THE MEAN SEA SURFACE DTU10MSS - COMPARISON WITH GPS AND TIDE GAUGES

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ABSTRACT

Satellite altimetry and the Global Position System (GPS) are conveniently given in the same reference frame and can therefore be used to construct a vertical reference surface for offshore navigation. Here a new Mean Sea Surface DTU10MSS is presented with a vertical accuracy better than 10 cm in most areas of the world confirmed by extensive comparison with GPS leveled tide gauges around Britain and Norway. It is proposed that this model is used as a global vertical reference.

This paper briefly outlines the update of the previous DTU model to DTU10MSS and presents comparisons on GPS positions measured at the ship relative to the sea surface model.

1. INTRODUCTION

The most important requirements for ship safety are the ability to determine clearances between the sea floor and the keel of the ship, and between the mainmast and overhead structures.

For many years ship positions have been referenced to local datums maintained by separate countries and transformations are often required to transfer the GPS positions into chart coordinates in these systems. Furthermore, these datums might be time-dependent and time-variant because of local updates.

Here it is proposed that an altimetric mean sea surface is used as vertical reference. In this way GPS position measured at the ship will be relative to the sea surface and determination of clearances will be very simple and independent of any local transformation. The only departure from the mean sea surface, that the navigator must account for are the local tides and oceanographic signal such as surges.

The situation is shown in Figure 1 adapted from Maul and Kumar (2005)

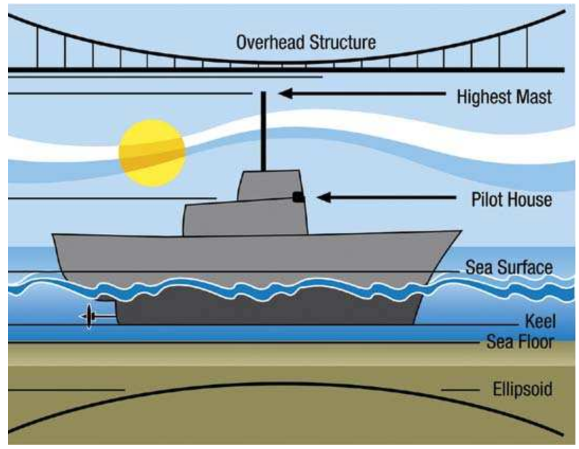

Figure 1. GPS observations used to navigate the ship gives the 3 coordinates of i.e. the Pilot House or where ever the GPS antenna is mounted. Using this information along with knowledge about the ship, the two clearances are easily determined when the sea surface height and the height of the overhead structure is given relative to the same reference frame. Figure adapted from Maul and Kumar (2005)

The local tides can globally be determined very accurately using tide models like GOT4.7 (Ray, 1998) or Andersen 06 (Andersen, 1995) global ocean tide model. All of these models are accurate to the decimeter level even in many shallow water regions (Andersen et al., 1995)

It must naturally be ensured that the mean sea surface is determined relative to the same ellipsoid used to determine the GPS position. Furthermore it must be ensured that the two surfaces are processed using the same tide system.

2. THE DTU10 MEAN SEA SURFACE

Previous studies by Andersen and Knudsen 2009 described in detail a global mean sea surface DNSC08MSS. This model was derived from the physically observed time-averaged height of the ocean's surface from a total of 8 different satellites and a total of 8 different satellite missions like i.e., the T/P, ERS, ENVISAT and ICESat.

The DTU10MSS is derived from seventeen years of repeated observations from TOPEX/Poseidon measured along widely spaced ground-tracks and merged with

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dense non-repeating data from the Geodetic Mission satellites from the GEOSAT and ERS-1 satellite missions to give mean sea surface resolving structures down to 20 km wavelength. Direct interpolation of the averaged sea surface height (SSH) observations or the along track SSH gradients using various sophisticated interpolation techniques is used to generate the MSS (Andersen and Knudsen, 1998; Hwang et al., 2000; Hernandez and Schaeffer, 2002). The DTU10MSS is shown relative to the WGS84 Ellipsoid in Figure 2

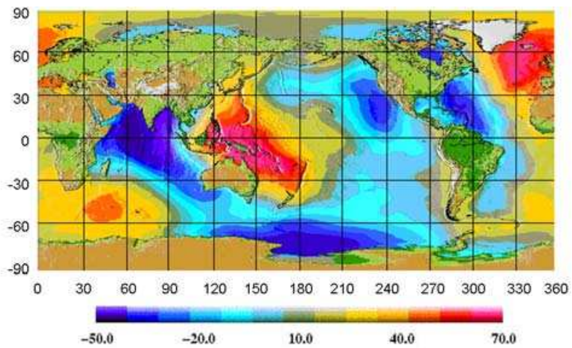

Figure 2. The height (in meters) of the DTU10MSS relative to the WGS84 ellipsoid.

The DTU10MSS/DNSC08MSS interpolation error which is a proxy for the vertical accuracy of the mean sea surface is shown in Figure 3. The spatial variations of the error estimate with zones of higher and lower error correlate with the sea state and the availability of satellite altimetry observations. The interpolation error is on average approximately 6 cm globally.

DTU10MSS has extended time-series (1993-2009), improved range corrections (using i.e., Dynamic Atmosphere correction MOG2D in stead of the traditional inverse barometer correction) and improved sea level determination at high latitudes using 14 month of ICESat lowest level filtered data.

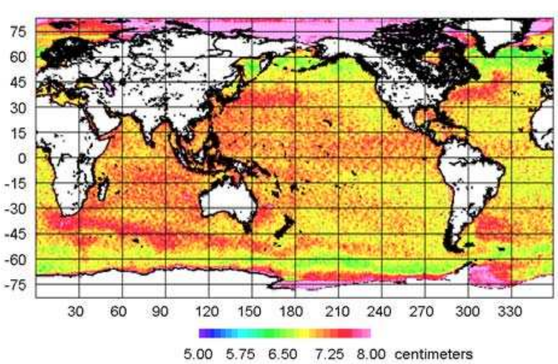

Figure 3. Global interpolation error fields for the DNSS08MSS. The color scale is given in centimeters.

For oceanographic purposes, a high resolution 1 minute global geodetic Mean Dynamic Topography called DTU10MDT has also been calculated from the smoothed difference between the DTU10MSS and the EGM2008 geoid.

3. DIFFERENCES BETWEEN BETWEEN DTU10MSS AND DNSC08MSS

Figure 3 shows the differences between the DNSC08MSS and the DTU10MSS indicating a mean value around 3 cm.

The two centimeters are due to the use of the improved MOG2D Dynamic Atmosphere correction compared to the old inverse barometer correction. The different mean pressures in the two models (1013 versus 1011 mbar) raises the MSS by roughly 2 cm.

The last cm is contributed to the fact that 6 years of additional data enters the DTU10MSS (2004-2009) shifting the center by 3 years. Sea level change is currently around 3 mm/year which raises the MSS by another 1 cm over 3 years.

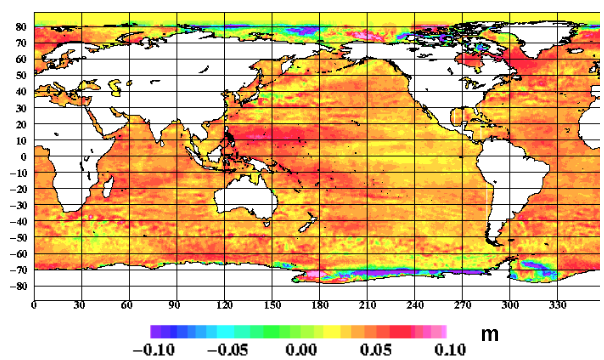

Figure 3.1 Differences between the DNSC08MSS and the DTU10MSS.

4. IMPROVING THE DTU10MSS IN THE ARCTIC

High latitude regions provide special problems for determining MSS and MDT models. This is because sea ice causes the radar return to be distorted.

Laser altimetry from ICESat data were used to augment radar altimetry in the partly ice-covered parts of the Arctic Ocean (between 70°N - 86°N, 100°E - 270°E) and at latitudes above 80°N in all of the Arctic Ocean in order to extend the MSS towards the North Pole.

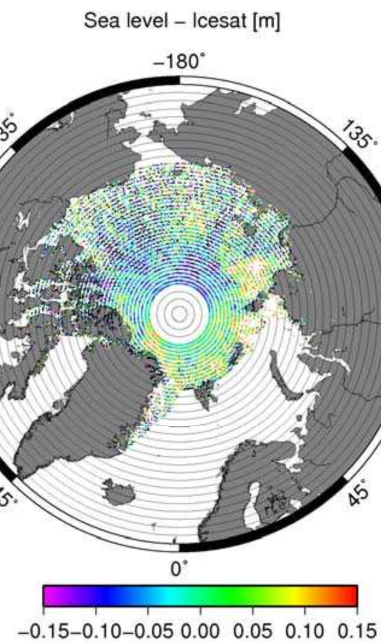

Figure 4.1) The mean difference between 14 months of ICESat laser observations and DTU10MSS. The color scale ranges +/- 15 cm

The ICESat data were only used in partly ice-covered regions due to the short averaging period as shown in Figure 4.1. In order to investigate any possible inter-satellite differences between ICESat and the radar altimetric derived MSS, the difference between 14 concatenated months of ICESat data and the previous DTU model DNSC08 is shown in Figure 4.2.

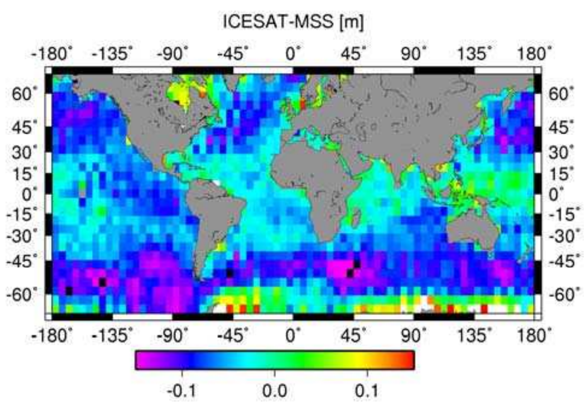

Figure 4.2) Difference between 14 concatenated months of ICESat data and DNSC08

The difference is remarkable small and consistent, despite the fact that only 14 months was used. However, the investigation indicates, that the different ICESat lasers give a global sea level trend of 2.0 cm/years. See Figure 4.3. This is the currently the subject of further investigation and the reason why the use of ICESat was limited to the icecovered regions in the Arctic and Arctica where no other data were available from primarily ENVISAT.

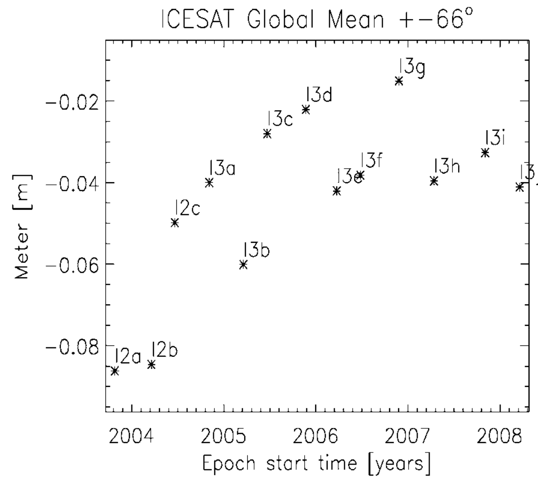

Figure 4.3 Global data and latitude weighted average of ICESat epoch data from GLAS 15. Result is consistent with similar findings by Gunter et al., 2009

5. GPS OBSERVATIONS OF SEA SURFACE HEIGHT.

An experiment was carried out on the Danish Galathea-3 Expedition during 2007. In this experiment it was investigated how accurate the sea surface height could be measured with GPS and the level of agreement with the DNSC08MSS could be made.

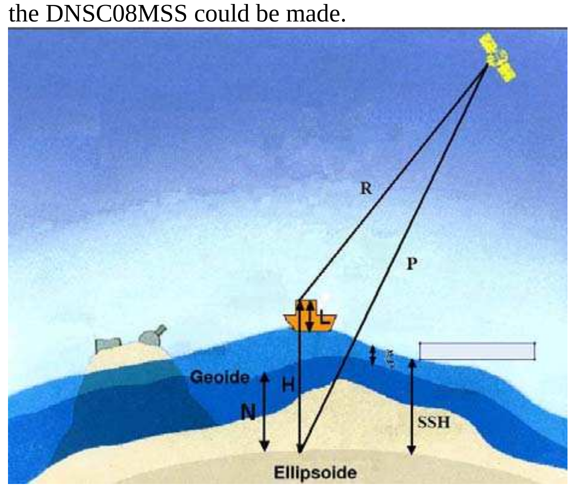

Figure 5 *Sea surface height from GPS on-board a ship compared with sea surface height from satellite. GPS measures the height* $H = N+L+\xi$ *relative to the ellipsoid.*

The observed GPS height h is related to the ocean dynamic topography and the geoid height through

$$H(t) = MSS + L(t) + \xi(t) + e \quad (1)$$

Where N *is* the geoid height above the reference ellipsoid, ξ is the timevariable ocean topography, L is the antenna height above the sea surface and e is the error. The setup is illustrated in Figure 5. The observation error e comprises direct observation errors by the GPS height observations along with contributions from errors in the geoid height, dynamic topography, GPS processing, and antenna height.

The GPS antenna height is in principle a proxy for the instantaneous sea surface height, if the distance between the GPS antenna and the sea surface is known precisely. However, the situation is considerable more complex as one should account for the ship's own movements and changing weight.

In the Galathea-3 experiment two GPS antennas were mounted on the roof of the Bridge of the ship in order to have a redundant system. The GPS antennas were mounted to the portside and starside of the ship and placed such that no objects on the ship shade for the antennas (see figure 6 where the GPS antennas are indicated with arrows).

Mounting the antennas on the roof of the Bridge is roughly 13 meters above sea-level and the distance between the antennas and the sea surface will depend on the speed and the weight of the ship along with the tilt and roll movements due to i.e. waves. In order to measure the distance between the GPS antennas and the sea surface and to transfer the GPS height to sea surface heights, a laser were mounted at the side of the Bridge of the ship. It was found that when averaged observations were used a constant of 13 meters could be used for the GPS antenna height above sea level and this number was used to transfer the GPS height of the roof to sea surface height observations.

Figure 6. The GPS antennas mounted onboard the roof of the ship during the GALATHEA-3 test between the Virgin islands and Boston crossing the Gulf Stream.

The continuous GPS observations collected on board Galathea-3 were post-processed using precise point position (PPP) technology based on precise orbit and clock products from IGS. The "TriP" PPP software system was used (Zhang, 2005). This software has successfully been used to determine height variations of the Amery ice shelf for tidal studies (Zhang and Andersen, 2006).

It is important that the GPS data is processed in the same tidal system as was used for the derivation of the geoid. For the current investigation we used EGM2008 (Pavlis et al., 2008) given in the zero tide system. The GPS data are processed in the tide free system, and the difference was corrected for in order to get the data into the zero tide system.

The time-variable part of the ocean topography $\xi(t)$ comprises the ocean tide signal and the time-variable signal related to wind, waves, temperature, salinity, and pressure. Globally, the tides dominate the time variable dynamic ocean topography and analysis from altimetry (Fu and Cazenave, 2001) shows that globally, more than 70% of the dynamic topography variations are due to ocean tides.

It was, consequently, decided only to account for the ocean tides in this first investigation. The ocean tide model GOT4.7 (Ray, personal communication) is a improved version of the GOT 99 and GOT00.2 ocean tide model (Ray, 1999), and is believed to be among the very best global ocean tide models presently available.

The results presented here were taken from a north going transect between St. Croix on the Virgin Island and Boston on the US east coast, was used for this preliminary investigation. Sailing northwards towards Boston only the last part of the route marked with black arrows from around 28ºN and northwards were used. Around 38ºN the mean dynamic topography dips by around one meter as the ship crosses the Gulf Stream going from the warm water in the center of the Atlantic Ocean to the cooler water toward the coast of North America.

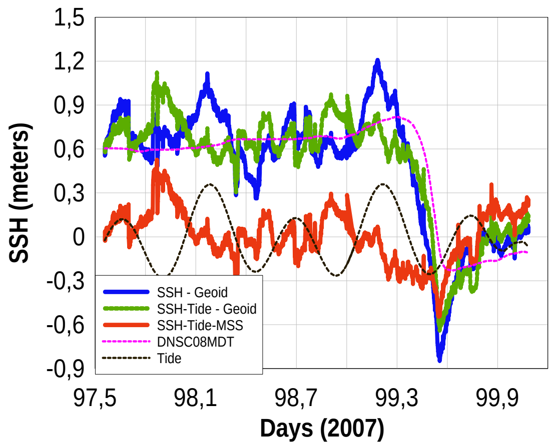

Figure 7 *The GPS observed sea surface height on-board Galathea-3 as the ship sails from 28º N towards Boston crossing the Gulf Stream between day 99.1 and 99.6.. GPS heights relative to the geoid without correction for ocean tides are shown in Blue and with ocean tide correction shown in Green. GPS heights relative to the MSS do not contain the Gulf Stream height effect and is shown in Red. The ocean tide effect is shown in Black.*

The results from the experiment is shown in Figure 7 and the comparisons are summarized in Table 1 as the ship sails from 28º N in the Atlantic ocean north of the Virgin Islands towards Boston crossing the Gulf Stream between. The Gulf Stream is roughly crossed at day 99 of 2007. GPS heights relative to the geoid without correction for ocean tides are shown in Blue and with ocean tide correction shown in Green.

Both of these curves relative to the Geoid show the dramatic drop as the Gulf Stream is passed. This is due to the fact that the ship goes from warmer to cooler water as it crosses the Gulf Stream. Thermal expansion in the upper 200 meters of water column creates a sea surface height signal (Mean Dynamic Topography) of roughly 2 meters

GPS heights relative to the MSS do not contain the Gulf Stream height effect and is shown in Red. The comparison between the instantaneous sea surface height and the mean sea surface height still contains a contribution from dynamic sea surface variations due to i.e., wind and pressure. The comparison is presented in Table 1. When the tidal signal is still present the comparison between 30 and 300 seconds averaged GPS sea surface height observations and the DNSC08MSS is roughly 42 cm. This drop to below 20 cm once to the tides have been removed and the best comparison is achieved for the 300 sec averaged sea surface height with a comparison of 17 cm. Similar comparison on other transects confirms a comparison of roughly 17 cm.

	Std Dev (30 sec av)	**Std Dev (300 sec av)**	**Mean**
SSH_{GPS} - $MSS_{SatAltim}$	**0.42**	**0.41**	**0.51**
SSH_{GPS}-Tide-$MSS_{SatAltim}$	**0.17**	**0.16**	**0.05**

Table 1. Comparison between the DNSC08MSS mean sea surface and instantaneous sea surface height observations onboard the Galathea 3 transect between the Virgin Island and Boston during one week of 2007.

6. CONCLUSION

The DTU10MSS Mean Sea surface (based on the previous DTU model DNSC08MSS) is presented and proposed to be used as a vertical reference in sea navigation.

A comparison of DNSC08MSS with 30/300 seconds averaged GPS sea surface height observations measured onboard the Danish Galathea-3 expedition in 2007 was presented. The comparison revealed a deviation of 17 cm between the two methods on a transect going from the Virgin Islands to Boston achieved without correcting for the effect of dynamic sea surface topography due to the wind and waves.

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