ON THE MEAN SEA SURFACE DATA IN THE GDR FILES OF THE TOPEX/POSEIDON, JASON-1, 2, AND 3 MISSIONS

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ABSTRACT:

Altimetry satellites of the TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 missions have provided the ocean study community with an unprecedented long-term time series of sea level observations from space. In this paper, we aim to investigate the mean sea surface (MSS) data given by the GDR files of the mentioned missions starting from the 1992 TOPEX/Poseidon mission to the latest GDR files of Jason-3. Due to climate change, it is expected that there be changes in the MSS value and furthermore, its trend is detectable in the time series of thirty years of mentioned altimetry observations. More specifically, we would like to know within long-term altimetry observations how the effect of sea level change is handled in the GDR files of TOPEX/Poseidon, Jason-1, 2, and 3 missions, and whether there are cares to be considered when using the MSS data given in the GDR files of these missions? Answer to this question and other related issues are discussed in the paper. Our benchmark for verifications of MSS data in the GDR files is the time series of the sea level heights (SSH) at 30 passes of the mentioned missions over the Baltic Sea.

1. INTRODUCTION

An altimetry satellite with its on board radar device measures the distance between the satellite and the ocean surface and the water bodies. The sea surface at its instantaneous state, reflects the transmitted signal and the altimetry system measures the round-trip time of the pulse. The distance of the satellite to the instantaneous sea surface is then derived by knowing the speed of light and the half-time of the round-trip of the signal. The instantaneous height above sea level is called the "range" of the satellite. Since the position of the satellite in its orbit is determined with high accuracy, the height of the satellite with respect to the reference ellipse (WGS84) is accurately known. As a result, the instantaneous height of the sea surface at each observation point relative to the reference ellipse is calculated from the following formula (Fu, 2001):

$$\text{Sea Surface Height} = \text{Altitude} - \text{Range} \tag{1}$$

Naturally, the measured range of the satellite is contaminated with different systematic errors that must be removed to calculate the correct distance. These systematic errors are mainly due to ionosphere, wet troposphere, dry troposphere, refraction and delay, inverse barometric pressure, sea level bias (electromagnetic bias), solid earth tide, ocean tide, pole tide, and centre of mass changes of the satellite. The correction values for all these effects are available in the GDR files of the missions for every observation point. Having the corrections, the corrected range can be calculated as follows (Dumont et al., 2017):

Corrected Range = Range + Ionospheric Correction + Wet Tropospheric Correction + Pole Tide + Dry Tropospheric Correction + Centre of Gravity Movement Correction + Inverse Barometer Correction + Electromagnetic Bias + Solid Earth Tide + Ocean Tide (2)

Consequently, the corrected sea level heights is derived from:

$$\text{Sea Surface Height} = \text{Altitude} - \text{Corrected Range} \tag{3}$$

The point that should be mentioned is that if the goal is to analyse the sea level variations, "ocean tide correction" should not be applied.

In this study, we focus on the TOPEX/Poseidon, Jason-1, 2, and 3 missions over the period of 1992-2020. The time period of two consecutive visits of these satellite missions over a point on the sea surface, called "cycle", is 9.9156 days. Therefore, using these observations, point-wise time series of the sea level state at every 9.9156 days along the satellite passes can be developed.

The information related to every individual sea surface height observation is given in the GDR files. Such information can be used to derive the corrected sea surface height (SSH) at every observation point. There is also information such as the mean sea surface (MSS) and ocean tide data, which are derived from their corresponding models. The latter information can also be derived from the analysis of the SSH time series along the satellite passes. Our focus in this paper is on the MSS data included in the GDR files and their verification based on the time series of the data at points over the Baltic Sea. Table 1 shows the version of the GDR files of the TOPEX/Poseidon, Jason-1, 2, and 3 missions.

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Mission	GDR file version
TOPEX/POSEIDON	MGDR_C
Jason-1	GDR-E
Jason-2	GDR-D
Jason-3	GDR-T,D

Table 1. GDR file version names of TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3.

2. MEAN SEA SURFACE

As the name suggests, the MSS is the time-averaged height of ocean's surface. However, that would be true only when the mean part and the variable parts are separated properly, which requires infinite sea surface sampling in both time and space domains. Therefore, the main challenge of MSS determination is how to achieve the most accurate separation between the temporal and the mean parts by using the sea level observations with limited time-span and spatial-resolution (Andersen and Knudsen, 2009).
The MSS is an important reference in geodesy, geophysics, and oceanography. The MSS is the reference surface for chart datum determination and the studies related to sea level variations (Jin et al., 2016, Ophaug et al., 2021). Moreover, MSS together with the geoid model (G) can result the mean dynamic topography (MDT) as follows.

$$MDT=MSS - G \tag{4}$$

The MDT is mainly due to the ocean surface currents and large-scale ocean circulations and as such, any improvement in the geoid and MSS estimation directly affects the insight into the mean ocean circulations (Wunsch, 1993; Wunsch and Gaposchkin, 1980; Andersen and Knudsen, 2009).
Various study groups at universities and research institutions around the world, using satellite altimetry data, have developed MSS models. The MSS model that is presented in the GDR files of early satellite altimetry missions including TOPEX/Poseidon is the OSUMSS92 model, which is developed by using Geos-3, Seasat, and Geosat ERM satellites on a 0.125°×0.125° grid (Basic and Rapp, 1992). This model is subsequently replaced by the OSUMSS95 model which is an improved version of OSUMSS92, derived by performing more elaborate computations and corrections including removing the inverse barometric (IB) effect and using the gridded geoid models computed by merged JGM-3/OSU91A geopotential model. Details on development and evaluations of the OSUMSS95 model can be found in Yi (1995). This model became the benchmark for subsequent GDR files during the TOPEX/Poseidon mission. By the advent of the follow-up missions of Jason-1, 2, and 3, the MSS data in the GDR files is substituted by the MSS_CNES_CLS11 model, shown in colour contour map in Fig. 1. The OSUMSS95 and MSS_CNES_CLS11 models are briefly introduced in Tables 2 and 3, respectively.

Name of model	OSUMSS95
Reference ellipsoid	T/P or WGS84
Data period	Based on 1993–1993 (1 year)
Geographic coverage	Global from 80°S and 82°N
Geographic resolution	This surface is a regular grid with a (1/16°×1/16°, 5 minutes)
Altimetry data	TOPEX/POSEIDON: 1 year ERS-1: 1 year, (35-day repeat cycle) ERS-1: first cycle (168-day repeat cycle) Geosat: 1 year

Table 2. Summary of main parameters of the OSUMSS95 model.

Name of model	MSS_CNES_CLS11
Reference ellipsoid	T/P or WGS84
Data period	Based on 1993-2009 (16 years)
Geographic coverage	Global from 80°S and 84°N
Geographic resolution	This surface is a regular grid with a (1/30°×1/30°, 2 minutes)
Altimetry data	Mean profiles of Topex/poseidon, ERS-2, GFO, Jason-1, Envisat and ERS-1 geodetic phase.

Table 3. Summary of main parameters of the MSS_CNES_CLS11 model (https://www.aviso.altimetery.fr).

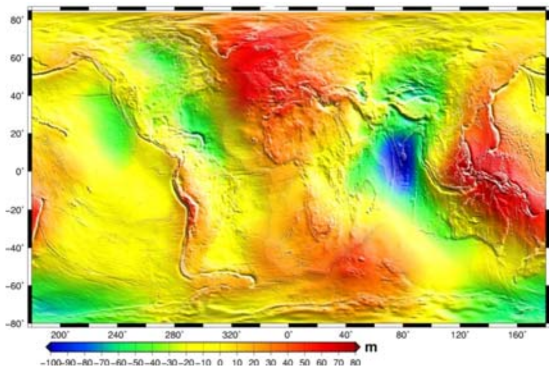


Figure 1. MSS_CNES_CLS11 global MSS model (https://www.aviso.altimetery.fr).

3. INPUT DATA AND STUDY AREA

Each footprint cycle of satellite altimetry is made up of two "passes" and their repetition over the seas generates the grid of passes and crossovers. Figure 2 shows the 30 passes of the TOPEX/Poseidon, Jason-1, 2, and 3 satellite missions over the Baltic Sea that is used to verify the MSS models of GDR files in this study.
Using the repeated observations of the mentioned satellites at every 9.9156 days, time series of SSH observations can be

produced once we introduce the radius of a search circle and the associated SSH observations within each circle to its central point (Fig. 2). Here we selected the radius of 3km to generate point-wise time series at every 6km along the satellite's ground tracks.

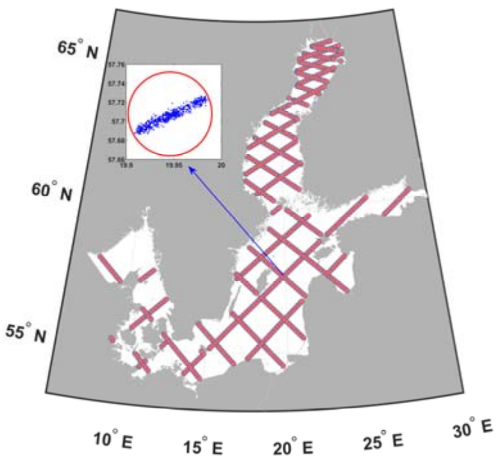


Figure 2. Search circles with the radius of 3km and the SSH observations within each circle that is associated to the central point of the circle to generate the point-wise time series of SSH at every 6km along the satellite's ground tracks over the Baltic Sea.

Furthermore, the outliers within the time series are detected and removed by using Baarda's method (Baarda, 1968) in 95% confidence level.

4. NUMERICAL EVALUATIONS

4.1 Study of MSS data in the GDR files of TOPEX/Poseidon, Jason-1, 2, and 3

In this section, we present the result of our study over the MSS data in the GDR files of TOPEX/Poseidon, Jason-1, 2, and 3 missions. Table 4 shows the MSS models used in different GDR versions over the life time of the missions (Picot et al., 2016; Dumont et al., 2017; Dumont et al., 2018; Blanc, 1996).

Missions	GDR file version	MSS model
TOPEX/POSEIDON	MGDR-C	OSUMSS95
Jason-1	GDR-E	MSS_CNES_CLS11
Jason-2	GDR-D	MSS_CNES_CLS11
Jason-3	GDR-T, D	MSS_CNES_CLS11

Table 4. MSS models used in different GDR file versions of TOPEX/Poseidon, Jason-1, 2, and 3 missions.

According to Table 4, different MSS models have been used by different missions. The aim of this work is to compare these MSS models and detect the possible inconsistencies. Sample plots of the MSS values given in the GDR file for the time spans covering the four missions at four sample point time series generated over the Baltic Sea are shown in Fig. 3. In columns 2 of Fig. 3, we sea jumps in the MSS values given in the GDR files. From Fig. 3 we can identify 3 levels for the MSS values related to (1) TOPEX/Poseidon, (2) Jason-1, and (3) Jason-2, 3. It is worth noticing that although the Jason-1 Jason-2, and Jason-3 missions use the same MSS model, namely, MSS_CNES_CLS11 (see Table 4), we still observe a jump between the MSS values of these missions. The other issue is that once we define a search circle with a certain radius and dedicate the SSH observations within that circle to its centre, in order to generate a time series of the altimetry observations along the satellite passes, since the real coordinate of those points within a circle are slightly different in the range of the radius of the search, it is expected that their MSS values show some small ripples which are also visible in Fig. 3, columns 2.

To quantify and remove the jumps, the mean and standard deviations of MSS values within each of the three levels of MSS values in GDR files are calculated as follows:

$$\Delta = M_{J1} - M_{T/P} \tag{5}$$

$$\sigma_{\Delta}^{2} = \sigma_{M_{J1}}^{2} + \sigma_{M_{T/P}}^{2} \tag{6}$$

where $M_{T/P}$ and M_{J1} corresponds to the mean of MSS values during the period of TOPEX/Poseidon and Jason-1 GDR data, respectively. The same computations are also done for the jumps between the MSS values of the Jason-1 and Jason-2, and 3. Our investigation based on the MSS values available in the GDR files at the time series of the points over the Baltic Sea revealed the value of (9.12 ±0.106) cm for the jump of MSS data in the GDR files of TOPEX/Poseidon with respect to Jason-1. In addition, for the jump of MSS values in the GDR files of Jason1 and Jason-2, and 3, we obtained the values of jump and its standard deviation as (2.201 ±0.029) cm. Table 5 summarizes the results of the estimated MSS jump between these missions according to the GDR data of the time series that we generated in our test area over the Baltic Sea.

Pair of MSS data	Estimated jumps and its STD
T/P-J1	(9.122 ±0.106) cm
T/P-J23	(6.944 ±0.108) cm
J1-J23	(2.201±0.029) cm

Table 5. Jumps of MSS values given in the GDR files, computed based the time series of points over the Baltic Sea.

In column 1 of Fig. 3 we have offered the value of jumps shows of the MSS values in time series of four points over of Baltic Sea. Column 2 and 3 of this figure shows the MSS values at these four points as given by the GDR files, before and after removal of the offsets, column 2 and 3, respectively.

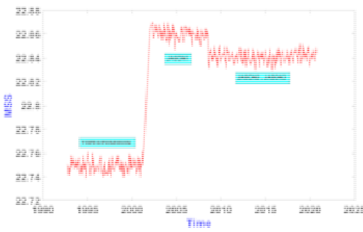
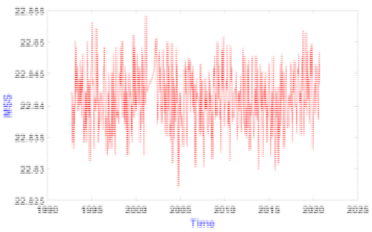
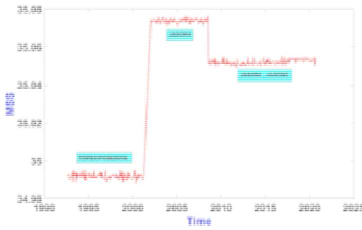
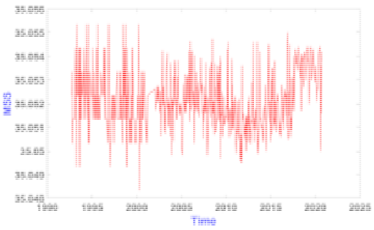
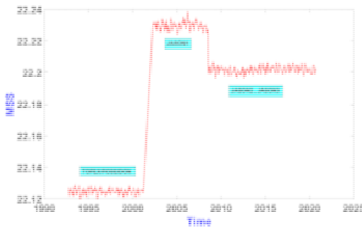
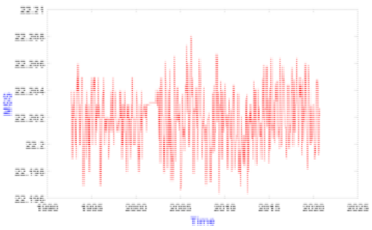
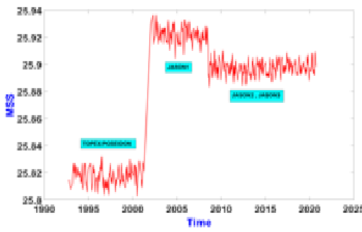
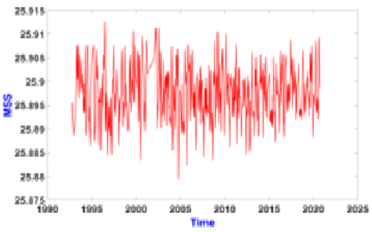
Estimated value of the jumps	Existing jumps	After removal of the jumps
T/P-J23: 7.46+-0.14cm J1-J23:1.95+-0.2		
T/P-J23: 8.82+-0.28cm J1-J23:2.17+-0.32 cm		
T/P-J23: 7.45+-0.47cm J1-J23:2.79+-0.38cm		
T/P-J23: 8.62+-0.34cm J1-J23:2.51+-0.28 cm		

Figure 3. Plot of MSS values given by GDR files (column 2), the value and STD of the jumps (column 1) and the plots after removal of jumps (column 3) at four sample points over the Baltic Sea.

4.2 Assessment of MSS data in the GDR files via the SSH observations

To get an insight over the quality of MSS and tidal models given in GDR files, we used the time series of SSH values generated at the points shown in Fig. 2, at our test area in Baltic Sea. All corrections introduced in Eq. (2), except the tide effect, are applied to SSH values and the time series of those values are generated and used to verify the accuracy of MSS and ocean tide data that are given in the GDR files. In GDR files for every data point we are given the ocean tides values based on two tidal solutions, namely "tide solution 1" and "tide solutions 2", which are introduced in Table 6.

The MSS values given in GDR files are added to the given ocean tide solutions and the resulted SSH values are compared with the observations ones. Figure 4 shows the values of MSS plus tide solutions 1 and 2, versus the corresponding observed values.

Tide Solution 1	Tide Solution 2

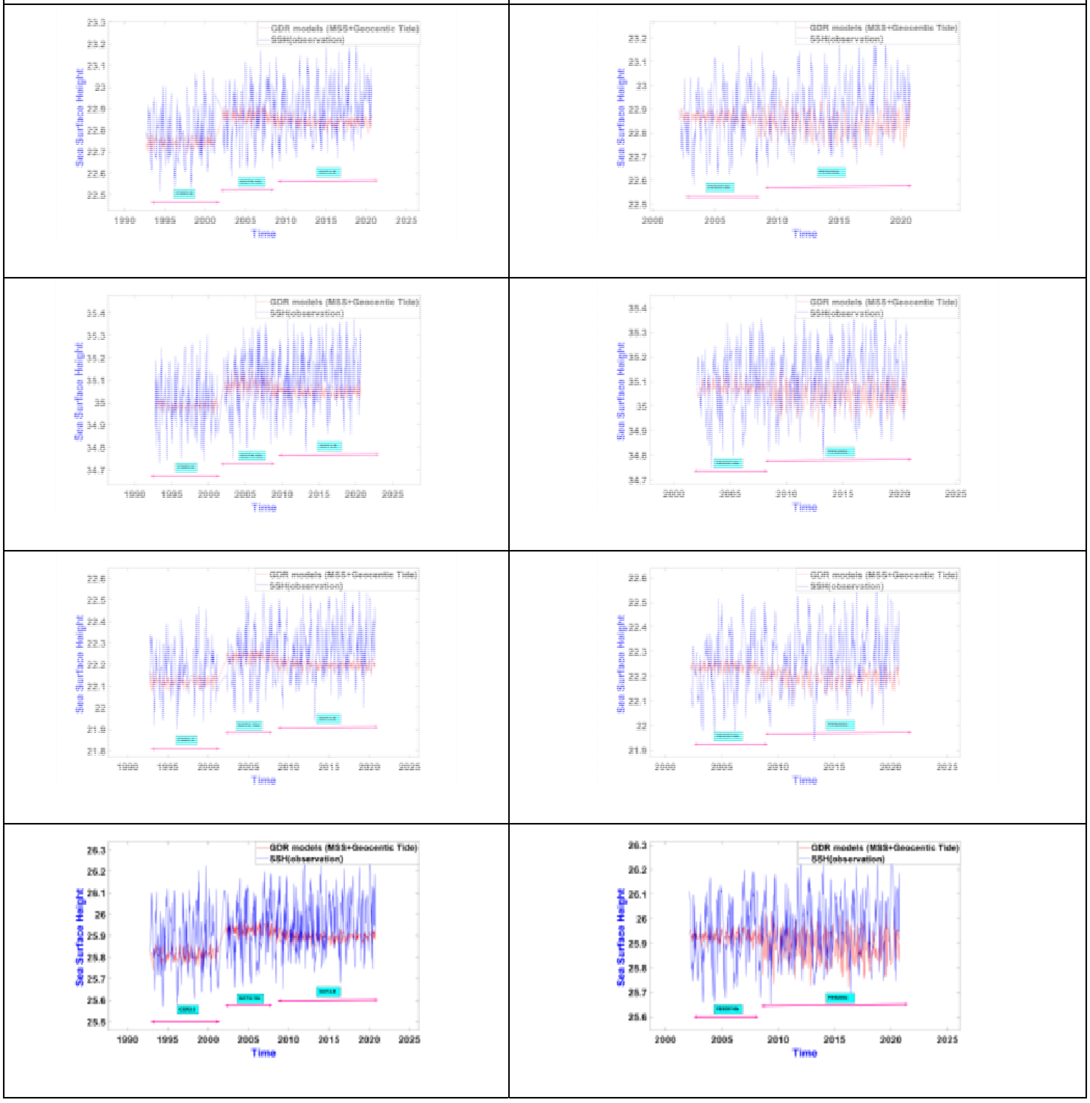


Figure 4. SSH values generated by the sum of ocean tide and MSS values given in GDR files (red plots) and observed ones (blue plots) at four sample points over the Baltic Sea, based on tide solution 1 (red plots of column 1) and tide solution 2 (red plots of column 2).

In Fig. 4, the red plots show the sum of MSS and ocean tide values at the four points whose MSS values are shown in Fig. 3, and the blue lines are the observed SSH values which are corrected according to Eq. (3). In this figure, the first and second columns are related to tidal solutions 1 and 2, respectively. It should be mentioned that the tide solution 2 is not given for the TOPEX/Poseidon mission in GDR files. As Fig. 4 indicates the jumps in the MSS values are still visible in the generated SSH values by the sum of MSS and tidal solutions given in GDR files. Besides, the SSH values generated by the content of GDR files are of quite poor quality as their comparison with observed SSH values show. It must be noted that our finding about the quality of the tidal solutions given in GDR files is based on our test area over the Baltic Sea and should not be regarded as an overall conclusion.

Missions	**GDR file version**	**Ocean tide model**	
		Tide Solution 1	**Tide Solution 2**
TOPEX/Posiedon	MGDR-C	CSR 3.0	FES 95.2
Jason-1	GDR-E	GOT 4.10c	FES 2014 + GOT 4.8ac load tides
Jason-2	GDR-D	GOT4.8 + S1 (ocean tide and load tide)	FES2004 + S1 and M4 (ocean tide and load tide)
Jason-3	GDR-T, D	GOT4.8 + S1 (ocean tide and load tide)	FES2004 + S1 and M4 (ocean tide and load tide)

Table 6. Ocean tide models used in different GDR file versions.

To quantify the difference between the SSH values derived from GDR files and those that are observed, we resort to mean absolute error (MAE), which can be computed as follows:

$$\mathrm{SSH}_{\mathrm{GDR}} = \mathrm{MSS}_{\mathrm{GDR}} + \mathrm{OceanTide}_{\mathrm{GDR}}$$
$$e = \left|\mathrm{SSH}_{\mathrm{GDR}} - \mathrm{SSH}_{\mathrm{Observation}}\right| \tag{7}$$
$$\mathrm{MAE} = \sum_{i=1}^{n} \frac{e_i}{n}$$

where $\mathrm{SSH}_{\mathrm{GDR}}$ is the SSH computed from the $\mathrm{MSS}_{\mathrm{GDR}}$ and $\mathrm{OceanTide}_{\mathrm{GDR}}$ data, which are given in the GDR files, and $\mathrm{SSH}_{\mathrm{observation}}$ are the corresponding observed values, and |.| is the absolute value operator. The MAE value for each mission is computed separately in order to quantify the accuracy of the missions separately. Furthermore, we computed the average of MAE value at all the test points over the Baltic Sea, which are shown in Table 7.

	Tide Solution 1+MSS	**Tide Solution 2+ MSS**
TOPEX/Poseidon	(13.05 ±0.67) cm	Not given
Jason1	(9.89 ± 0.35) cm	(9.77 ± 0.31) cm
Jason2-3	(11.11 ±0.41) cm	(8.60 ± 0.42) cm

Table 7. Average of MAE values at all test points over the Baltic Sea for the TOPEX/Poseidon, Jason 1, 2, 3 altimetry missions.

As Table 7 shows, the SSH values derived from Tide Solution 2 are a bit superior over Tide Solution 1, and the GDR data for Jason1 gives better results for SSH generation over the Baltic Sea as compared with the other three missions.

5. CONCLUSIONS

We showed that the MSS data in the GDR files in the long term time spans are subject to systematic jumps/offsets. The values of those jumps are found to be on average (9.122 ±0.106) cm between the MSS data of TOPEX/Poseidon and Jason 1, (6.944 ±0.108) cm between the MSS data of TOPEX/Poseidon and Jason-2, and 3, and (2.201 ±0.029) cm between the MSS data of Jason-1 and Jason-2, and 3. Although those estimated average values obtained from our time series over the Baltic Sea, can be regarded as overall estimates, however we suggest the computation of the MSS jumps in the GDR files for individual time series when more accurate estimations are concerned. Furthermore, we showed that tidal solutions given in GDR files are of very poor quality and that became obvious when the sum of MSS and tidal solution data are used to synthesis the observed SSH values.

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