling radiation at the top (t superscript) and bottom (b super-
 801 script) of layer i propagating with a zenith angle θ_i . The goal is to calculate the upwelling radiation emerging
 802 at the surface of the slab, in the atmosphere (formally denoted by the index $i = 0$): J_0^b . For this we formulate 1)
 803 the angles of propagation in the layers, 2) the propagation through layers, 2) the transfer through the interfaces
 804 between the layers and 3) the enforcement of the boundary conditions at the top and bottom of the slab.

805 *Zenith angle of propagation*

806 Applying the Snell-Descartes formula for loosely media (Maetzawa & Miyauchi, 2009) to account for the re-
 807 fraction between the layers relates the propagation angle θ_i in every layer i to the angle in the air θ_0 :

$$\mu_i = \frac{\Re \sqrt{\epsilon_i - \epsilon_0(1 - \mu_0^2)}}{\Re \sqrt{\epsilon_i}} \quad (\text{A.1})$$

808 where we have defined the cosine $\mu_i = \cos(\theta_i)$, and \Re denotes the real part. μ_i is guaranteed to be ≤ 1 because
 809 the air is the less refractive material.

810 *Propagation within the layers*

811 The downwelling radiation at the bottom of layer i is the result of the downwelling radiation coming from
 812 the top of the layer and reaching the bottom with an attenuation equals to $A_k = \exp(-\tau_i/\mu)$, and by the natural
 813 thermal emission within the layer which is the product of the emissivity and temperature T_i . The emissivity is
 814 equal to the opacity of the layer, i.e. $(1 - \exp(-\tau_k/\mu))$ according to Kirchoff's law. Similarly for the upwelling
 815 radiation at the top, the propagation through the layer including the emission forms a system of two equations:

$$I_i^b = \exp(-\tau_i/\mu)I_i^t + (1 - \exp(-\tau_i/\mu))T_i \quad (\text{A.2})$$

$$J_i^t = \exp(-\tau_i/\mu)J_i^b + (1 - \exp(-\tau_i/\mu))T_i \quad (\text{A.3})$$

816 which can be written in a matrix form as follows:

$$\begin{pmatrix} I_i^t \\ J_i^t \\ 1 \end{pmatrix} = \begin{pmatrix} 1/A_i & 0 & -(1/A_i - 1)T_i \\ 0 & A_i & (1 - A_i)T_i \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} I_i^b \\ J_i^b \\ 1 \end{pmatrix} \quad (\text{A.4})$$

817 with the radiation at the top of the layer on the left and the bottom on the right.

818 *Propagation through the interfaces*

819 For each interface, the upwelling and the downwelling radiation can be written as the sum of the reflected
820 and the transmitted radiation, leading to the two following equations:

$$J_{i-1}^b = r_i I_{i-1}^b + t'_i J_i^t \quad (\text{A.5})$$

$$I_i^t = t_i I_{i-1}^b + r'_k J_i^t \quad (\text{A.6})$$

821 where r_i and t_i are the reflection and transmission coefficient from layer $i - 1$ to layer i , and r'_i and t'_i from
822 layer i to layer $i - 1$. Given that the propagation angles in adjacent layers are related through Snell-Descarte's
823 law, $r'_i = r_i$ and $t'_i = t_i$, and by energy conservation $t_i = 1 - r_i$. Written in matrix form this yields:

$$\begin{pmatrix} I_{i-1}^b \\ J_{i-1}^b \\ 1 \end{pmatrix} = \frac{1}{1 - r_i} \begin{pmatrix} 1 & -r_i & 0 \\ r_i & 1 - 2r_i & 0 \\ 0 & 0 & 1 - r_k \end{pmatrix} \begin{pmatrix} I_k^t \\ J_k^t \\ 1 \end{pmatrix} \quad (\text{A.7})$$

824 *Combined transfer matrix*

825 Combining Equations A.4 and A.7 provides the transfer matrix M_i which links the radiance at the bottom of
826 two successive layers:

$$M_i = \frac{1}{1 - r_1} \begin{pmatrix} P_i & -r_i P_i & (-(1/P_i - 1) - r_i(1 - P_i)) T_i \\ r_i/P_i & (1 - 2r_i) P_i & (-r_i(1/P_i - 1) + (1 - 2r_i)(1 - P_i)) T_i \\ 0 & 0 & 1 - r_i \end{pmatrix}. \quad (\text{A.8})$$

827 To represent the substrate at the bottom of the slab (characterized by its reflection coefficient r_{sub} and tem-
828 perature T_{sub}), it is possible to add a semi-infinite layer with the transfer matrix M_{n+1} given by Eq A.8 where
829 $r_{n+1} = r_{\text{sub}}$ and $T = T_{\text{sub}}$ and $P_{n+1} = 0$.

830 Then, combining the transfer matrices for each layer and the substrate leads to:

$$\begin{pmatrix} I_0^b = 0 \\ J_0^b \\ 1 \end{pmatrix} = \prod_{i=1}^{n+1} M_i \begin{pmatrix} I_n^b \\ J_n^b = 0 \\ 1 \end{pmatrix} \quad (\text{A.9})$$

831 where the downwelling radiation coming from the atmosphere at the top of the slab is $I_0^b = 0$ and the upwelling
832 radiation coming from the bottom of the infinite layer representing the substrate is $J_{n+1}^b = 0$.

833 *Emerging radiation*

834 Equation A.9 provides two linear equations with two unknowns J_0^b and I_n^b , which is solved to yield the
835 emerging radiation at the top of the slab as follows:

$$J_0^b = (-m_{21}m_{13}/m_{11} + m_{23})/m_{33} \quad (\text{A.10})$$

836 where m_{jk} are the elements of the matrix $\prod_{i=1}^{n+1} M_i$. This solves the problem.