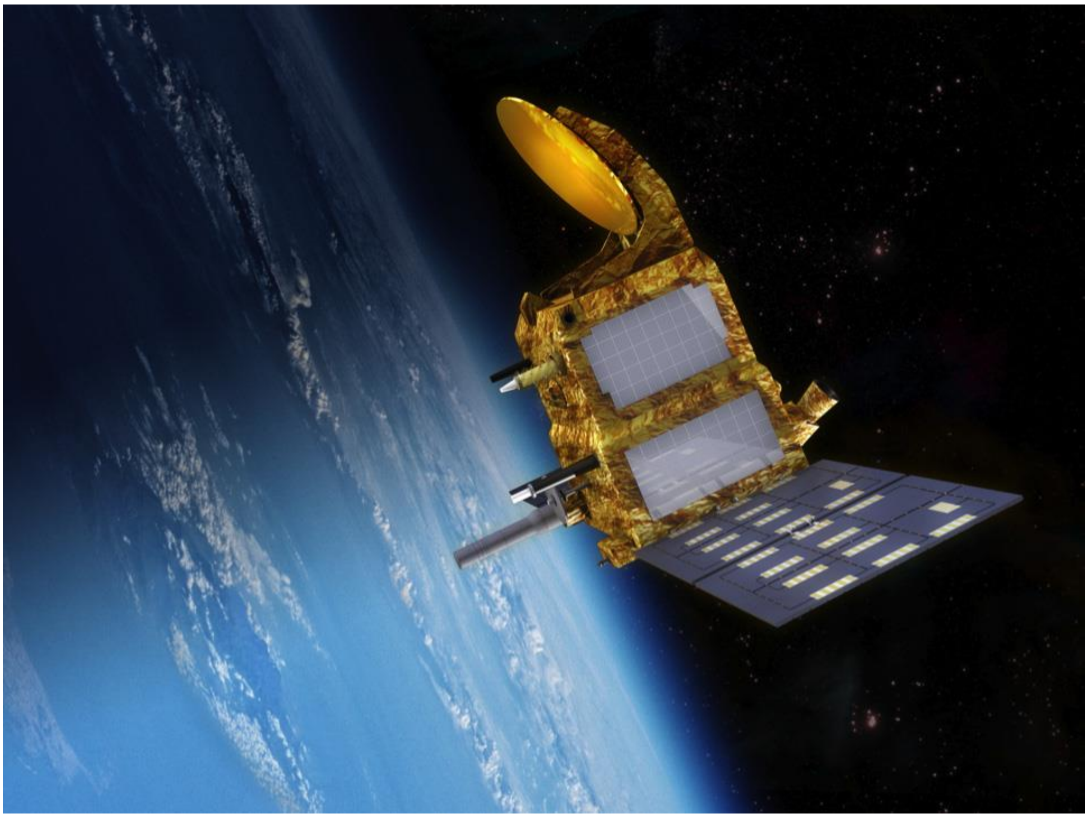
SARAL/AltiKa Ice Sheet Product User Handbook



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1. Introduction

SARAL (Satellite with Argos and AltiKa), is a CNES/ISRO satellite radar altimetry mission launched in 2013. SARAL/AltiKa is still in operation and flies on the same orbit of the preceding ERS and ENVISAT missions. In order to extend the satellite lifetime, SARAL initiated a so-called drifting phase since Spring 2016, where the satellite altitude is no longer maintained.

The main mission goal is ocean topography, and therefore there is no operational product or processing dedicated to ice sheet and sea-ice surfaces. Nevertheless, SARAL orbit covers high latitudes up to +/-81.5°, providing valuable information of the Earth's polar cryosphere. The "S-GDR + IceSheet product" was designed to provide additional and valuable data over the Antarctica & Greenland ice sheets, to fulfil user requirements.

Compare to the other conventional LRM altimetry missions, the on-board altimeter ALTIKA brings several major innovations:

- **It is the first mission carrying a Ka-band frequency altimeter (35.75GHz)**. Ka-band radar wave interacts differently with snow compared to Ku band, due to the different signal wavelength (0.84 cm in Ka band / 2.21 cm in Ku band). In Ka band the signal penetrates less deeply into the snowpack, subsequently the measure is therefore less sensitive to volume scattering compared to Ku band. There is a high potential to exploit synergy between Ku/Ka measurements to derive snowpack properties and parameters, such as snow depth over sea-ice.

- **The altimeter has a higher bandwidth (480 MHz) compared to the other altimetry missions (320 MHz).** AltiKa has therefore a better vertical resolution (~31cm compared to ~47cm for the other missions), meaning the on-ground surface is more finely sampled. For that reason, the radar footprint is also reduced (~11 km diameter for SARAL, compared to ~15 km diameter for Envisat / Sentinel-3 / CryoSat-2).

- **The shorter decorrelation time of sea echoes at Ka-Band** allows to implement a higher Pulse Repetition Frequency (4KHz instead of 2KHz in Ku-band) leading to a better along track sampling (40Hz instead of 20Hz).

Several papers already described the benefits and scientific applications of SARAL/AltiKa (Bonnefond et al.[2018] ; Verron et al. [2018]).

This handbook describes the processing and content of a SARAL/AltiKa product dedicated to ice-sheet: the so-called "S-GDR + IceSheet product", generated by CLS in the frame of a CNES R&D project.

2. Product overview

2.1. Product description

The S-GDR + IceSheet product follows the S-GDR product format, with additional fields dedicated to ice sheet surface. These fields include:

- the measurement relocation at Point Of Closest Approach (POCA)
- an estimation of the ice sheet elevation at POCA
- a surface type flag to discriminate between ice sheet, ice shelves, bedrock and ocean
- a waveform classification
- the nadir surface elevation and topographic slope from an auxiliary DEM
- a specific flag to edit the AltiKa mispointing events

The S-GDR + IceSheet product is a R&D product, backed on operational S-GDR products. All fields available in the S-GDR are also available in the S-GDR+ IceSheet product, with extra fields added to the product. The dataset generated covers the Antarctica and Greenland ice sheets, over a one-year time period: from October 2018 to October 2019.

The figure below presents the different type of AltiKa products and their characteristics:

SARAL/AltiKa Level-2 Products

	OGDR family	IGDR family	GDR family
Reduced 1Hz	OGDR-SSHA	IGDR-SSHA	GDR-SSHA
1Hz + 40Hz	OGDR OGDR-BUFR*	IGDR	GDR
1Hz + 40Hz +waveforms	-	S-IGDR	S-GDR
Latency	3 - 5 Hours	< 1.5 days	~ 40 days

Size & Complexity

Latency & Accuracy

* All files in NetCDF format except OGDR-BUFR, which contains no 40 Hz data

Figure 1: overview of SARAL/AltiKa products

The SARAL/AltiKa products are thoroughly described in the [SARAL/AltiKa Products Handbook](). The present document focuses on the additional ice sheet parameters.

2.1.1. Nomenclature of files

The files have the following nomenclature:
SRL_GPS_2PTP<cycle>_<pass>_<date_begin>_<date_end>.CNES_ice_sheet_product.nc.gz
Where

<cycle>	is the cycle number on 3 digits
<pass>	is the pass number on 4 digits
<date_begin>	is the date of the first measurement of the pass: YYYYMMDD_HHNNSS
<date_begin>	is the date of the last measurement of the pass: YYYYMMDD_HHNNSS

The file is zipped.

2.2. Ice sheet extra fields in summary

The following table presents the additional fields recorded in the S-GDR + IceSheet product. All these fields are described with more details in the following sections of this document. These fields are available at 40Hz rate, except for the antenna mispointing flag available at 1hz rate – but always at a same value for the whole track (see section 3.6).

Additional data	Fields name in the NetCDF	Brief description
Measurement relocation (ie: slope-induced error correction)	ice_sheet_lat_poca_40hz	POCA latitude
	ice_sheet_lon_poca_40hz	POCA longitude
	ice_sheet_elevation_correction_poca_40hz	vertical correction to derive surface elevation at POCA
	ice_sheet_qual_relocation_40hz	flag indicating relocation processing status
Ice sheet elevation at POCA	ice_sheet_elevation_ice1_40hz	Surface elevation computed at POCA, using range from ICE-1 retracking
Nadir elevation and slope from DEM	ice_sheet_elevation_model_40hz	Nadir surface elevation from auxiliary DEM
	ice_sheet_surface_slope_model_40hz	Nadir surface slope from auxiliary DEM
Waveform classification	wvf_main_class_40hz	Waveform main class
	wvf_main_class_proba_40hz	Waveform main class probability
Surface type flag	ice_sheet_surface_type_40hz	Surface type between: ocean / ice_free_land / grounded_ice / floating_ice / lake_vostok
Antenna mispointing flag	antenna_mispointing_flag	Flag indicating a potential SARAL mispointing event

3. Ice sheet extra fields and associated algorithms

3.1. Measurement relocation (slope-induced error correction)

Algorithm description

In practice, the range estimated in conventional altimetry generally corresponds to the distance between the antenna and the nearest point of the surface [Brooks et al., 1978]. Over a broadly flat surface, such as the ocean, this point is located at the nadir. Otherwise, for a more irregular topography, this point is shifted in the upslope direction of the surface, leading to an error in the estimated elevation of the satellite nadir point. This error depends on slope steepness, this is well documented in the literature [Brenner et al. 1978, Bamber et al. 1994].

To correct for this effect, SARAL/AltiKa measurements are relocated at POCA following the methodology of Roemer et al. [2007]. In a nutshell, the POCA on-ground location is determined using an auxiliary Digital Elevation Model of the surface. The algorithm outputs the POCA coordinates in longitude/latitude, along with a vertical correction ("Hcorr" in the figure below) to be applied on the estimated range, accounting from range displacement from nadir to POCA.

The figure below displays a schematic illustration of the measurement relocation processing. For all details about the method, see the publication from Roemer et al. [2007]. In addition, the processing accounts for Earth curvature, improving the relocation accuracy.

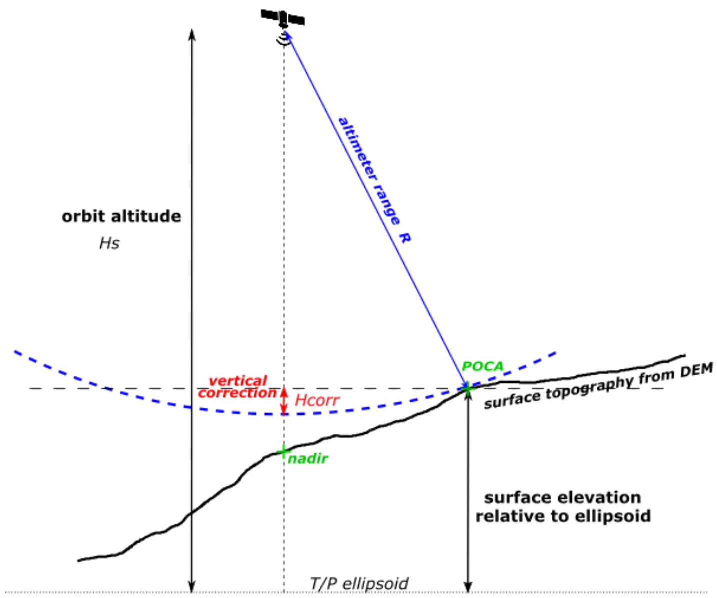

Figure 2: Schematic illustration of the measurement relocation processing

Over Antarctica the auxiliary DEM used to relocate the altimetry measurements is the Reference Elevation Model of Antarctica (REMA), at 200 meters resolution [Howat et al., 2019]:
https://www.pgc.umn.edu/data/rema/

Over Greenland the auxiliary DEM used to relocate the altimetry measurements is the ArcticDEM, at 500 meters resolution:
https://www.pgc.umn.edu/data/arcticdem/

Output fields

The following fields are recorded in the NetCDF:

- **ice_sheet_lat_poca_40hz:** latitude of POCA
- **ice_sheet_lon_poca_40hz:** longitude of POCA
- **ice_sheet_elevation_correction_poca_40hz:** Vertical correction to be applied on range (correspond to “Hcorr” in Figure 2)
- **ice_sheet_qual_relocation_40hz:** A flag indicating the relocation processing status:
  - **0**: Successful relocation
  - **1**: Unsuccessful relocation
  - **2**: POCA location is estimated outside of the antenna aperture at θ_{3db} (further than a ~7.5km horizontal displacement on-ground)
  - **3**: Measurement outside of ice sheets areas

3.2. Ice sheets surface elevation

Algorithm description

Following the measurement relocation processing, an estimation of the surface elevation at POCA is determined using the range from ICE-1 retracking, already available in the nominal S-GDR dataset. The computation is the following (name of NetCDF fields between brackets):

Surface elevation *=* **altitude of satellite** *(“alt_40hz”) –*
ice-1 corrected altimeter range *(“ice1_range_40hz”) +*
POCA vertical correction *(“ice_sheet_elevation_correction_poca_40hz”) –*
Σ geophysical correction

The surface elevation is computed over ice sheets and ice-shelves surfaces. Geophysical corrections are not the same between both surfaces, as it is mandatory to account for ocean dynamics over the ice shelves. **The table below summarizes the geophysical corrections applied to derive the surface elevation:**

<table>
<tr><th></th><th>ice sheet</th><th>ice shelves</th></tr>
<tr><td rowspan="3">Atmospheric propagation corrections</td><td colspan="2">Dry troposphere
(“model_dry_tropo_corr”)</td></tr>
<tr><td colspan="2">Wet troposphere
(“model_wet_tropo_corr”)</td></tr>
<tr><td colspan="2">Ionospheric
(“iono_corr_gim”)</td></tr>
<tr><td>Ocean surface corrections</td><td>/</td><td>Inverse barometric correction
(“inv_bar_corr”)</td></tr>
<tr><td rowspan="3">Tidal corrections</td><td colspan="2">Solid Earth Tide
(“solid_earth_tide”)</td></tr>
<tr><td colspan="2">Geocentric Polar Tide
(“pole_tide”)</td></tr>
<tr><td>Ocean loading tide
(“load_tide_sol1”)</td><td>Ocean tide
+ Ocean loading tide
+ Ocean long period equilibrium tide
(“ocean_tide_sol1”)</td></tr>
</table>

Output field

The following field is recorded in the NetCDF:

- **ice_sheet_elevation_ice1_40hz:** Surface elevation estimated at POCA, using range from ICE-1 retracking. The surface elevation estimated is relative to the TOPEX/Poseidon ellipsoid.

Note 1: *Ice sheet surface elevation is computed if:*

- *relocation processing was successful ("ice_sheet_qual_relocation_40hz" = 0)*
- *measurement is located over ice sheet or ice shelves ("ice_sheet_surface_type_40hz" = 2/3/4)*

Note 2: *While the ice sheet elevation at POCA was validated against ICESat-2 data, ice-shelves elevations at POCA have not yet been assessed. On-going studies.*

3.3. Nadir surface elevation and nadir surface slope from DEM

Algorithm description

The objective of this algorithm is to derive the surface elevation and the topographic slope at nadir location using an auxiliary DEM.

- **Surface elevation computation:** The surface elevation is computed at SARAL measurements nadir, using a bi-linear interpolation on the DEM grid, beforehand projected in stereographic coordinates.
- **Surface slope computation:** The surface slope is computed over a 3km scale around nadir measurements. The computation methodology itself is based on an ArcGIS algorithm: *https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-slope-works.htm*

The same DEMs as used in the relocation processing are employed for these computations (REMA for Antarctica, ArcticDEM for Greenland). References can be found in section 3.1.

Output fields

The following fields are recorded in the NetCDF:

- **ice_sheet_elevation_model_40hz:** Ice sheet elevation at nadir, computed from an auxiliary DEM, referenced to TOPEX/Poseidon ellipsoid.
- **ice_sheet_surface_slope_model_40hz:** Ice sheet surface slope around nadir, computed from an auxiliary DEM (in degrees unit).

3.4. Waveform classification

The SARAL/AltiKa neural network waveform classification has been developed in the frame of the CNES PEACHI project and is implemented in the GDR-F AltiKa products. The AltiKa waveform classification uses exactly the same method as the ENVISAT/RA-2 waveform classification described in Poisson et al., [2018]. The AltiKa waveform classification is based on a neural network algorithm that takes geometrical parameters as input that describes the waveform. Then a class number is attributed to the waveform by the algorithm among the 13 AltiKa waveform classes presented in **Figure 3**.

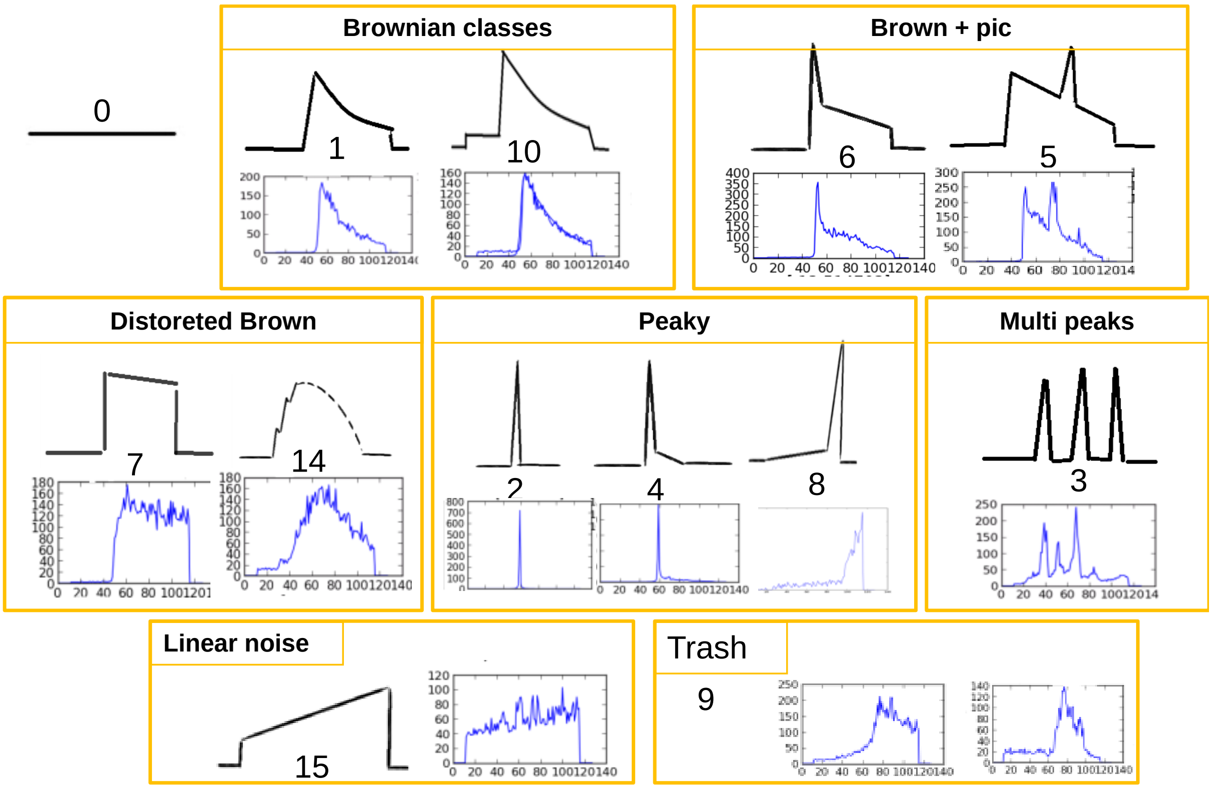

Figure 3: List of the 13 SARAL/AltiKa waveform classes

A short description of the waveform classification is given here:

- Class 0: null waveform
- Class 1: Brownian waveform
- Class 2: strong peak
- Class 3: multi peaks / strong noise
- Class 4: strong peak with a weak trailing edge
- Class 5: Brownian waveform with a peak on the trailing edge
- Class 6: Brownian waveform with a peak on the leading edge or with a steep trailing edge
- Class 7: Brownian waveform with a flat trailing edge
- Class 8: strong peak at the end of the analysis window
- Class 9: trash waveform
- Class 10: Brownian waveform with a high thermal noise plateau
- Class 14: waveform with a disturbed leading edge
- Class 15: linear rising noise

The implementation and the parameterization of a neural network are critical steps which determine the classification performance. For the SARAL/AltiKa classification we choose to implement a single hidden layer neural network using a sigmoidal function. To avoid the "curse of dimensionality", we reduced the number of inputs by not considering all the waveform bins as input of the neural network, but instead a set of 8 parameters which fully describe the waveform. The list of the 8 parameters is given hereafter:

- Mean
- Kurtosis
- Skewness
- Flag of peak detection on the trailing edge
- Slope between bins 60 to 70
- Mean amplitude between bins 40 to 60
- Slope between bins 40 to 60
- Slope between bins 60 to 112

Then the learning phase has been performed using a learning database of 3503 SARAL/AltiKa waveforms where every single waveform has first been classified by hand. After the learning phase, the neural network classification has been tested on a test database that have been built with 2000 more AltiKa waveforms, independent from the learning database. The total error of the SARAL/AltiKa classification estimated on the test database is about 9%. But the error on the most important classes (1, 2, 4, 5, 6 and 10) is about 4.8 %.

<u>Output fields</u>

The following fields are recorded in the NetCDF:

- **wvf_main_class_40hz:** The main class associated to the waveform measurement
- **wvf_main_class_proba_40hz:** Estimated probability associated to this class number by the neural network algorithm, from 0 to 1. The closer to 1 the more robust is the classification estimation.

<u>Recommendation to users</u>

We recommend to discard 40Hz estimations from waveforms <u>class 9</u> (trash waveform) ; <u>class 3</u> (multi-peak waveforms) ; <u>class 8</u> (strong peak at the end of the analysis window) and <u>class 15</u> (linear rising noise). *Unless the expert user provides its own level-2 retracking solution to correctly handle these specific measurements.*

3.5. Surface type flag

In the nominal S-GDR dataset, a surface type field is already available to discriminate between open-ocean, inland waters, continental ice and land. An additional surface type flag is now available in the S-GDR + IceSheet product, providing a more detailed information about the ice sheet type of surface.

Over Antarctica the flag is based on the MEaSUREs BedMachine Antarctica dataset [Morlighem et al., 2019]: https://nsidc.org/data/NSIDC-0756/versions/1

Over Greenland the flag is based on the IceBridge BedMachine Greenland dataset [Morlighem et al., 2018]: https://nsidc.org/data/idbmg4

Output field

The following field is recorded in the NetCDF:

- **ice_sheet_surface_type_40hz:** A flag indicating the ice sheet surface type, with the same terminology as used in the source dataset:
  - **0:** ocean
  - **1:** ice_free_land
  - **2:** grounded_ice
  - **3:** floating_ice
  - **4:** lake_vostok

3.6. Antenna Mispointing editing

Since the beginning of the mission SARAL occasionally experiences some issues affecting the antenna nadir pointing accuracy. The number of mispointing events has raised from September 2015 due to an increase in reaction wheel friction. In case of strong plateform mispointing, the measured waveform can be dramatically distorted. This could lead to large level-2 retracking errors.

To avoid this issue, a strategy was set up at CLS to detect and edit SARAL mispointing events. The objective is to use the mispointing information retrieved by the Brown MLE4 retracker over open ocean. If the mean estimated mispointing over open ocean is greater then 0.025 deg^2 (~0.16°), then the whole track is considered as invalid, and the "**antenna_mispointing_flag**" field is set to 1 for all track measurements.

Output field

The following field is recorded in the NetCDF:

- **antenna_mispointing_flag:** A flag set to 1 in case of SARAL mispointing event detection

4. Accessibility of the product

The products are available via the authenticated **Aviso+ FTP (online products)**:

- You first need to register via the Aviso+ web portal and sign the License Agreement: https://www.aviso.altimetry.fr/en/data/data-access/registration-form.html
- You have to choose the product "Altimetry Ice Sheet (SGDR+) products" in the list of products

A login /Password will be provided via email with all the necessary information to access the products.

5. References

Bamber, J. L. 1994, **Ice sheet altimeter processing scheme**, Int. J. Remote Sens., 15, 925–938

Bonnefond, P.; Verron, J.; Aublanc, J.; Babu, K.N.; Bergé-Nguyen, M.; Cancet, M.; Chaudhary, A.; Crétaux, J.-F.; Frappart, F.; Haines, B.J.; Laurain, O.; Ollivier, A.; Poisson, J.-C.; Prandi, P.; Sharma, R.; Thibaut, P.; Watson, C. **The Benefits of the Ka-Band as Evidenced from the SARAL/AltiKa Altimetric Mission: Quality Assessment and Unique Characteristics of AltiKa Data**. *Remote Sens.* 2018, *10*, 83.

Brenner, A. C., Bindschadler, R. A., Thomas, R. H., and Zwally, H. J. 1983, **Slope-induced errors in radar altimetry over continental ice sheets**, J. Geophys. Res., 88, 1617–1623

Brooks, R.I., Campbell, W.J., Ramseier, R.O., Stanley, H.R., Zwally, H.J. 1978, **Ice sheet topography by satellite altimetry**. Nature 274, 539–543

Howat, I. M., Porter, C., Smith, B. E., Noh, M.-J., and Morin, P.: **The Reference Elevation Model of Antarctica**, The Cryosphere, 13, 665-674, https://doi.org/10.5194/tc-13-665-2019, 2019.

Morlighem, M. et al. 2017, updated 2018. ***IceBridge BedMachine Greenland, Version 3***. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/2CIX82HUV88Y. [Date Accessed].

Morlighem, M. 2019. ***MEaSUREs BedMachine Antarctica****, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/C2GFER6PTOS4. [Date Accessed].

Poisson J., Quartly G. D., Kurekin A., Thibaut P., Hoang D. and Nencioli F., "**Development of an ENVISAT Altimetry Processor Providing Sea Level Continuity Between Open Ocean and Arctic Leads**", in IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 9, pp. 5299-5319, Sept. 2018.

Roemer, S., Legrésy, B., Horwath, M., and Dietrich, R.: **Refined analysis of radar altimetry data applied to the region of the subglacial Lake Vostok/Antarctica**, Remote Sens. Environ., 106, 269–284, doi:10.1016/j.rse.2006.02.026, 2007.

Verron, J.; Bonnefond, P.; Aouf, L.; Birol, F.; Bhowmick, S.A.; Calmant, S.; Conchy, T.; Crétaux, J.-F.; Dibarboure, G.; Dubey, A.K.; Faugère, Y.; Guerreiro, K.; Gupta, P.K.; Hamon, M.; Jebri, F.; Kumar, R.; Morrow, R.; Pascual, A.; Pujol, M.-I.; Rémy, E.; Rémy, F.; Smith, W.H.F.; Tournadre, J.; Vergara, O. **The Benefits of the Ka-Band as Evidenced from the SARAL/AltiKa Altimetric Mission: Scientific Applications**. *Remote Sens.* 2018, *10*, 163.