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Article

Validation of recent altimeter missions at non-dedicated tide gauge stations in the Southeastern North Sea

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Abstract: Consistent calibration and monitoring is a basic prerequisite for providing reliable time series of global and regional sea level variations from altimetry. The precision of sea level measurements and regional biases for six altimeter missions (Jason-1/2/3, Envisat, Saral, Sentinel-3A) is assessed at eleven GNSS-controlled tide gauge stations in the German Bight (SE North Sea) for the period 2002 to 2019. The gauges are partly located at the open water, partly at the coast close to mudflats. The altimetry is extracted at virtual stations with distances from 2 to 24 km from the gauges. The processing is optimized for the region and adjusted for the comparison with instantaneous tide gauges readings. An empirical correction is developed to account for mean height gradients and slight differences of the tidal dynamics between gauge and altimetry which improves the agreement between the two data sets by 15-75%. The precision of the altimeters is depending on location and mission and is shown to be at least 1.8 to 3.7 cm based on an assumed precision of 2 cm for the gauges. The accuracy of the regional mission biases is strongly dependent on the mean sea surface heights near the stations. The most consistent biases are obtained based on the CLS2011 model with mission dependent accuracies from 1.3 to 3.4 cm. Hence, the GNSS-controlled tide gauges operated operationally by WSV might complement the calibration and monitoring activities at dedicated CalVal stations.

Keywords: regional sea level; satellite altimetry; tide gauge; validation; mission bias; North Sea; Sentinel-3A; Jason-1; Jason-2; Jason-3; Envisat; Saral

1. Introduction

Coastal zones are exposed to manifold natural and anthropogenic forces potentially threatening habitats and societies. Among them, extreme sea levels and long term sea level rise are of special concern [1,2] and require substantial investments in coastal protection measures.

For more than a century the coastal sea level has been observed with tide gauges. They are well maintained and have a proven record of accuracy [3,4]. Tide gauges deliver localized high-resolution sea level data which are valuable for operational purpose, but also for monitoring surges, extremes, or tsunamis [2,5]. A number of studies employed this data to characterize global sea level rise [6,7] or local effects such as coastal subsidence [5,8].

Since more than three decades radar altimetry has now been used for sea level research and increasingly for operational applications [2,9]. Over the years a multitude of satellites have been and are used to continuously observe the instantaneous sea level globally. This requires a harmonization and intercalibration of contemporaneous and consecutive missions. The precision of altimeter missions and biases between the missions have been assessed on a global basis [10–12], however these values are not necessarily valid for regional applications. In coastal areas the precision is frequently diminished and geographically correlated orbit errors induce regional inhomogeneous mission biases [13,14]. There exist only a few continuously operated dedicated CalVal stations for altimetry [15–18]. However, globally distributed tide gauge stations have been used to monitor the precision and long-term sea level trends observed by altimetry [19–21].

Our study area is the German Bight, located on the European continental shelf in the southeastern corner of the North Sea. It covers an area of about 77000 km^2 and is very shallow with maximum water depths of about 50 m. The Wadden Sea with its mudflats spans about 10-12 km off the coast and is bordered by the chain of the Frisian Islands. Altimeter data might help to improve storm surge and climate models used by local authorities for sea level forecasts, marine safety, search and rescue as well as for the monitoring of drifting pollutants like oil spills.

Here, we aim to assess the accuracy of recent altimeter missions in the German Bight by comparing altimetry with tide gauges controlled by global navigation satellite systems (GNSS) measurements. In contrast to previous work in the region [22–25] our study is more comprehensive, it evaluates six altimeter missions and uses data from eleven high-rate tide gauge stations since 2002. The focus is on the mission biases and the precision of the instantaneous height measurements. CalVal at non-dedicated stations can be hampered by poorly known differences in ocean dynamics between the two sensor locations. Here, an empirical model is introduced to align the two data sets. For an assessment of altimetric accuracy on seasonal to decadal time scales in the region the reader is referred to [26].

The paper is structured as follows: Section 2 provides a description of the used data sets. Since the data is not exactly collocated in space it must be corrected for systematic effects related to this. An empirical position correction for this purpose is described in Section 3. The precision of the altimetry measurements and regional mission biases are derived in Section 4. Finally, the performance of the non-dedicated tide gauge stations for calibration and monitoring of altimeter data is discussed in Section 5.

2. Data

We compare ellipsoidal heights from multi-mission altimetry at nine virtual stations to data from eleven nearby tide gauge stations located in the German Bight (eight coastal and three open water stations). The names of these virtual stations, the corresponding altimeter missions and collocated tide gauge stations are given in Table 1, the positions are shown in Figure 1. In the following we describe the satellite and in-situ data. For our assessment we use standard statistical quantities (RMS of height differences and explained variances) to assess the altimeters' accuracy.

Table 1. Virtual positions, the available missions, collocated tide gauges and the distance between both for Jason-1 (J1), Jason-2 (J2), Jason-3 (J3), Envisat (Env), Saral/AltiKa (Sa), Sentinel-3A (S3A). FINO platforms are equipped with two gauge sensors (FINO/Fino) with different measurement periods.

Virtual station	Missions	Distance [km]	Tide gauges
Alte Weser	J1, J2, Env, Sa, S3A	8.9 8.7	LT Alte Weser, Wangerooge Nord
BORKUM	J2, Env, Sa, S3A	15.9	Borkum Südstrand
Dwarsgat	J2, Env, Sa, S3A	7.4	Dwarsgat
FINO1	J2, J3, Sa, S3A	12.2, 5.0, 24.6	FINO1, Fino1
FINO3	J2, J3, Sa	7.4, 17.1, 1.9	FINO3, Fino3
Helgoland	J1, J2, J3, Env, Sa, S3A	12.7	Helgoland
SYLT	J1, J2, J3, Env, Sa, S3A	15.9	Hörnum
Wittdün	J1, J2, J3, Env, Sa, S3A	8.1	Wittdün
ZEHN	Env, Sa	5.0 14.7	Zehnerloch, Cuxhaven

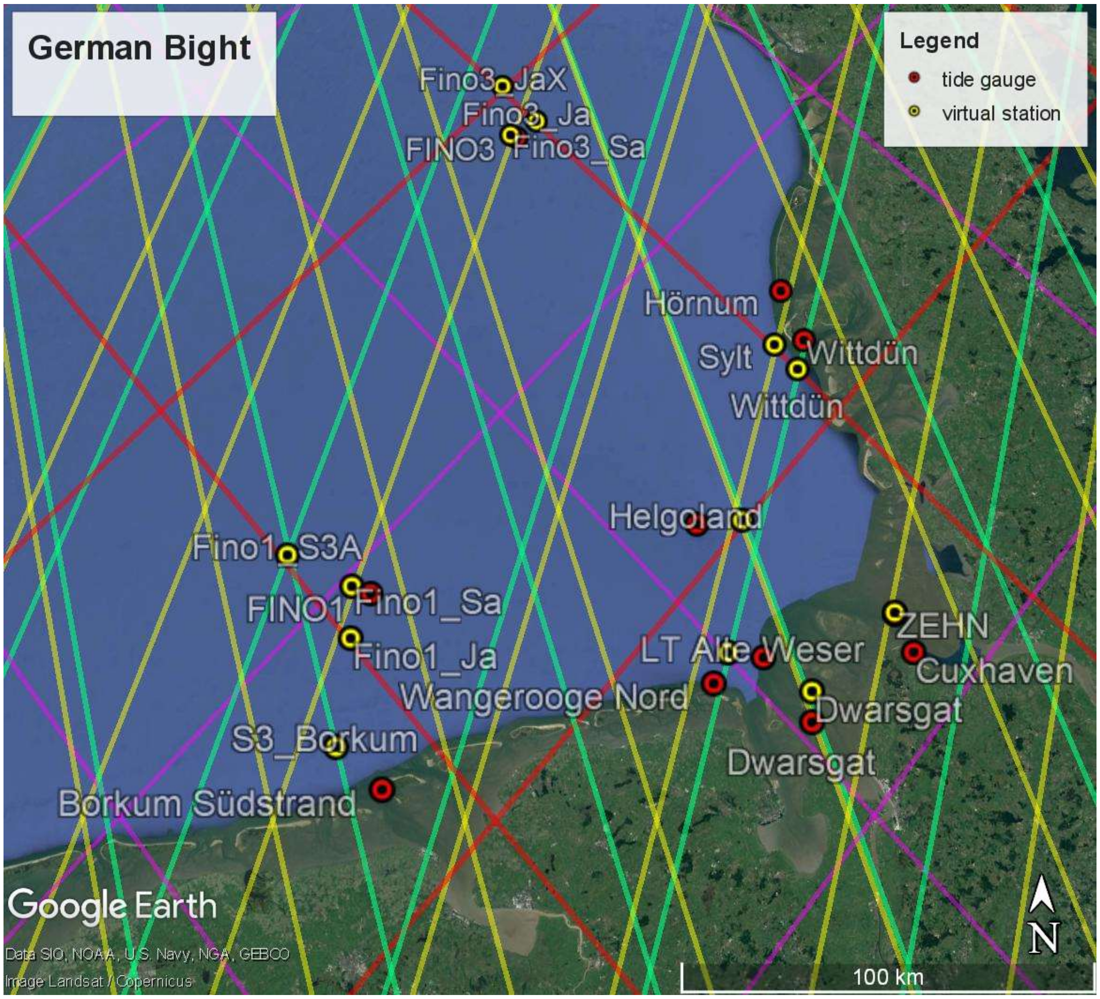


Figure 1. Positions of virtual altimetry (yellow) and tide gauge (red) stations, and ground tracks during exact repeat periods for Jason in standard (red) and interleaved phases (purple), Envisat/Saral (yellow), Sentinel-3A (green).

2.1. Altimetry

Instantaneous sea surface heights are derived from six altimeter missions - Jason-1 (01/2002-02/2012), Jason-2 (07/2008-09/2019), Jason-3 (since 02/2016), Envisat (06/2002-08/2011), Saral (since 03/2013) and Sentinel-3A (since 04/2016) - at eleven virtual stations which are located close to tide gauges. The altimeter data originate from the operational geophysical records (GDR) or rather non time critical (NTC) data files which are homogenized and processed within GFZ's Altimeter Data System (ADS) [27]. They are based on the standard OCEAN retracker (SAMOSA2 for Sentinel-3A) and the most recent revisions of the data. The applied correction models are chosen with regard to the homogenization of the missions and the situation close to the coast. An overview of the applied correction models is given in Table 2. Since the data shall be compared to the instantaneous tide gauge data it is transposed to the WGS84 ellipsoid in the ITRF2014 mean tide system; corrections for ocean tides, pole tides and dynamic atmosphere are not applied.

Table 2. Correction models applied for the instantaneous sea surface heights from different missions

Correction model	Envisat (GDR-V3)	Saral (GDR-F)	Sentinel-3A (SAR, marine baseline 004)	Jason-1/-2/-3 (GDR-E/D/D)
Orbit	GFZ VER11 [28]	CNES Rev_F	GMV	CNES Rev_E/F/F
Ionosphere	GIM CODE (GNSS) [29]			
Dry troposphere	ECMWF			
Wet troposphere	GPD+ [30]	ECMWF		GPD+
Earth tides	IERS Conventions [31]			
Loading tides	EOT11A Loading [32]			
Sea state bias	4-parameter model (GFZ)			

To account for more frequent invalid data close to the coast we use high frequency (20/40Hz) data inside a radius of 11 km around the virtual stations to perform an outlier detection/elimination and to estimate median and root mean square (RMS) values for each overflight. Finally, for each virtual station and mission the RMS of the median values is used to detect and eliminate outliers in the times series (3σ-critereon).

2.2. Tide gauges

We use high-frequency tide gauge data of the period 2002 to end of 2019 originating from eleven stations operated by the German Waterway and Shipping Administration (WSV). The positions are shown in Figure 1. Sea surface heights relative to the WGS84 ellipsoid (ITRF2014, conventional tide free) are provided every minute and are absolutely referenced by collocated permanent GNSS measurements originating from the BfG network [33]. The data has been quality edited (outlier removal and short term temporal smoothing) by the WSV. Three gauges are located in open water: Helgoland Binnenhafen and the research platforms FINO1 and FINO3. Seven are located at the coast: Borkum Südstrand, Wangerooge Nord, LT Alte Weser, Dwarsgat, Cuxhaven, Zehnerloch, Wittdün and Hörnum, several of them being located at the landward side of islands or in the Wadden Sea. For most gauges continuous measurements are available throughout the whole period. However, this is not the case for the FINO platforms. FINO1 data is available since 03/2013 and has degraded quality for the last two years, FINO3 data is available since 06/2015. In addition, we use FINO provided by Bundesamt für Seeschifffahrt und Hydrographie (BSH) which are not absolutely referenced and are patchy but span different time periods. These series are called Fino1 (since 03/2013) and Fino3 (03/2013-02/2014) in the following.

For comparison with the altimetry the tide gauge data is linearly interpolated to the time of the satellite overpass. Inter- and extrapolation is only performed if there is a measurement available within 2.5 min.

2.3. Models of the mean sea surface

To account for sea surface gradients between to the virtual and tide gauge stations a precise mean sea surface model is needed. Here we assess the performance of global up to date models: CLS2011, CLS2015 [34,35], DTU2018, DTU2021 [36,37] and additionally the frequently used European Gravimetric quasigeoid model EGG2008 [38].

3. Position corrections

A comprehensive overview about calibration and validation of altimetry is given by [39]. The technique and error sources of indirect calibration of altimeter data are discussed by [40,41]. In the German Bight the instantaneous sea level is dominated by semi-diurnal tides with tidal ranges between 1 and 4 m with substantial contributions from wind driven surges on synoptic time scales. Here, we present a method to account for systematic differences between the altimeter and tide gauge data which are related to the distance between both measurements' locations. Since we are using tide gauge stations that are not dedicated for CalVal, tide gauge and altimetry data is in fact collocated in time but not necessarily in space. This may give rise to systematic mean and time variable differences between the two data sets. Mean differences are related to the differences of the mean sea surface heights (MSSH) between the two measurement locations [42]. The MSSH is composed of the mean geoid and the ocean dynamic topography. However, the geoid is the dominating quantity and may differ by up to 10 cm on spatial scales of 10 km in the region. The sea level anomaly (SLA), i.e. the time variable component of the SSH, may as well differ between the measurement locations in a systematic way, e.g. due to coastal waves and transient currents. Since these mean and time variable differences are not related to the accuracy of the sensors they should be eliminated before the comparison of the two sea level data sets if feasible. The observed SSH differences ΔSSH_{obs} (SSH_{Gauge}-SSH_{Alti}) between the two locations can be described as follows:

$$\Delta SSH_{obs} = Bias_{regional}+\Delta MSSH+\Delta SLA+\varepsilon \quad (1)$$

with the mean position correction $\Delta MSSH$ ($MSSH_{Gauge}$-$MSSH_{Alti}$), the time variable position correction ΔSLA (SLA_{Gauge}-SLA_{Alti}) and the combined measurement error ε of both sensors. The regional bias includes the global component due to the altimeter measurement itself but also a regional component which is mainly related to the orbit model (geographically correlated error) but also to other applied correction models. Accordingly, we define the absolute accuracy of the altimeter measurements via the consistency of the regional bias estimates at various stations in the region after correcting for the terms $\Delta MSSH$ and ΔSLA. On the contrary, the combined precision of the measurements ε is independent of the temporal mean differences. It can be assessed based on the observed time variable SLA difference between the two sensors corrected for the systematic time variable position correction (ΔSLA).

$$\Delta SLA_{obs} = \Delta SLA+\varepsilon \quad (2)$$

3.1. Mean position correction (ΔMSSH)

The mean position correction can be estimated from high-resolution geoid, quasi-geoid or MSSH models. To assess the accuracy the correction and to select the model which fits best in the region we have derived mean position corrections for ten station pairs from five up to date models: the quasi geoid model EGG2008, and the MSSH models CLS2011, CLS2015, DTU2018 and DTU2021. Data from the tide gauges Dwarsgat, Cuxhaven and Zehnerloch were not included in the analysis since there were only few collocated altimeter measurements from a limited number of missions. At the FINO platforms only the absolute reference sensors (FINO) are used. The RMS of the mean position corrections for every station pair estimated from these models is shown in Figure 2. The RMS value is between 1-5 cm, with higher values near complex coastal structures and for larger distances between both stations (e.g. near the island Sylt).

To find the model most suitable in the region we have calculated for each mission the mean regional bias based on all station pairs. The number of accurate collocated stations depends on the mission and varies between three and eight pairs (cf. Table 4). The standard deviation of these mission biases is shown in Figure 3. The closest agreement for all missions is found for the CLS2011 model. The most recent models CLS2018 and DTU2021 show far less consistent results (not shown). Therefore, we calculate the mean position correction based on the CLS2011 model.

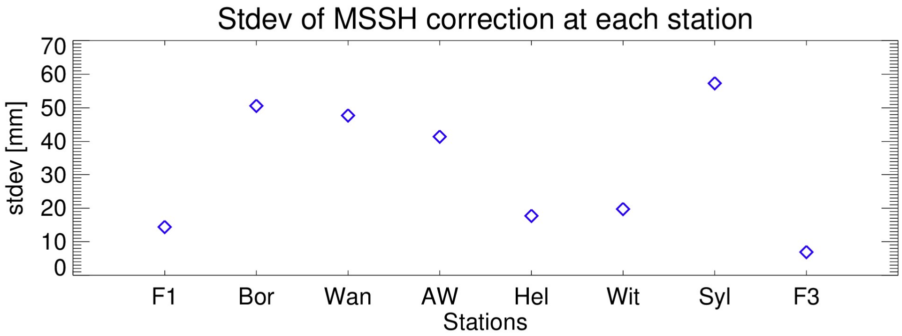


Figure 2. RMS of mean position corrections derived from one quasigeoid and four MSSH models for the virtual/tide gauge station pairs at FINO1 (F1), Borkum Südhafen (Bor), Wangerooge Nord (Wan), LT Alte Weser (AW), Helgoland (Hel), Wittdün (Wit), Sylt (Syl) and FINO3 (F3).

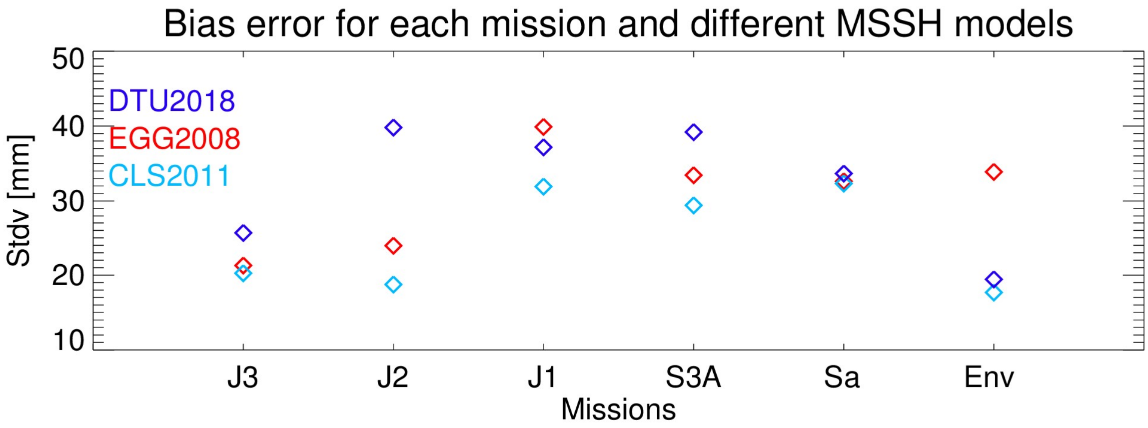


Figure 3. Standard deviation of (regional) mission biases for all station pairs with Jason-3 (J3), Jason-2 (J2), Jason-1 (J1), Sentinel-3A (S3A), Saral (Sa) and Envisat (Env) for three different models of the SSH (color coded). The number of collocated station pairs depends on the mission (3-8, cf. Table 4).

3.2. Time variable position correction (ΔSLA)

Systematic time variable SLA differences between virtual and tide gauge stations could be corrected based on a combined tide and surge model. Since we do not have model data with the sufficient spatial and temporal resolution available we have chosen to develop an empirical correction. The time variable SLA differences in the German Bight on scales of up to 15 km are mainly related to phase and amplitude differences of the dominant M_2 tidal wave. Figure 4 is a sketch highlighting the systematic changes in the difference between tide gauge and altimeter in case of a 5min shift and an amplitude difference of 5% for an M_2 tidal wave with 1 m amplitude. The small differences in our example give rise to extra RMS differences of 4 cm which are not related to measurement precision. They fluctuate in correspondence with the M_2 wave which cannot be adequately sampled by the altimeter giving rise to aliasing. There is a clear dependence of the differences from the absolute sea level. Here we describe and apply an empirical method to estimate time shifts for the tide gauge and scaling factors for the SLA series for every station pair making use of this relation.

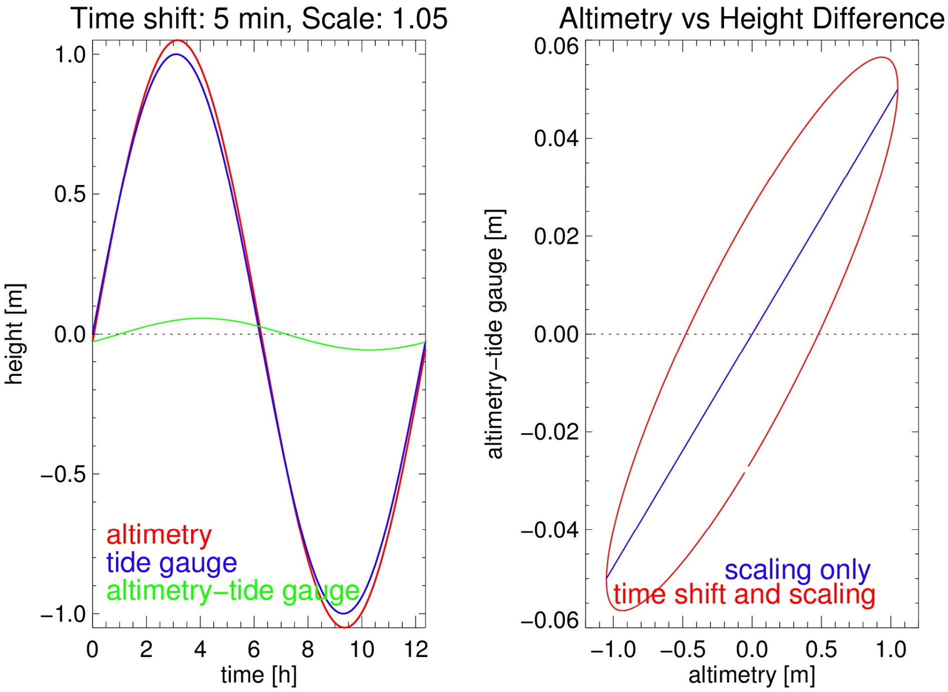


Figure 4. Sketch showing (**a**) two sea level series offset by 5 min for an M2 wave with 1 m / 1.05 m amplitude, (**b**) difference between the two series in dependence on the sea level for amplitude scaling (blue) and amplitude scaling plus time shift (red) .

We shift the gauge series every minute relative to the altimeter series and calculate a regression to estimate a mean bias and scaling factor for each station and altimeter mission separately. The criterion for the optimal time shift and scaling is the minimum value of the RMS differences. Choosing maximum correlation coefficients as criterion instead leads to almost the same results. This method reduces efficiently the systematic differences between the two data sets (e.g. for station LT Alte Weser, Figure 5) and is probably valid for all barotropic waves propagating counter-clockwise along the coast.

Note that a minimum of 15-20 measurement pairs is necessary for a reliable estimation of the parameters. Applying the time variable position correction implies that low frequency differences are scaled as well and seasonal to interannual signals are biased by this method.

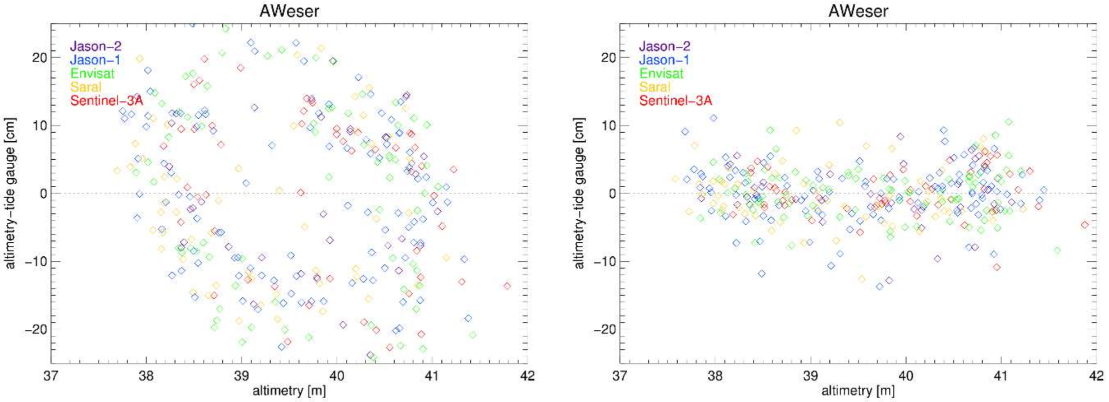


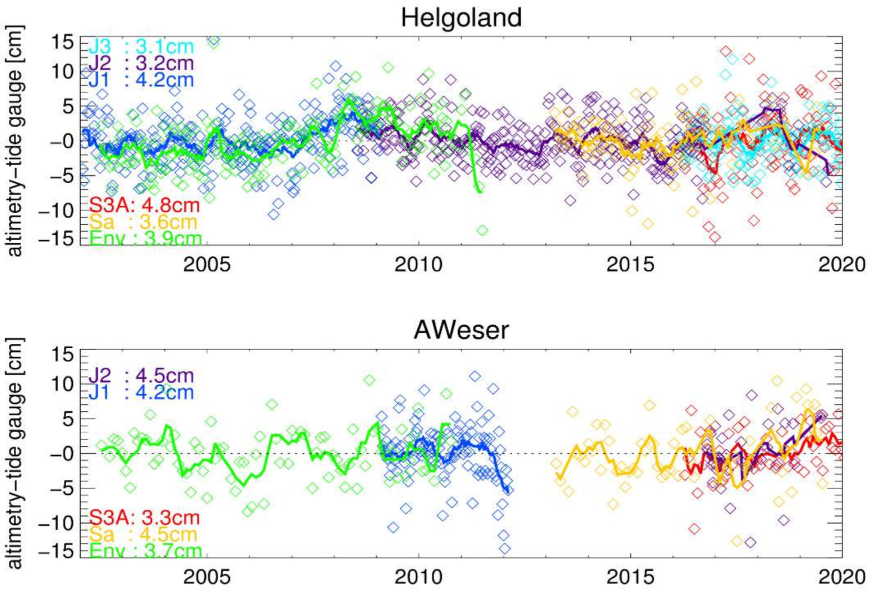
Figure 5. Difference between altimetry and tide gauge as function of absolute height for five missions at station LT Alte Weser (a) without and (b) with time variable position correction (Δt: 14-19 min., scale: 1.02-1.06).

4. Results

In this section the precision of the altimeter measurements and regional mission biases are assessed with respect to the tide gauge data.

4.1. Relative Precision

The analysis is based on the collocated tide gauge and altimetry sea level anomaly series for each station. We calculate the amount of variance of the tide gauge series explained by the altimetry series as well as the RMS of the difference series (RMS-D). The time variable position correction is applied, depending on the station pair it decreases the RMS-D by 15-75%. Figure 6 shows the remaining difference series for two stations in the open water (Helgoland) and close to the coast (LT Alte Weser). There is a high agreement between the two data sets, the RMS-D for Helgoland and LT Alte Weser is less than 5 cm for all missions.



Helgoland

AWeser

Figure 6. Difference between altimetry and tide gauge at stations (a) Helgoland (open water) and (b) LT Alte Weser (coastal) for up to six missions (color coded) with time variable position correction applied. Diamonds mark single measurements, thick lines 3 months box-car filter, RMS-D values are given at the left-hand side, and missions are color coded.

The explained variance and RMS-D counter clockwise along the coast for all missions is shown in Figure 7. The explained variance is more than 90% everywhere, at most stations it is even more than 98%. The RMS-D is less than 5 cm almost everywhere. The best agreement between tide gauge and altimetry is found at the open water stations Fino1, FINO3 and Helgoland. Even at Dwarsgat the RMS-D is still less than 10 cm for the recent missions after elimination of outliers (mainly low-water values). In areas with complex coastal structures (Sylt, Wittdün, Cuxhaven) and for older missions (Envisat, Jason-1) the agreement is diminished. Close to the station Wittdün the Jason-tracks pass very close to the island which recurrently leads to problematic Jason-1 and Jason-2 and missiing Jason-3 measurements. This is especially the case during winters and presumably related to high sea states. Better agreement can be achived when either using the ICE retracker or data from the more remote altimetry station SYLT (not shown).

To estimate the precision for each mission we pick the stations with the lowest RMS-D assuming that the precision is constant over the area more than 8 km away from the coast. The corresponding numbers for the best fitting stations for each mission are listed in Table 3. Best fitting stations are often stations, where the tide gauge and virtual station are very close to each other. The minimal RMS-D is between 2.7 and 4.2 cm with lower values for more recent missions. Since the RMS-D is composed of measurement errors of tide gauge, altimetry and uncorrected position errors, we can estimate upper bounds for the altimetry precision. Assuming that the precision of the tide gauge measurement is 2.0 cm (1.5 cm) results for Jason-1 in a minimum precision of 3.7 (3.9) cm and for Jason-3 of 1.8 (2.2) cm.

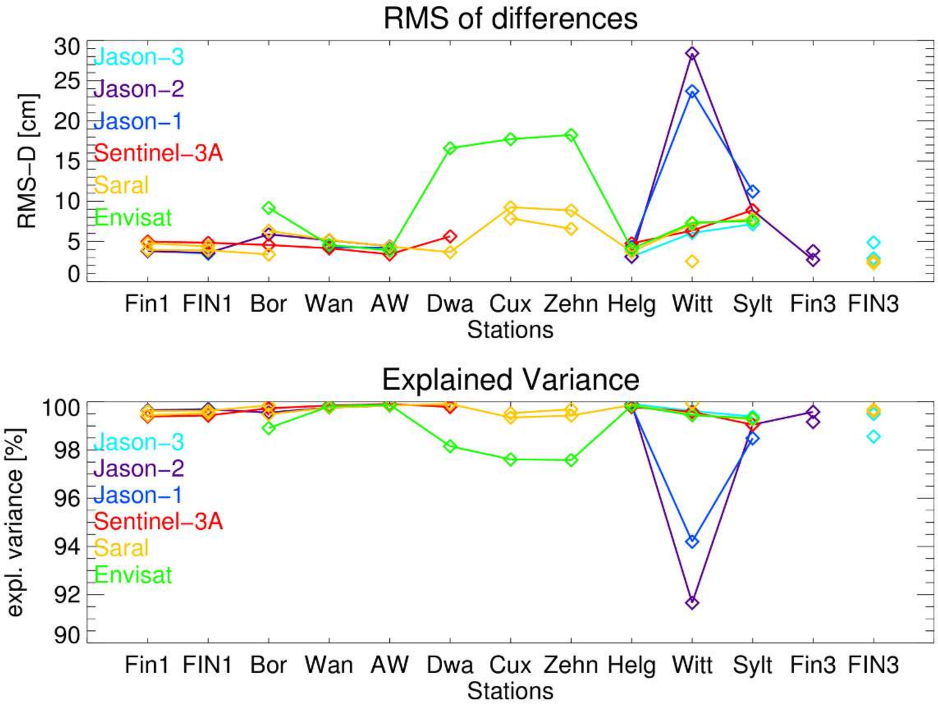


Figure 7. (**a**) RMS-D [cm] and (**b**) explained variance [%] counter clockwise along the coast for FINO1 (Fin1, FIN1), Borkum Südstrand (Bor), Wangerooge Nord (Wan), LT Alte Weser (AW), Dwarsgat (Dwa), Cuxhaven (Cux), Zehnerloch (Zehn), Helgoland (Helg), Wittdün (Witt), Sylt (Sylt) and FINO3 (Fin3, FIN3). Missions are color coded.

Table 3. RMS-D, explained variance, number of values and distance between gauge and virtual station for each mission for the best fitting station pair. The altimeter precision is estimated assuming that tide gauges have a precision of 2 cm (1.5 cm).

Mission	Station	RMS-D [cm]	Explained variance [%]	Distance [km]	count	Precision [cm]
Jason-3	FINO3	2.7	99	2	138	1.8 (2.2)
Jason-2	Helgoland	3.1	100	13	301	2.4 (2.7)
Jason-1	Helgoland	4.2	100	13	245	3.7 (3.9)
Sentinel-3A	LT Alte Weser	3.3	100	9	52	2.6 (2.9)
Saral	Fino1	3.1	100	2	49	2.4 (2.7)
Envisat	LT Alte Weser	3.7	100	9	81	3.1 (3.4)

4.2. Regional mission biases

Every altimeter mission is subject to global mean bias which is related to internal sensor delays. In addition, there are regional biases that are dominated by geographically correlated orbit errors with possible contributions from regional biases of correction models. Here, the regional mission biases are estimated relative to the absolute referenced tide gauge stations. The accuracy of the regional mission biases corresponds to the variance of the biases estimated at different stations. We omit three station pairs with minor agreement of the time variable component (Zehnerloch/Cuxhaven, Dwarsgat) from the analysis. Depending on the mission there are still three to eight collocated tide gauges available. Figure 8 shows the resulting regional mission biases derived with and without position corrections. Both position corrections influence the bias values and diminish the uncertainty considerably from 10-20 cm to finally 1.3-3.4 cm. The regional biases and the corresponding error margins are given in Table 4.

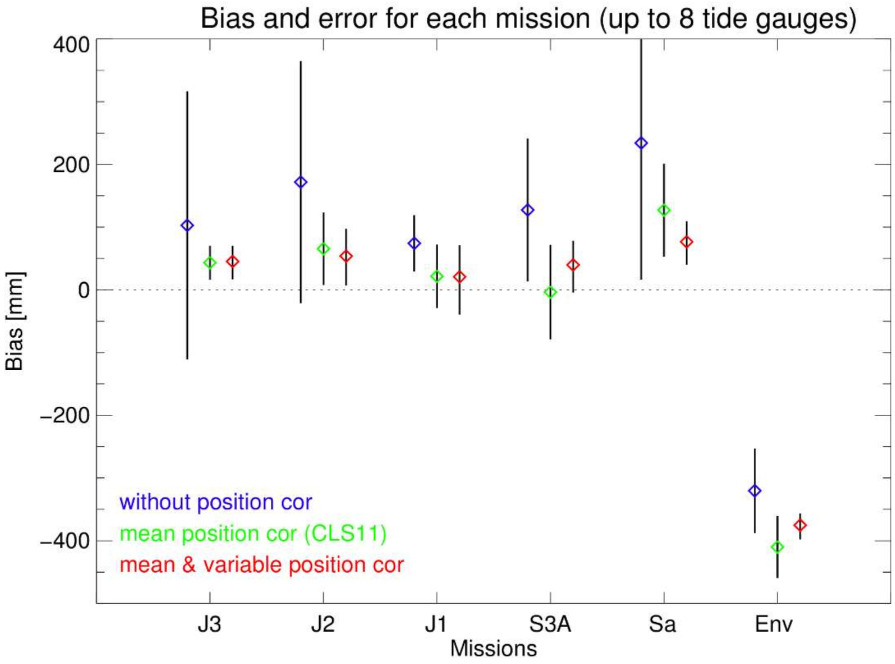


Figure 8. Regional mission biases and error margins for all missions derived from all collocated station pairs, without (blue), with mean (green), with mean and time variable (red) position correction for Jason-3 (J3), Jason-2 (J2), Jason-1 (J1), Sentinel-3A (S3A), Saral (Sa) and Envisat (Env).

Table 4. Absolute regional mission biases for each mission and number of contributing gauges for Jason-3 (J3), Jason-2 (J2), Jason-1 (J1), Sentinel-3A (S3A), Saral (Sa) and Envisat (Env).

	J3	**J2**	**J1**	**Env**	**Sa**	**S3A**
Bias [mm]	43±13	44±20	12±34	-391±16	73±31	36±28
No. gauges	5	5	3	5	8	7

5. Discussion

We have estimated absolute regional biases and altimetric measurement precision in the German Bight for six altimeter missions based on collocated tide gauge stations. The precision of the altimeter measurements was estimated from the RMS-D relative to eleven tide gauge stations. In addition to sensor errors the RMS-D depends on the distance between two sensor locations and on the scales of the local sea level dynamics. The RMS-D can be considerably diminished (up to 75%) by applying the time variable position correction. The RMS-D values range between 2.7 to 4.2 cm at the best fitting stations; the

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values are given for each mission separately in Table 3. These values are comparable with the results at Corsica [15] where RMS-D values between 3.0 and 3.3 cm are observed. The results for Sentinel-3A at Helgoland are considerable improved relative to the study by [23] (4.8 cm vs. 6.5 cm) and much better than the mean values for the northwestern European shelfs from [21]. From our analyses we estimate the altimeters' precision to be at least 1.8 to 3.7 cm depending on the mission. The precision should further improve when using updated coastally adjusted retrackers like SAMOSA+ and ALES+ [24–26].

Regional mission biases were derived relative to eight GNSS-referenced tide gauge stations with good agreement between altimetry and gauge data (Table 4). The biases range between -39 cm and 4.4 cm. The absolute numbers differ by several cm from the values derived at dedicated CalVal stations. However, apart from orbit related geographically correlated errors the biases are to some extend dependent on the chosen retracker and correction models (especially sea state bias). The bias estimated at Helgoland for Sentinel-3A by [23] agrees within a few mm with our estimation. Having applied the mean and time variable position corrections the accuracy of the regional mission biases is between 1.3 and 3.4 cm. This is in the same order of magnitude as the less than 2 cm reported by [43] but considerably more than the 0.5 cm reached at Corsica [15]. The analysis shows that the accuracy is very sensitive to the MSSH model used for the mean position corrections. Best results are obtained with the CLS2011 model, followed closely by the DTU2018 model. The most recent models CLS2015 and DTU2021 are far less suited for this application. Hence, the accuracy of the biases could be further increased by either eliminating problematic stations more stringent from the analysis and by enhanced MSSH models.

The presented empirical time variable position correction is a powerful tool to adjust for differences in ocean dynamic between altimeter and tide gauge measurements. It facilitates the estimation of biases and measurement precision in regions where the tides are not adequately known on small spatial scales. The method could be easily applied in similar coastal regions where sea level is dominated by tides. Hence, the study has shown that altimetry in the German Bight is sufficiently accurate to deliver valuable information for regional applications of local authorities. The operational tide gauges operated by WSV could complement the results obtained at dedicated CalVal stations.

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Data Availability Statement:
Tide gauge data is available upon request via BfG (Datenstelle-M1@bafg.de) and after registration from BSH http://fino.bsh.de/; GNSS data is available upon request from BfG (gnss@bafg.de); satellite altimeter data is available after registration from: https://aviso-data-center.cnes.fr/ and https://navigator.eumetsat.int/ and upon request from ESA (eohelp@esa.int).

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Conflicts of Interest: The authors declare no conflict of interest

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