Mean Dynamic Topography for satellite altimetry: Two approaches, from oceanographic data or satellite gravimetry.

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Satellite altimetry measures the ocean surface height with an accuracy better than 5 cm (Fu et al., 1994). This height is relative to the Earth ellipsoid chosen to reference the satellite orbits. This height is the sum of the marine geoid *N* and the sea level variations due to ocean currents and thermodynamical processes, tides, atmospheric loading effects over the sea: $R = N + h + \ldots$. Since the ERS-1 launch in 1991, satellite altimetry offers a global and continuous coverage of sea level measurements, that have been used to analyse the ocean processes and their variations. In particular, the ocean dynamic topography, *h*, can be deduced from these measurements, to directly monitor the ocean currents. A detailed review of satellite altimetry and the major outcomes for oceanography can be found in Fu and Cazenave (2001).

Unfortunately, the geoid uncertainties do not allow to properly extract the dynamic topography from altimetric Sea Surface Height ($SSH = N + h$). Instead, assuming the geoid is stationary, a mean sea height $\overline{SSH} = G + \bar{h}$ that contains the geoid plus the mean dynamic topography ($MDT = \bar{h}$) is computed, then subtracted to the SSH: $SSH - \overline{SSH} = N + \bar{h} + h' - \left(N + \bar{h}\right)$ to provide Sea Level Anomalies ($SLA = h'$ with $h = \bar{h} + h'$). A first presentation of satellite altimetry, and the resulting Mean Sea Surface, that is, a global mapping of the mean sea height over a given period ($MSS = \overline{SSH} = G + \bar{h}$) was presented at the JLG 84th session by Hernandez (1998). SLA have been useful for understanding all transient processes of the ocean dynamics. However, the *MDT* witnesses mean currents that play a major role in the most energetic areas of the ocean. In particular, the lack of precise *MDT* estimate is a limitation for ocean modelling and forecasting. With the raising operational oceanography that aims to predict ocean state at the weekly or the seasonal scale, the use of satellite altimetry that offers an unpreceeding coverage (at the present day, four satellites are flying: ERS-2, TOPEX/Poseidon, GEOSAT FOLLOW ON and Jason-1), the need of an accurate *MDT* is crucial.

Different approaches were developed to replace or estimate a *MDT* that can be added to altimetric SLA, in order to provide the absolute dynamic topography necessary for ocean forecasting. We discuss here the four approaches commonly used, and focus on the two promising in the next decade: the combination of altimetric and in-situ oceanic data through the synthetic geoid method ; or the use of independent space products: the altimetric MSS and gravimetric geoid.

1. Ocean climatology, like the Levitus climatology (Levitus and Boyer, 1994 ; Levitus et al., 1994), based on historical hydrographic data that are merged and spatially averaged. They usually give a good first approximation of the ocean water masses, because this is what they represent. However, hydrographic data can only provide dynamic height estimate down to the hydrographic profile depth, and part of the full geostrophic signal (baroclinic and barotropic components) is missing. Moreover, their sparseness in time and space makes the averaging not identically homogeneous (not the same averaged dynamical signal) and accurate (few data over some oceans). Thus, spatial averaging are rarely better than 1°x1°, and the corresponding circulation is barely too smooth. Moreover, the temporal averaging of the climatology is hardly ever consistent with the altimetric averaging, and mean currents are not corresponding. In the near future, international programs like CLIVAR and ARGO will intend to provide a larger number of hydrographic data, with a dedicated spatial and temporal sampling that will allow to estimate more energetic ocean climatology.
2. Mean circulation, from ocean modelling. The run of a global ocean model over a long period can be used to compute a mean dynamic topography, characterised by the same spatial resolution and coverage than the model. For instance, the Parallel Ocean Climate Modelling experiment provides several years of realistic global simulation on a _° resolution (Semtner and Chervin, 1992). This approach guarantees an homogeneous description of the resulting mean field, and gradients can have the correct magnitude (Smith et al., 2000). Moreover, the time averaging can perfectly match the altimetric period. Unfortunately, the models are still unrealistic and the resulting mean dynamic topography will be polluted by improbable ocean features (Stammer et al., 1996). Besides, the most realistic ocean simulations need high spatial/temporal resolution and are tremendously costly in term of computation.
3. Synthetic climatology. This approach consist in comparing in-situ ocean measurements that provide the absolute dynamic topography, with altimetric SLA, then estimate the *MDT* from the difference: $h_{insitu} \square h_{alti}\square = \bar{h}_{Syn} \square MDT$. This technique has been widely used in different areas (Mitchell et al., 1990 ; Glenn et al., 1991 ; Qiu et al., 1991 ; Ichikawa et al., 1995 ; Uchida et al., 1998), but suffers from both the lack of precision of the data, and their inconsistency. Nonetheless, future ocean programs would supply promising set of accurate in-situ data that will be merged using inverse technique to provide improved global *MDT* at short scales. Note also that this approach offers a MDT over the same time-averaging period that the altimetric data.
4. From satellite altimetry and satellite gravimetry, one can compute a *MDT* independently from oceanographic measurements. This is the basic idea of satellite altimetry: just remove the geoid (deduced from satellite gravimetry) to altimetric *SSH*, to give the absolute dynamic topography. Or remove the geoid to the *MSS*, and use the resulting *MDT* added to SLA to again supply absolute dynamic topography. In any case, this approach allows to fully use altimetric data, either repeat or non-repeat orbit measurements. Moreover, the assumption of a stationary geoid is not necessary if an absolute time evolving geoid is available. Altimetry and gravimetry from space

guarantee also by this way a global and permanent supply of absolute dynamic topography, with an overall consistent accuracy level. As we said earlier, the geoid are unfortunately not accurate enough at the present day. However, the gravimetric missions like CHAMP, GRACE, and GOCE should help to determine geoid with the expected accuracy (1 cm at the 100-km wavelength).

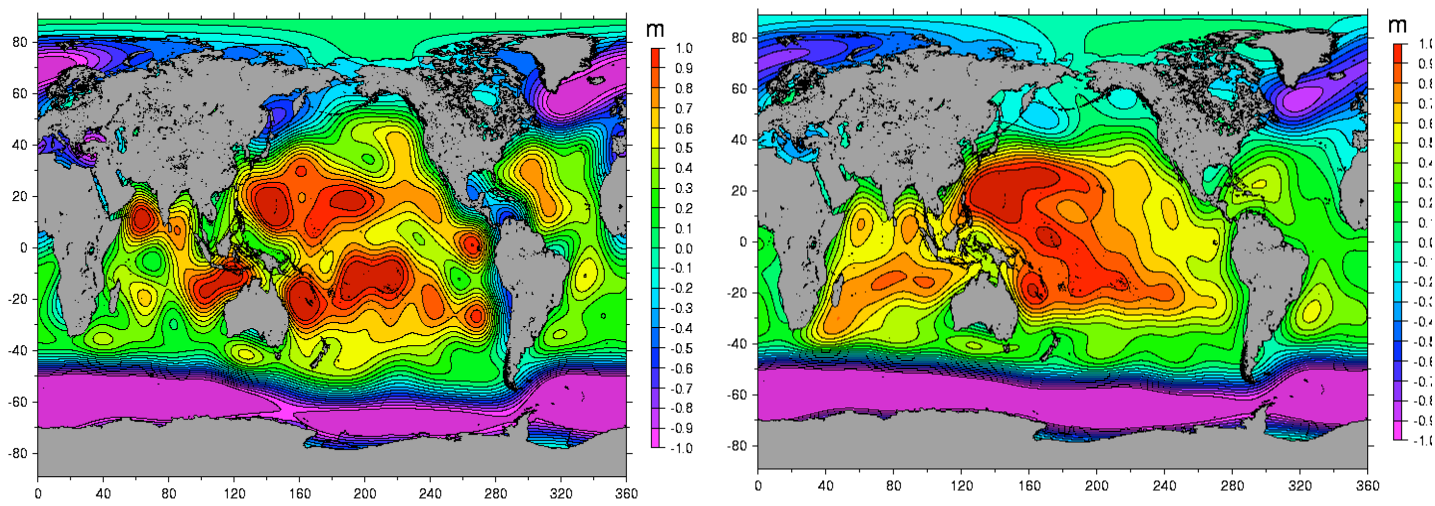
At the present time, these four approaches are not equally efficient, as several study conducted in our team at CLS showed it. We have analysed the *MDT* produced by these different approaches in term of oceanic information: the tested *MDT* are added to SLA and compared to concurrent oceanic in-situ measurements.

1. The direct comparison between the Levitus climatology and a synthetic climatology estimated with XBT data (computed and kindly provided by Stéphanie Guihehut at CLS) demonstrates the improvement afforded by the synthetic geoid technique: dynamic topography computed using the synthetic climatology as *MDT*, instead of Levitus, are better correlated with in-situ hydrographic data (0.73 instead of 0.66) and height discrepancies are reduced by more than 30% (7.7 instead of 9.3 cm rms). An illustration is given by figure 2b in Le Traon et al. (2001).

2. We have compared the *MDT* based on the simulated dynamic topography from the MERCATOR modelling experiment ; and a synthetic climatology estimated using both hydrographic and surface drifter data. Again, the synthetic climatology *MDT* allow to reduce by 30-40% the differences with drifter velocities (see Table 1) and the general circulation patterns are intensified and more realistic, as indicated by the regression analysis.

Velocity comparison	Regression slope	RMS differences (cm/s)
(Model *MDT* + *SLA*) vs drifter velocity		
U: zonal velocity	0.60	11.7
V: meridional velocity	0.64	10.2
(Synthetic climatology *MDT* + *SLA*) vs drifter velocity		
U: zonal velocity	0.77	9.2
V: meridional velocity	0.70	9.4

Table 1 : Comparison with drifter velocities

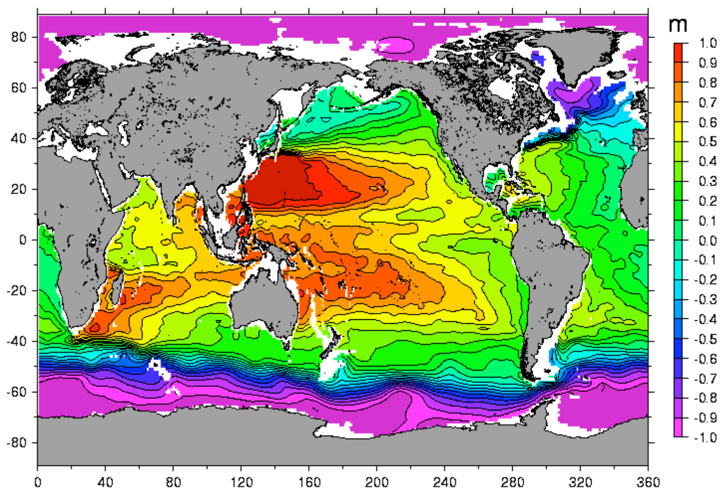


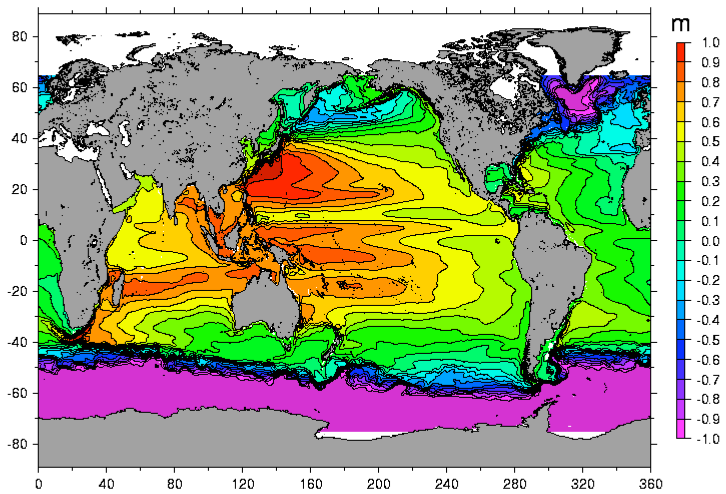
1) MSS CLS_SHOM98.2 – GRIM5_S1_CHAMP 2) MSS CLS_SHOM98.2 – EGM96

Thus, among the three approaches using oceanographic data (climatology or synthetic climatology) or oceanographic knowledge (i.e., from numerical models), the synthetic geoid technique offers the more realistic and accurate *MDT*. The fourth approach provides *MDTs* by subtracting a geoid to a MSS. These *MDT* are still unrealistic, but their accuracy level can be quantified in term of wavelength. Using the recent CLS_SHOM98.2 *MSS* (Hernandez and Schaeffer, 2000), we have subtracted the EGM96 geoid (Lemoine et al., 1998) to produce the *MDT* illustrated by figure 2. Note that this geoid can be considered at the present time as the most complete geoid, integrating all available data (altimetric, marine/continental and space gravimetry). On the other hand, the French/German cooperation has been developing the GRIM5 geoids: GRIM5-C1, a version up to degree 120 combining all the possible set of data (Gruber et al., 2000), and a pure satellite version GRIM5-S1 (Biancale et al., 2000). The GRIM5-S1 has been upgraded by including the first days of CHAMP data, to produce the GRIM5-S-CHAMP geoid. The resulting *MDT* is illustrated in figure 1.

Grid differences	degrees	Resolution	RMS differences (m)
GRIM5_S1_CHAMP – GRIM5_S1	72	~550 km	0.81
GRIM5_S1_CHAMP – GRIM5_S1	36	~1100 km	0.27
GRIM5_S1_CHAMP – EGM96	36	-	0.65
GRIM5_S1_CHAMP – GRIM5_S1	14	~2800 km	0.09
GRIM5_S1_CHAMP – GRIM5_C1	14	-	0.05
GRIM5_S1_CHAMP – EGM96	14	-	0.31
GRIM5_C1 – EGM96	14	-	0.32

Table 2 : Comparison between geoids at different spherical harmonics degrees





3) Synthetic climatology MDT 4) Model POCM_4B MDT

Table 2 shows that CHAMP data are strongly improving the satellite only solution. However, the decomposition has to be limited to degree 14 (~2800 km) to get compared with EGM96 at the same level than the GRIM5-C1 solution. However, compared to the synthetic climatology

MDT (figure 3) or the model *MDT* (figure 4), the *MDT* computed using *MSS* and geoid do not depict correctly the large scale oceanic circulation.

As mentioned earlier, Table 3 shows that no one of the four approaches offers a globally accurate *MDT*. Differences between the model and the oceanographic data *MDT* reach 13 cm rms, and the synthetic climatology *MDT* is the more accurate where in-situ data are available. Thus, the synthetic geoid approach, or a complete inverse modelling are potentially the most promising techniques.

Mean Dynamic Topography at degree 14 RMS diff (m)	POCM	Levitus	Synthetic climatology	MDT from EGM96
MDT from GRIM5_S1champ	0.21	0.20	0.20	0.26
MDT from EGM96	0.16	0.15	0.16	
POCM model		0.13	0.13	
Levitus climatology	0.13		0.08	

Table 3 : Comparison at spherical harmonics degree 14 between the MDT resulting from the different approaches.

The *MDT* deduced from the *MSS* and the gravimetric geoid exhibits the largest discrepancies. Nonetheless, this approach is promising because the few CHAMP data have improved the GRIM5 S1 geoid. We expect that the full set of CHAMP data will raise the GRIM5 accuracy to an acceptable level (less than 20 cm rms) at higher degrees (e.g., at degree 40, ~1000 km). Moreover, the GRACE (2002), then the GOCE (2005) missions should considerably improve the gravimetric geoid accuracy (less than 20 cm at the 100 km wavelength, e.g., Gruber, 2001), and thus, yield to an equally accurate *MDT* , providing its full efficiency to satellite altimetry.

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