A TWO-DECADE TIME SERIES OF EDDY-RESOLVING DYNAMIC OCEAN TOPOGRAPHY (iDOT)

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ABSTRACT

The significant improvements of GOCE derived gravity fields allows now to infer the dynamic ocean topography (DOT) by subtracting the geoid from sea surface heights (SSHs). While the geoid, derived from a band-limited gravity field model, is relative smooth and can be computed everywhere, the SSHs are observed along the altimeter ground tracks and exhibit high frequency variations. Thus, geoid and SSHs are to be consistently filtered. We apply a "profile method" performing such a filtering and subtraction along individual ground tracks. This way instantaneous DOT profiles (iDOT) can be generated for all ground tracks of any altimeter satellite. We apply this method to carefully cross calibrated multi-mission altimetry available since 1993. Subsequently, the combined set of all iDOT profiles is gridded with 10-day sampling periods to construct a DOT time series spanning the period 1993 up to now. The high quality of GOCE gravity fields allows to reduce the filter length down to some 70 km such that the DOT time series resolves meso-scale Eddies. For the western boundary currents animations show the evolution of Eddies and of the associated geostrophic velocity field which in turn allows to infer the Eddy kinetic

1. INTRODUCTION

Since long time it is known that the sea level is not in a perfect balance with gravity. Using the simple hydrostatic equation, the integration of density profiles – as performed, for example, by Levitus (1994) – indicate that the sea level deviates from a geopotential surface by about ±1–2 m. These deviations between the sea level and a geopotential surface are called dynamic ocean topography (DOT). The DOT is of great interest in Earth system sciences as it allows inferring the sea surface circulation and – with additional data the complete mass and heat transport in the ocean.

Already in 1968 the famous Williamstown report (Ref) was published and expressed the vision, that future satellite missions would allow to estimate the DOT by simply subtracting the geoid (a geopotential surface at sea level) from the sea surface heights as monitored by satellite altimetry. This induced the simple equation

$$DOT = h - N \qquad (1)$$

where h are the sea surface heights and N are geoid heights describing the geopotential surface both w.r.t. a Earth reference ellipsoid. Using this Eq. will be further on called the "geodetic way" to estimate the DOT – in contrast to the oceanographic efforts to model the DOT numerically. However, the equation is by no way as simple as it seems. The two quantities to be subtracted have completely different spectral properties. The geoid height N is rather smooth as it is derived from a band-limited spherical harmonic series, representing the Earth gravitational potential. In contrast, the sea surface height h contain a rich spectrum of details observed by the satellite altimeter (c.f. Fig.1).

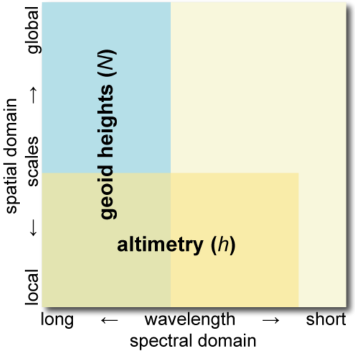

Figure 1. The different spectral properties of geoid height N and altimetry derived sea surface heights h.

In order to perform the difference in Eq. (1) in a proper way the two quantities h and N are to be filtered in a consistent way. We consider a linear filter operator by the symbolic notation 2D[•] and apply this to the right hand side of Eq. (1):

$$DOT = 2D[\, h - N \,] = 2D[h] - 2D[N\,] \qquad (2)$$

The linearity of the filter allows to apply the 2D-operator not only to the difference but also to the individual terms h and N.

Unfortunately, Eq. (2) could not be applied for a long time because the knowledge of the Earth gravity field was too poor in order to compute N with sufficient accuracy. Only with the dedicated gravity field mission CHAMP, GRACE and in particular GOCE it was possible to compute N with sufficient accuracy (say sub-decimetre level) in order to get an acceptable signal-to-noise ratio for estimating the DOT (±1–2 m) by the “geodetic way”. The results presented here are based on the GOCO02S gravity model (Gogenginger et al. 2011), a combination of GRACE with 6 months of GOCE observations. It should be emphasized that the N in Eqn. (1) and (2) should be computed from a satellite-only gravity field model to avoid the risk that altimetry enters these equation twice e.g. by using combined gravity models, using marine gravity derived from satellite altimetry.

In the last years many attempts have been made to apply Eq. (2). Often the investigations were combining Eq. (2) with hydrodynamic modelling. As it is not the scope of this paper to review this, we refer to Maximenko et al. (2009) comparing three different combination methods to determine the DOT. The pure “geodetic ways” shall be discussed in more detail as (i) we express some concerns and (ii) introduce in section 2 an alternative approach.

The general strategy to evaluate Eq. (2) is to perform the filtering in the spectral domain, that is representing all quantities in terms of spherical harmonics. As N is already given in terms of spherical harmonics the sea surface heights h must be also expressed in spherical harmonics. This is accomplished by

- taking a mean sea surface height model (MSS) as a proxy for $h \leftarrow h_{\mathrm{MSS}}$ (MSS models are provided for example by CLS or DTU),
- extending the sea surface heights h_{MSS} towards land, and
- expanding h_{MSS} into a spherical harmonic series.

As a result Eq. (2) can now be evaluated as

$$\mathrm{DOT} = 2\mathrm{D}[h_{\mathrm{MSS}} - N\,] \qquad (3)$$

and the filter operator can be performed by simply multiplying the harmonic coefficients by the filter coefficients. The result of this “global approach” is a mean dynamic topography which is representative for the period of time used to construct the MSS.

There are two general concerns for the global approach:

- To perform a temporal mean in the western boundary currents with strong meandering and eddy formation is problematic. The uncertainty of h_{MSS} at those areas will be governed by sea level variability.
- Even more critical is the artificial extension of h_{MSS} towards land which is most often filled with geoid data. Then either a filtering or an iterative procedure is performed in order to get smooth land-ocean transition zones – with the risk to generate Gibbs effects in the spherical harmonics.

The profile approach described in the following section is designed to circumvent these problems.

2. THE PROFILE APPROACH

The rationale of the profile approach developed by Bosch & Savcenko (2010) is based on the goal to lose as little as possible information from the high resolution along-track sea surface height data. An initial gridding of the sea surface heights shall be avoided, as any gridding already implies an undesirable smoothing, difficult to control. Also, the artificial extension towards land shall be bypassed. The objective is to filter the instantaneous sea surface heights h along-track and only at locations where they have been observed. This way we will estimate an instantaneous DOT (iDOT). The problem is then, how to ensure a consistent filtering of the along-track sea surface heights h. Taking Eq. 2 we add a one-dimensional filter operator 1D[•] applied to h and immediately subtract it to keep the equality (both indicated in bold), such that

$$\mathrm{iDOT} = \mathbf{1D}[\boldsymbol{h}] + 2\mathrm{D}[h] \mathbf{-} \mathbf{1D}[\boldsymbol{h}] - 2\mathrm{D}[N].$$

Now we read this equation for the iDOT estimate in a different way **–** with other terms indicated in bold.

$$\mathrm{iDOT} = 1\mathrm{D}[h] \mathbf{+} \mathbf{2D}[\boldsymbol{h}] \mathbf{-} \mathbf{1D}[\boldsymbol{h}] - 2\mathrm{D}[N] \qquad (4)$$

The first term on the right is what we intend to realize with the profile approach: to filter in one dimension the sea surface heights along-track. Computing the last term on the right is straight forward: a two-dimensional filtering of the geoid heights which can be performed e.g. in the spectral domain. Then the bold terms in Eq. 4 have to be considered as a correction, compensating the systematic differences caused by replacing the 2D-filtering of h with the 1D-filtering. Therefore the term

$$\mathrm{FC} = 2\mathrm{D}[h] - 1\mathrm{D}[h] \qquad (5)$$

will be further on called filter correction.

The most obvious way to compute the filter correction FC would be to use the sea surface heights h_{MSS} as used in the global approach, extended towards land and expanded into spherical harmonics. Then, we have

$$\mathrm{FC} = 2\mathrm{D}[h_{\mathrm{MSS}}] - 1\mathrm{D}[h_{\mathrm{MSS}}]$$

and Eq. 4 would become

$$\mathrm{iDOT} = 1\mathrm{D}[h] + 2\mathrm{D}[h_{\mathrm{MSS}}] - 1\mathrm{D}[h_{\mathrm{MSS}}] - 2\mathrm{D}[N]$$

or, after a re-ordering

$$\mathrm{iDOT} = 1\mathrm{D}[h - h_{\mathrm{MSS}}] + 2\mathrm{D}[h_{\mathrm{MSS}} - N\,] \qquad (6)$$

The first term right hand in Eq. 6 implies a one-dimensional along-track filtering of the differences $h - h_{\mathrm{MSS}}$ which is nothing else than the sea level anomalies, the differences of the instantaneous sea surface heights w.r.t a mean sea surface. As sea level anomalies are not related to a geopotential surface the second term is needed. However, this second term is just the 2D-operator to be performed for the global approach (c.f. Eq. 3), which we want to circumvent. Thus, the strategy to compute the filter correction FC by means of a mean sea surface height model is rejected and no longer considered in the present paper.

The alternative for computing the filter correction FC is based on the ultra-high resolving gravity field model EGM2008 (Pavlis et al. 2008). This model is given in spherical harmonics and has been expanded up to degree and order 2160 (for some degrees even up to 2190). The geoid N_{EGM08} computed from EGM2008 nicely follows the small-scale structure of the mean sea level. The deviation of N_{EGM08} to sea level is of long-wavelength nature and this suggests to take N_{EGM08} as a proxy for the sea surface heights h in the filter correction, Eq. 5

$$\mathrm{FC} = 2\mathrm{D}[N_{\mathrm{EGM08}}] - 1\mathrm{D}[N_{\mathrm{EGM08}}]\ .$$

In this case Eq. 4 becomes

$$\mathrm{iDOT} = 1\mathrm{D}[h] + 2\mathrm{D}[N_{\mathrm{EGM08}}] - 1\mathrm{D}[N_{\mathrm{EGM08}}] - 2\mathrm{D}[N]$$

or, again after a re-ordering

$$\mathrm{iDOT} = 1\mathrm{D}[h - N_{\mathrm{EGM08}}] + 2\mathrm{D}[N_{\mathrm{EGM08}} - N\ ]. \qquad (7)$$

This appears now as a convenient equation. It implies to filter along-track with the 1D-operator applied to the difference between the instantaneous sea surface heights and the ultra-high resolution geoid. The second term of Eq. 7 is now also well suited as it requires the 2D-filtering of the difference of two quantities, N_{EGM08} and N, both available in terms of spherical harmonics. Eq. 7 has another advantage: while the filter correction, Eq.4 requires a treatment of every individual track, the second term of Eq. 7 can be computed once in advance. The results shown below were derived using Eq. 7.

3. FILTER SPECIFICATIONS AND DATA

In the context of estimating the mean dynamic topography several filters were proposed to accomplish the consistency between h and N (c.f. Eq. 2). A discussion on that is found, for example, in Bingham et al. (2010). For the present investigation we use a simple isotropic Gauss-type filter as proposed by Jekeli (1981) and illustrated in Fig. 2.

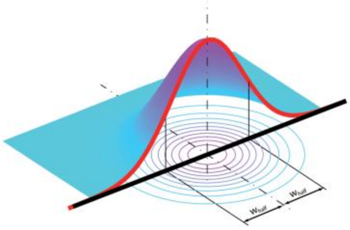

Figure 2. The Gauss filter with the blue surface being effective for the 2D-filter and the red curve indicating the shape of the 1D-filter.

The filter specifications were adapted to the potential resolution of the satellite-only gravity field models used to compute N. The first experiences with the profile approach were performed with the GRACE model ITG03S (Mayer-Gürr 2007). As all GRACE based gravity models were plagued by an artificial meridional striping, the filter length was initially set to 240 km, corresponding to degree 60 of the spherical harmonic series. (c.f. Tab. below). The GOCO02S gravity field model (Goiginger et al. 2011), a combination of CHAMP, GRACE as well as six month of GOCE data, provided a significant better resolution. Therefore the filter length for GOCO02S was gradually decreased up to 69 km (degree L=210).

Length [km]	Degree L	Gravity model(s)
240	60	ITG03S, GOCO02S
120	120	GOCO02S
97	150	GOCO02S
81	180	GOCO02S
69	210	GOCO02S, GOCO03S

Although the filter length of 69 km somehow overestimates the actual resolution capability of GOCO02S, the results of the corresponding iDOT-profiles were plausible from an oceanographic point of view and appeared by no way noisy. Thus, already with GOCO02S we approached meso-scale resolution, allowing to identify Eddies and other pattern of turbulent flow present in the strong western boundary currents (see results below). Recently, GOCO03S (Mayer-Gürr 2011) has been published. It is an update of the GOCO-gravity field models and contains now 18 month of GOCE data. GOCO03S will even more justify a filter length of only 69 km. The corresponding DOT computations are on-going and will be provided at the same URL as the results of GOCO02S (see below).

With the GOCO02S gravity field model and the filter length specified above Eq. 7 was processed for all passes of most of the altimeter satellites operating since 1992 (c.f. Fig. 3). This includes the ESA missions ERS-1, ERS-2 and Envisat, the CNES/NASA missions TOPEX/Poseidon, Jason-1 and Jason-2, as well as the GFO mission. Data of the CryoSat-2 mission will be included later, as soon as the quality of the official products is sufficiently consolidated.

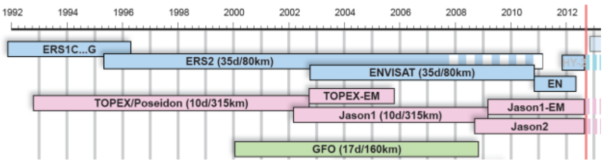

Figure 3. Multi-mission scenario of altimeter missions operating since 1992.

In order to allow a combination and gridding of all iDOT-profiles determined for all altimeter systems it is essential that a cross-calibration has been performed in advance. This is accomplished by global multi-mission cross calibration using crossover differences computed in all combinations for all missions shown in Fig. 3. The approach has been developed by Bosch (2007) and Bosch & Savcenko (2007) and was recently applied to dedicated investigations calibrating Envisat and Jason-2 (Dettmering & Bosch 2010a,b). The cross calibration realizes a consistent set of multi-mission altimeter data which can be merged as if it would have been observed by a single mission.

4. RESULTS

Fig. 4 shows the results of evaluating Eq. 7 for just the (cross-calibrated) sea surface heights on altimeter ground tracks observed during the common 10-day cycles 380 and 37 of TOPEX and Jason-1 respectively.

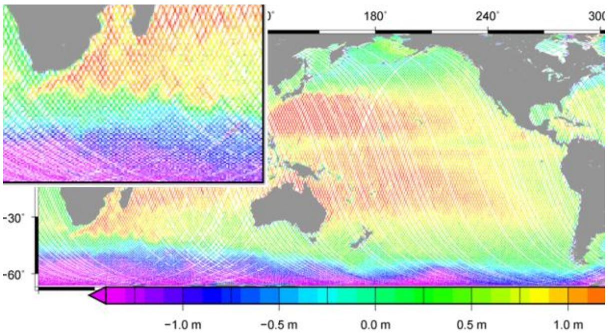

Figure 4. A 10-day snapshot of the iDOT-profiles for the ground tracks of TOPEX (cycle 380) and Jason-1 (cycle 37) with a zoom to the Agulhas counter current South of Africa. TOPEX was already on a shifted orbit such that the spatial resolutions of both missions were doubled.

All well-known pattern of the DOT are visible, the large basin-scale gyres in North and South Pacific with the Western boundary currents, the Antarctic Circumpolar Current and by the zoom to the Agulhas counter current the strong meandering and eddy formation South of Africa. Due to the cross-calibration the ground tracks of TOPEX and Jason-1 don´t show any trackiness. It is therefore reasonable to perform a simple gridding with the result shown in Fig. 5. The data of this figure has been processed with a filter length of 97 km. Fig.6 is a zoom of the gridded DOT estimates to the Aghulas counter current, processed with a filter length of 69 km while Fig. 7 shows the same area with the geostrophic velocities translated from the DOT by means of the geostrophic equations.

Fig. 5–7 are only snapshots of the DOT for a particular epoch. They have been derived by gridding just those iDOT-profiles observed by satellite altimetry during this epoch. As iDOT-profiles have been computed for all passes of all satellites of the multi-mission scenario shown in Fig. 3 it was possible to generate a time series of DOT snapshots for the two decades from 1992 up to 2012. These DOT snapshots have been gridded and used to generate animations in order to illustrate the temporal evolution of the DOT over the two decade period. The animation can be seen at the URL www.dgfi.badw.de/?333 . They are also available at the anonymous ftp.dgfi.badw.de at directory iDOT where all iDOT-profiles, computed with the 69 km filter length and the GOCO02S gravity field model, are available in

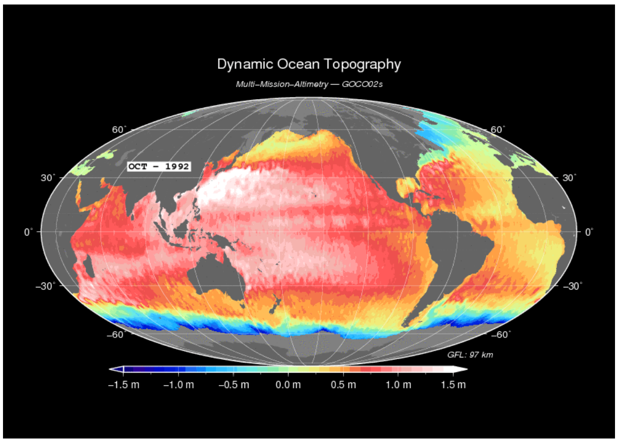

Figure 5. Gridded snapshot of the iDOT-profiles for Oct. 1992 (TOPEX and ERS-1). Filter length is 97km.

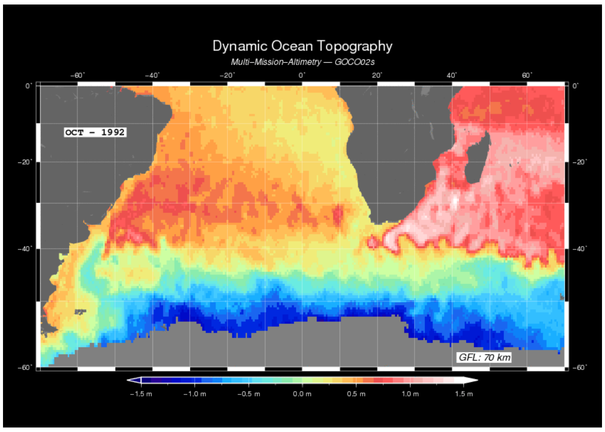

Figure 6 . Gridded iDOT-profiles for the South Atlantic and Agulhas counter current. Filter length is 69 km.

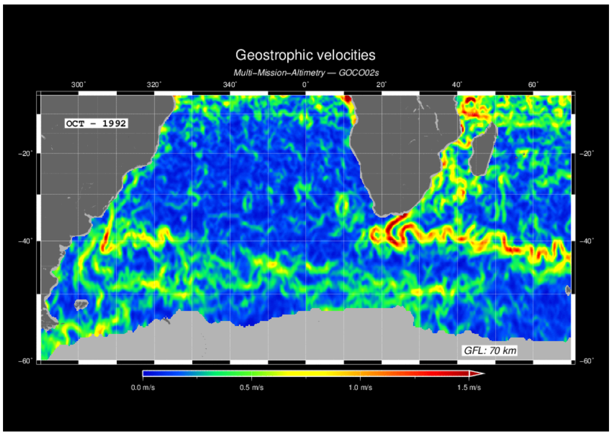

Figure 7. Same as Fig.6 with the gridded iDOT translated into geostrophic currents

terms of netcdf-files each one compiling the iDOT-profiles for all passes of an individual cycle. For every mission of the scenario in Fig. 3 there are as many netcdf files as the mission has cycles.

5. DISCUSSION AND OUTLOOK

It should be emphasized that the variation and meso-scale structures visible in Figs. 5–7 and the corresponding animations are *not* based on sea level anomalies (SLA). Sea level anomalies may exhibit more details of ocean variability, they refer however to a mean sea surface, a virtual surface which never exists and has no physical meaning. SLA are just the residuals w.r.t a mathematically averaged surface. In contrast to this the iDOT-pattern and the geostrophic velocity field shown above have a physical meaning. The smoothing of the iDOT-profiles is indispensable in order to ensure consistency with the geoid. However, the iDOT estimates follow hydrodynamic laws. Fig. 7 for example was derived by applying the geostrophic equations. Consequently, iDOT-profiles are much more suited for assimilation into numerical models than SLA. Indeed, the profile approach has been developed in the context of a project aiming to improve estimates of mass and heat transport by a numerical model assimilating the geodetic DOT. Preliminary results of this assimilation are described in the paper of Janijc et al. (2012).

The results shown here are considered only as preliminary and have to be gradually improved. It was already indicated that a re-processing with the latest GOCO03S gravity model is already under way. All iDOT-profiles will be computed with GOCO03S, gradually completed for additional profiles observed by Jason-1, Jason-2, CryoSat-2, and hopefully SARAL/ Altika and made available at the same ftp server. In general any new combined GRACE/GOCE gravity field model providing a substantially improved resolution will give rise for another re-processing.

In near future the error characteristics of the iDOT-profiles will be characterized by mission-specific auto-covariance functions (ACF). An ACF for the sea surface heights *h* is already available from the multi-mission cross calibration (Dettmering & Bosch 2012) described in section 3 above (see Fig. 8). For the geoid component the ACF is still to be evaluated.

Once, the ACF of the iDOT-profiles is available it should be used for the gridding which is up to now assuming uncorrelated iDOT estimates. The correlations taken into account give more realistic error estimates and will allow to propagate the iDOT errors to the velocity components

Finally, the validation with independent data is outstanding. Drifter and ARGO floats will be used to obtain a measure for the quality of the iDOT-profiles.

Fig. 9 indicates a very first attempt to compare the iDOT pattern with the surface velocities of ARGO-floats.

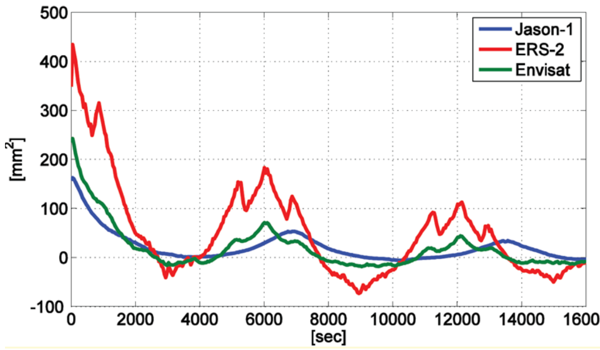

Figure 8. Empirical auto-covariance functions of Jason-1, ERS-2 and Envisat as derived from a multi-mission cross-calibration (Dettmering & Bosch 2012).The relative maxima after the first and second revolution are indicative for geographical correlated errors.

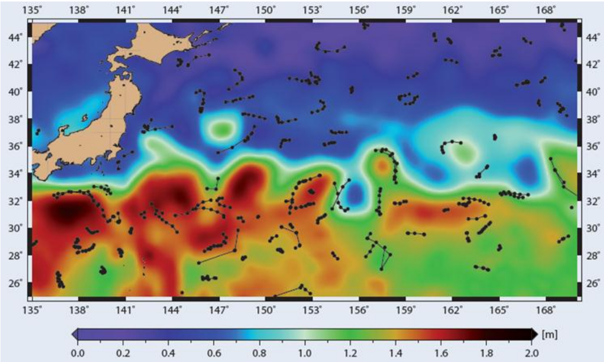

Figure 9. Snapshot of iDOT-pattern for 2012-12-05 of the Kuroshio area with an overlay of surface movements of ARGO-floats

6. ACKNOWLEDGEMENT

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