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Letter

Assessment of the "Zero-Bias Line" Homogenization Method for Microwave Radiometers Using Sentinel-3A and Sentinel-3B Tandem Phase

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Abstract: The long-term stability of microwave radiometers (MWR) on-board altimetry missions is critical to reduce the uncertainty on the global mean sea level estimate. Harmonization and homogenization steps are applied to MWR observations in that perspective. The Sentinel-3 tandem phase provides a unique opportunity to quantify the uncertainties on the "zero-bias line" homogenization approach defined by Bennartz et al. (2020). Initially developed to improve the performance of the wet tropospheric correction retrieval, it is used here to provide a common reference for the inter-calibration between Sentinel-3A and Sentinel-3B MWR. A simplified version of the "zero-bias line" approach, a linear correction depending on brightness temperatures, allows to strongly reduce the bias between the two radiometers for both channels (about 0.5 K) and the standard deviation of the difference (0.3 K). The full version of the approach adding a dependency on wind speed has improved the quality of the WTC retrieval (Bennartz et al. 2020) but degrades the performance of the homogenization. It is thus recommended to apply the simplified version of this approach in the processing of fundamental data record. The quantification of the uncertainties on the homogenization approach is only possible due to the ideal configuration of the Sentinel-3 tandem phase. The same dataset and the same metrics could be used to assess other approaches.

Keywords: microwave radiometry; altimetry; homogenization; fundamental data record; tandem phase; sentinel-3

1. MWR Instruments On-Board Sentinel-3A and Sentinel-3B

The Sentinel-3 Microwave Radiometer (S3 MWR) (see Figure 1) is a two-channels noise injection microwave radiometer. Following the heritage of ERS-1, ERS-2 and Envisat, it operates at 23.8 GHz to observe atmospheric water vapour and at 36.5 GHz to record the presence of atmospheric liquid water.

By using feed horns that are not directly on the boresight of the antenna, the 24 km diameter footprint at 23.8 GHz is located 28 km in front of the sub-satellite point and the 18.5 km diameter footprint at 36.5 GHz is located 27 km behind. Thus, the time series of brightness temperatures at the two frequencies have to be shifted to match the spatial locations of the altimeter measurements.

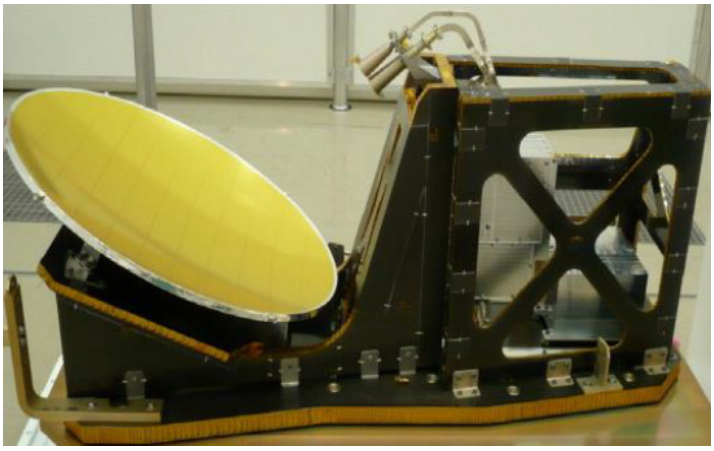

Figure 1. Photo of the MWR antenna plus two feed horns. Source: Sentinel-3 SRAL Marine User Handbook [1].

MWR brightness temperatures (T_B) are used to infer the amount of water vapour and liquid water in the sub-satellite atmospheric column, and to subsequently calculate the Wet Tropospheric Correction (WTC), i.e. the correction to the range, and the atmospheric attenuation (correction to the altimeter backscattering coefficient, σ_0) to support altimetry observations. Table 1 contains a summary of MWR instrument specifications.

Table 1. Key characteristics of the MWR flown on the Sentinel-3 series of satellites. Source: Sentinel-3 SRAL Marine User Handbook [1] and https://www.wmo-sat.info/oscar/instruments/view/348.

Parameter	23.8 GHz	36.5 GHz
Spatial resolution	23.5 km	18.5 km
Radiometric sensitivity (main path, NIR mode)	0.29 K	0.34 K
Noise (at 25 °C)	<4.4 dB (main path)	<5.1 dB (main path)
Along-track pointing angle	1.99°	−1.94°
Polarization	linear	
Integration time (typical)	152.88 ms	
Bandwidth	200 MHz	
Radiometric accuracy	<3 K	
Radiometric stability	0.6 K	
Main reflector size (projected diameter)	0.6 m	
Calibration	Noise injection Dicke radiometer configuration with a separate deep space viewing sky horn to provide cold reference at 50% and 100% noise injection. Dedicated instrument calibration sensors.	
Mass/power/data rate	24.2 kg/26 W/5 kbps	
Launch date	16-02-2016 (S3-A) and 25-042018 (S3-B)	
First acquisition date	29-02-2016 (S3-A) and 08-05-2018 (S3-B)	

2. Harmonization and Homogenization and the Sentinel-3 Tandem Phase

The stability of the wet tropospheric correction is a critical aspect of the characterization of the global mean sea level (GMSL) rise: any artificial trend on the WTC has a direct impact the quality of the GMSL. The reprocessing of long-term timeseries of microwave radiometers on-board altimetry missions, correcting for any instrumental drift, is thus an essential step in the improvement of our knowledge of the impact of the global warming on the ocean.

Methods to build consistent long time series between different sensors have been formalized by the FIDUCEO (http://www.fiduceo.eu/vocabulary) project. Once an instrument is launched, the first step is the harmonization. Each sensor is calibrated to a common reference, but, depending on the characteristics of each instrument, two harmonized sensors may observe different signals when looking at the same location and the same time.

Historically, MWR on-board altimetry missions have been harmonized by adjusting the parameterization of the radiometric model, the quasi-linear relation between raw antenna counts and the brightness temperatures based on internal calibration. The new set of parameters are adjusted within the accuracy limits defined by the on-ground test. The goal is to minimize the differences on T_B directly compared to the already operational MWR on-board previous altimetry missions [2] or compared to common references, using a vicarious calibration approach [3,4]. In Figure 2, the radiometric model is referred as $f(G, C_A, T_{offset})$, G being the instrumental gain, C_A the antenna counts and T_{offset} an offset temperature. Considering two distinct instruments A and B, two specific and independent functions f_A and f_B are established. At this step, the harmonized ${T_B}^h_A$ and ${T_B}^h_B$ still differ.

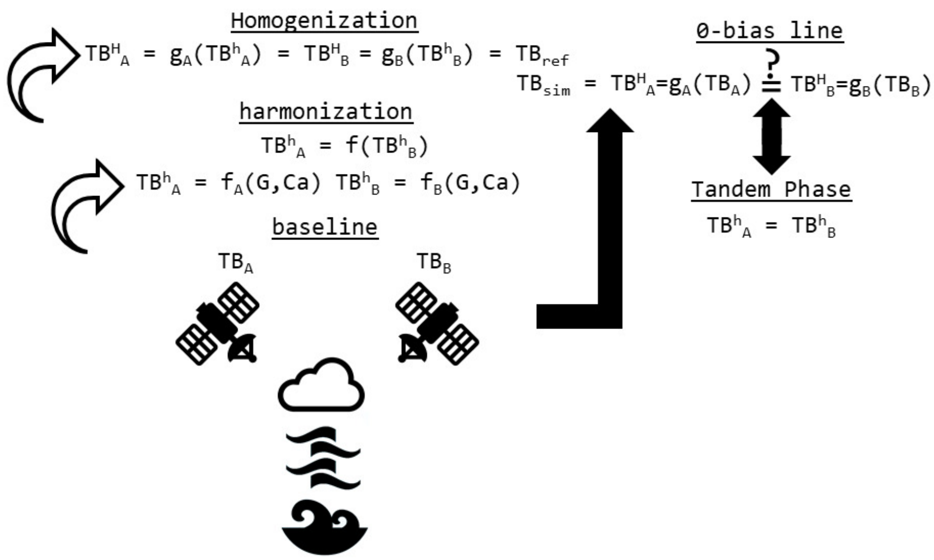

Figure 2. Simplified representation of harmonization and homogenization steps. In the context of the Sentinel-3 tandem phase, the harmonization directly provides homogenized T_B. The "zero-bias line" homogenization is here applied to baseline T_B and assessed comparing ${T_B}^H_A$ and ${T_B}^H_B$ that should be as close as possible.

The second step is the homogenization. This principle applied to Earth Observation consists on forcing all satellites to look the same such that when looking at the same location at the same time they would (in theory) give the same signal. In practice, it consists on adding corrections terms independently to each instrument.

The correction terms may be computed by comparison to a reference instrument. For instance, the GPD+ solution proposed by Fernandes et al. (2016) ([5]) relies on a calibration of the MWR on-board altimetry missions against Special Sensor Microwave Imager (SSM/I) and the SSMI Sounder (SSMIS).

In the past years, there have been different initiatives funded by ESA (European Space Agency) to propose homogenized and harmonized datasets of altimetry products for the ERS-1, ERS-2 and Envisat missions. The REAPER project was the first attempt to reprocess the radiometer measurements with a common radiometric model (harmonization) and to propose an intercalibration of the different instrument based on vicarious calibration [6]. A couple of years after, in the frame of the EMIR study, Bennartz et al. [7] propose an alternative intercalibration scheme for the same three missions relying on the same mathematical framework than for the retrieval of the WTC. It consists on finding an optimal bias to be applied to the T_B at the input on a one-dimensional variational approach (1D-VAR).

This optimal bias minimizes the difference between the retrieved water vapour and the first guess, also minimizing the amount of retrieved liquid water path over clear sky conditions. As illustrated by Figure 2, the adjustment functions g_A and g_B project respectively the harmonized TB_A^h and TB_B^h onto the reference TB_{ref}. At this step, the harmonized ${T_B}_A^H$ and ${T_B}_B^H$ are as close as possible to each other and to the reference, that is with a negligible bias and a standard deviation of the difference of the order of the instrument sensitivity.

The validation of the homogenization approaches is limited by the uncertainties on the references (variability of the vicarious calibrations, uncertainties on the radiative transfer model) or the spatial and temporal distance between the current instrument and the target (collocation with analysis from a numerical weather prediction model or match-up with a reference instrument).

The tandem phase of the Sentinel-3 missions offers an ideal situation to quantity those uncertainties.

During the first six months of the mission, between the 7 June 2018 and the 16 October 2018, Sentinel-3A (S3-A) and Sentinel-3B (S3-B) satellites flied in close formation, separated by only about 30 s. Taking into account this delay, the remaining distance between the closest measurement is about 2 km (see Figure 3). During this period, the S3-B observations have been processed using the pre-flight parameterization of the radiometric model. So, differences existed in this dataset between the brightness temperatures observed quasi-simultaneously by Sentinel-3A and Sentinel-3B. Benefiting from the conditions of the tandem phase, Collecte Localisation Satellite, responsible for the monitoring and the processing of the radiometers, has since updated the radiometric model of Sentinel-3B in order to minimize the difference with Sentinel-3A [8]. As illustrated by Figure 2, in the context of a tandem phase, the harmonization step actually blends with the homogenization: the reference is the T_B of S3-A and after the adjustment of the radiometric model on S3-B, observations from the two instruments are already as close as possible from one another.

The objective here is to quantify the uncertainties of a homogenization method in the lack of a harmonization process. On the contrary to the nominal sequence of harmonization and homogenization, the homogenization is directly applied to the baseline T_B, the raw observations computed with the default parameterization of the radiometric model (see Figure 2). Applying the homogenization to the baseline T_B does not follow the nominal procedure and is unusual. But such conditions, the lack of a robust harmonization step, can occur for the reprocessing of past missions with the objective of long-term stability for climate studies. It may happen that the parameterization of the radiometric model is no longer valid after the T_B are impacted by an instrument failure (ageing or failure of internal components). Indeed, this case is considered in the frame of the FDR4ALT ESA project (https://www.fdr4alt.org/) which aims at delivering harmonized and homogenized altimetry products covering the whole ERS-1, ERS-2 and Envisat area between 1992 and 2013. Fluctus SAS, Informus and CLS collaborate to the reprocessing of the radiometers on-board those missions. At the current stage of this project, it is not guaranteed that a correction of the radiometric model or a new parameterization will be sufficient to account for the large gain drop that occurred in June 1996 on ERS-2 (see [3]). The current work thus provides useful metrics to define the uncertainties on these datasets in case the homogenization step will directly correct the artificial biases observed on the T_B.

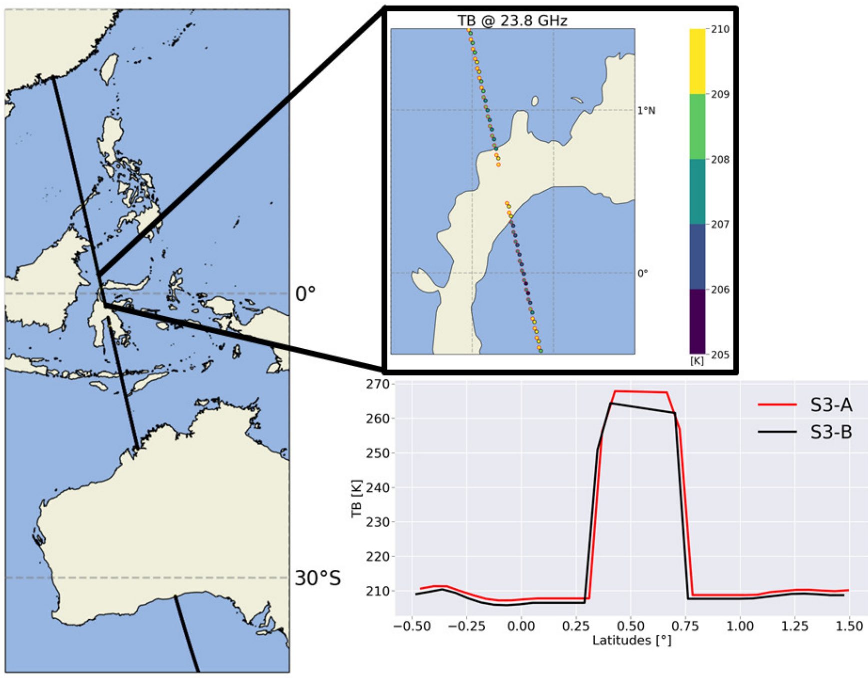

Figure 3. 23.8 GHz brightness temperatures observations from Sentinel-3A (red) and Sentinel-3B (black). 12 October 2018, 13:36, orbit 366, cycle 36 (S3-A) and cycle 13 (S3-B).

The context of the tandem phase provides a unique opportunity and a reference to assess the method: it is expected that the homogenization process corrects for the differences between the observations of the two instruments, which during this period, actually observe the same target at the same location and the same time.

3. Dataset and Homogenization Method

3.1. The Tandem Phase Dataset and Editing

For the purpose of the S3-Tandem study, the Reprocessing 2 dataset has been downloaded from the Copernicus Online Data Access—REProcessed (CODA-REP) server operated by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) (https://codarep.eumetsat.int/#/home) (registration required). Covering the period from 7 June 2018 to 16 October 2018, this Level-2 Marine Product dataset has been reprocessed with the Level 2 IPF version IPF-SM-2 06.14, corresponding to the S3A Processing Baseline 2.33/1.33 [9].

Land measurements are discarded, and no specific processing is applied in coastal areas so that contamination from land may occur above coastal waters at distances up to ca. 50 km offshore. Such potentially land-contaminated pixels are excluded from the analysis presented herein by rejecting any observation less than at least 100 km offshore.

The same validity criteria as defined in the S3MPC STM Annual Performance Report [10] is applied here. The objective is twofold:

- to remove measurements over sea ice: only observations within ±60° of latitudes are considered and the open_sea_ice product flag is applied
- to reduce the variability of the difference between the T_B of the two instruments (ΔT_B) due to outliers (thresholds applied to a set of parameters).

Details can be found in Table 7 of [10].

Finally, the variability of ΔT_B is also reduced by editing cloudy and rainy situations. The product flag rain_flag_01_ku is applied and the measurement for which the radiometer liquid water content

(LWC) is larger than +0.2 kg·m^2 are edited, taking into account a bias observed on the distribution of the LWC compared to the distribution observed on other instruments (not shown here).

Once land and coastal observations are discarded, an additional 33% of the remaining measurements is edited by those criteria.

3.2. The "Zero-Bias Line" Homogenization Method

The method defined below achieves the homogenization by focusing on the performances of the geophysical retrieval. The three main approaches applied to compute the wet tropospheric correction from the brightness temperatures measured by a MWR are the following:

- the JPL algorithm is a stratified logarithmic model which parameters are set using T_B simulated from radiosonde profiles [11].
- the CLS algorithm is a neural network approach which biases and weights are set using T_B simulated from ECMWF analysis [4,12].
- the 1D-VAR approach proposed by Bennartz et al. [7] and Hermozo et al. [13] relies on the minimization of the difference between the observed T_B and simulated T_B.

Despite the differences between these methods, they all have in common a preliminary step that consists on computing the optimal transfer function between the observations and the simulations. This step is critical for the performance of the retrieval since the retrieval will be optimal only if the statistics of the observations is similar to the statistics of the simulations.

The "zero-bias line" method was initially developed by Bennartz et al. (2020) [14] to optimize the performance of a one-dimensional variational approach (1D-VAR) to retrieve the WTC. As demonstrated in Bennartz el al. (2017) on the reprocessing of ERS-1, ERS-2 and Envisat microwave radiometer observations, it can also be used for the homogenization of different instruments. In this case, the reference for the homogenization is the simulated brightness temperatures used within the 1D-VAR minimization process.

Two different sources of differences between observations and simulations are addressed in Bennartz et al. (2020):

- systematic errors associated with the calibration of the passive microwave radiometer under consideration. Those biases might be caused by imperfect knowledge of the instruments' characteristics, instrument drift, or any other variables that directly affect the instrument calibration.
- systematic errors in the forward radiative transfer model used, including systematic errors and uncertainties in the surface emissivity model, systematic errors and uncertainties in spectroscopy of liquid water absorption, dry air absorption, and water vapour absorption.

While the second source of bias is not caused by the instrument, it will in effect yield the same biased retrievals as if it were caused by the instrument. Therefore, any correction for the purpose of retrieval studies does not necessarily need to separate the two, as long as it is capable of effectively correcting for the combined effect of the two error sources.

The details of the method can be found in Bennartz et al. (2020) [14]. The transfer function takes the shape of a 2-dimensional polynomial function δT_B that is subtracted to the observed T_B:

$$T_B^H = T_B^h - \delta T_B \quad (1)$$

$$\delta T_B = a_0 + a_1 T_B + a_2 u_{10m} + a_3 u_{10m}^2 \quad (2)$$

The originality of Bennartz et al. (2020) approach is the introduction of the dependency on 10-meters wind speed (u_{10m}) which is associated with forward modelling errors, typically on the surface emissivity.

The values of the parameters $a_i, i = 0, 3$ are independently obtained for each channel by a fit of the variation of the difference between observed and simulated T_B computed for different classes of T_B and wind speed. It's worth noting that the method proved to lead to a reduction of the dependency of the estimated WTC on wind speed [14], using the homogenized T_B in input to the retrieval (same paper). A question addressed by this paper is to assess if the same two-parameters approach can be directly use for the definition of homogenized T_B. Even if the difference between the two instruments is not expected to depend on wind speed, it is yet interesting to assess if the full definition of δT_B can be distributed in fundamental data records (FDR4ALT project).

In order to assess the impact of the two components onto the homogenization, two versions of δT_B are thus compared. In the following, *homogenized 1-p* or *h-1p* refers to δT_B only depending on T_B and *homogenized 2-p* or *h-2p* refers to full version of δT_B as defined by Equation (2).

The set of parameters is independently estimated for each channel and each instrument (see Table 2). Comparing the values for the two instruments, it appears that S3-A biases show a stronger dependency on absolute T_B than S3-B biases. T_B biases show a strong dependency on wind speed for both radiometers.

Table 2. Coefficients for Equation (2) (extracted from Bennartz et al. (2020) [14].)

Instrument	Frequency	a_0	a_1	a_2	a_3
S3-A	23.8	8.75311	−0.0374060	0.0387134	0.0181940
S3-B	36.5	4.22902	−0.0130407	0.1023970	0.0157970

4. Assessment Using S3-A and S3-B Tandem Phase

The bias between S3-A and S3-B (ΔT_B) is computed from the co-registered T_B (taking into account the 30 s delay).

Figure 4 shows the time series of the daily average (solid lines) and the daily standard deviation (shaded patterns) of ΔT_B for the baseline (orange), homogenized 1-p (green) and homogenized 2-p (blue). Some data gaps are noticed, corresponding to a few orbits up to a couple of days. Some gaps are related to downloading issues, some are related to instrumental unavailability: a list of known instrumental issues is available in the cyclic data product quality reports available on the dedicated ESA website. (https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-3-altimetry/data-quality-reports). Note that the presence of gaps does not change the general conclusion of this study.

During the tandem phase, the bias between the baseline observations of the two instruments is stable on both channels. The bias between S3-A and S3-B is about +2 K on the 23.8 GHz channel and about +1.15 K on the 36.5 GHz channel. The homogenization 1-p depending on T_B reduces the bias down to +0.5 K on the 23.8 GHz channel and −0.6 K on the 36.5 GHz channel. The variability of ΔT_B is also slightly reduced from 0.5 K (raw) to 0.3 K (h-1p) on the 23.8 GHz channel (stable and equal to 0.4 K on the 36.5 GHz channel). The homogenization 2-p depending on T_B and wind speed reduces the bias down to +0.6 K on the 23.8 GHz channel and +0.5 K on the 36.5 GHz channel. But the corresponding variability of ΔT_B increases up to 0.8 K on the 23.8 GHz channel and 0.9 K on the 36.5 GHz channel. Comparing h-1p and h-2p allows to attribute the increase of ΔT_B variability to the wind speed dependency in h-2p.

Since the radiometric model of S3-B is not optimized yet in this dataset, the differences ΔT_B between S3-A and S3-B are depending on the observed T_B as shown by Figure 5. The dependency on the raw ΔT_B is about the same on both channels, around −0.02 K/K. On the 23.8 GHz channel, the homogenization reduces this dependency by at least a factor three down to about +0.007 K/K (h-1p and h-2p). The impact of h-1p is lesser on the 36.5 GHz channel, with a reduction from −0.024 K/K (raw) to −0.013 K/K (h-1p). The impact of h-2p on the slope is larger with a final slope of +0.002 K/K but again with an increase of the variability of ΔT_B.

For such low frequencies as the 23.8 GHz and 36.5 GHz channels, the observed T_B also varies with the surface emissivity and thus with wind speed. So, it is expected that ΔT_B also shows a dependency on wind speed, as illustrated by Figure 6.

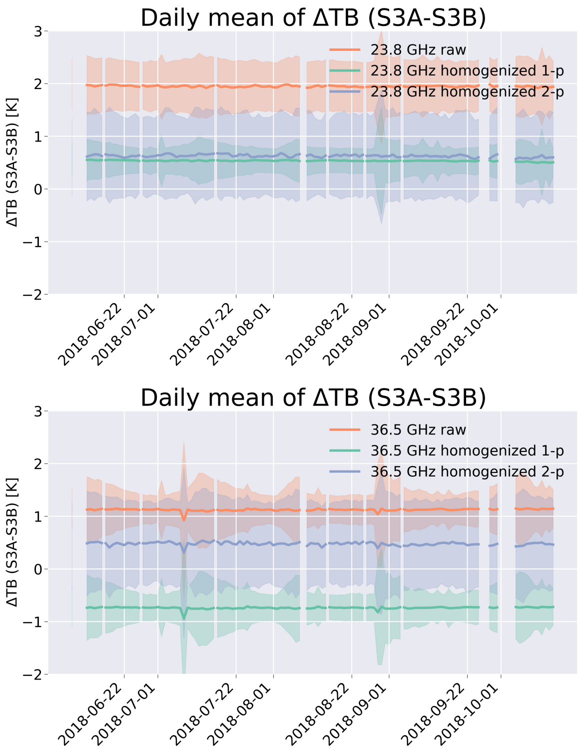

Figure 4. Monitoring of the bias between S3-A and S3-B T_B during the tandem phase, for the 23.8 GHz channel (**top**) and the 36.5 GHz channel (**bottom**). The solid lines refer to the daily mean and the shaded area to the standard deviation of the difference. The orange features refer to the baseline T_B, the green one to the homogenized h-1p T_B and the blue one to the homogenized h-2p T_B.

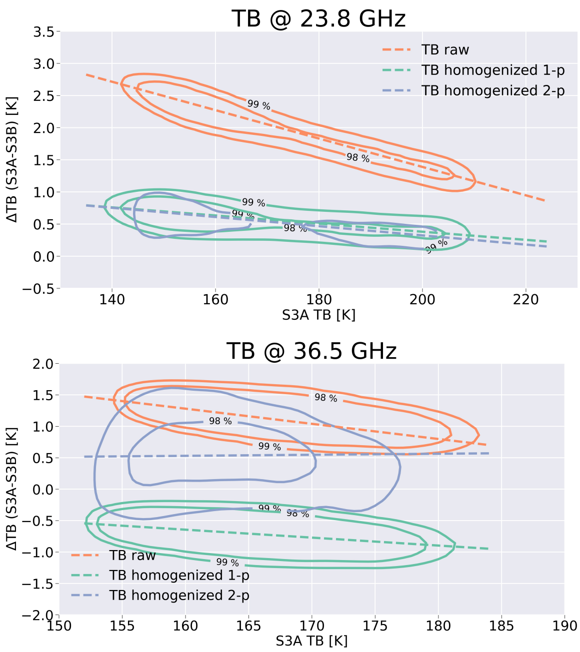

Figure 5. Density contour of the variation of the difference between S3-A and S3-B T_B with S3-A T_B. Orange contours refer to the baseline T_B, the light green contours refer to the homogenized h-1p T_B and the blue contours refer to the homogenized h-2p T_B.

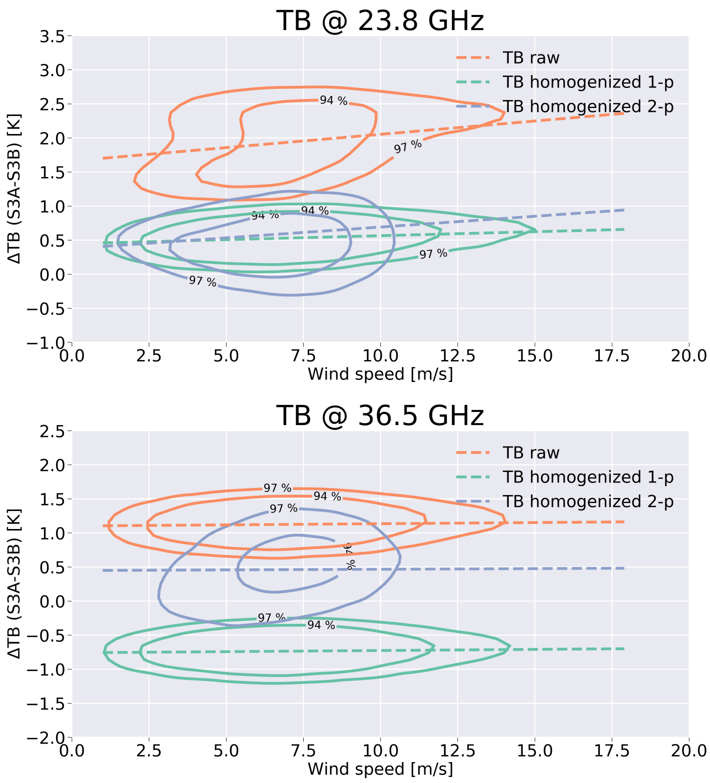

Figure 6. Density contour of the variation of the difference between S3-A and S3-B T_B with the wind speed. Orange contours refer to the baseline T_B, light green contours refer to the homogenized h-1p T_B and the blue contours refer to the homogenized h-2p T_B.

The 36.5 GHz being a window channel is less dependent on surface conditions. The homogenization 1-p has no impact on the slope, -0.033 K/m·s^{-1} for both raw and h-1p. The slope is reduced with the homogenization 2-p (-0.019 K/m·s^{-1}) but at the cost of a larger dispersion of ΔT_B.

The homogenization has a larger impact on the 23.8 GHz channel. The dispersion of the raw ΔT_B is the combination of two distributions, one along +2.5 K and the second along +1.5 K, resulting in a global slope of about +0.040 K/m·s^{-1}.

The two distributions correspond to two different geophysical conditions. The first one centered around a bias of 2.25 K corresponds to drier conditions (WTC below 12 cm) and the second one centered around 1.5 K corresponds to wetter conditions (WTC above 12 cm). This behaviour reflects the impact of the un-optimized radiometric model of Sentinel-B radiometer but no further detail could be found on a more precise explanation.

Still, it's worth noting that this pattern is corrected by the homogenization 1-p, which now exhibits a single distribution along about +0.5 K with a lesser slope of +0.012 K/m·s^{-1}. The dispersion and the slope of ΔT_B are larger with the homogenization 2-p (+0.032 K/m·s^{-1}).

Table 3 summarizes the statistics characterizing the difference between S3-A and S3-B T_B for both channels and for the baseline, h-1p and h-2p T_B. Except for the reduction of the slope of ΔT_B with T_B and the wind speed on the 36.5 GHz channel, the h-1p homogenization approach provide the best performances, reducing both the bias and the standard deviation, this latter being close to the instrumental sensitivity.

Table 3. Characterization of the difference between S3-A and S3-B T_B for both channels and for the baseline, h-1p and h-2p T_B.

Statistics ΔT_B = (S3-A-S3-B)	23.8 GHz			36.5 GHz		
	Raw	h-1p	h-2p	Raw	h-1p	h-2p
mean (daily)	+1.9 K	+0.5 K	+0.6 K	+1.15 K	−0.6 K	+0.5 K
standard deviation (daily)	+0.5 K	+0.3 K	+0.8 K	+0.4 K	+0.4 K	+0.9 K
vs. T_B, slope [K/K]	−0.022	−0.006	−0.007	−0.024	−0.013	+0.002
vs. u_{10m}, slope [K/m·s^{-1}]	+0.040	+0.012	+0.032	−0.033	−0.033	−0.018

5. Conclusions and Recommendation for Future Missions

Harmonization and homogenization of microwave radiometer observations on-board altimetry missions are essential steps to provide stable timeseries of the sea surface height for climate-oriented study. The Sentinel-3 tandem phase offers a unique opportunity to assess the homogenization approach proposed by Bennartz et al. (2020). Initially developed to optimize the performance of a 1D-VAR retrieval of the wet tropospheric correction, the "zero-bias line" method proposes a common reference, simulated T_B, for the observations of the two microwave radiometers.

This method proposed a polynomial correction of the T_B that depends linearly on the observed T_B and at the second degree on the wind speed. The introduction of this latter accounts for known errors on the radiative transfer model used to simulate T_B and proved to improve the quality of the retrieval.

Two versions of the homogenization have been compared, the full version (h-2p) depending on both T_B and wind speed and a simplified version (h-1p) depending only on T_B.

The homogenization processes have been applied to baseline T_B of Sentinel-3A and Sentinel-3B. Regarding the performances of the homogenization only, and not of the WTC retrieval, the h-1p approach provides better results than the h-2p on both channels. The h-1p homogenized T_B show a low bias (about 0.5 K) and a standard deviation of the difference of the order of the instrumental sensitivity on the 23.8 GHz and the 36.5 GHz channels. The introduction of wind speed in the homogenization process results in an increase of the standard deviation on both channels, from about 0.5 K to more than 0.8 K.

In the perspective of defining a fundamental data record, we recommend to use the "zero-bias line" approach in its simplified form, which results in a strong reduction of the biases and an improvement on the variability, even in the lack of a harmonization step. It is expected that the same method could also be successfully applied in the context of the harmonization of microwave radiometers series on-board missions dedicated to the atmosphere observation as MetOp (ESA/EUMETSAT).

It is worth noting that this fundamental data record would then be slightly different from the observation used for the retrieval since it has been demonstrated by Bennartz et al. (2020) that the full version of this approach does improve the performance of the WTC retrieval.

The quantification of the uncertainties on the homogenization approach is only possible due to the ideal configuration of the Sentinel-3 tandem phase. The same dataset could be used to assess other approaches, as the GPD+ proposed by Fernandes et al. (2016), and compared to the "zero-bias line" method. In the coming year, the Sentinel-3C mission will be launched: the combination of two tandem phases based on a given reference instrument (yet to be decided) would be a great opportunity to assess the impact of the ageing on the Sentinel-3A and Sentinel-3B microwave radiometers.

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