Mean and profile-based dynamic ocean topography determination in the Mediterranean Sea within the GOCE+++ project

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Introduction and Problems

It has been very recently concluded that GOCE, apart from a high-accuracy static gravity field, can offer unique insights to oceanographic, engineering and geophysical applications.

The relation between geodesy and physical oceanography is at the sea surface. The specific point where the two sciences interact is the deviation of the geoid from the mean sea surface, which is known as mean (or quasi-stationary) DOT.

The concept of DOT (ζ) estimation is quite simple in its notion and relies on the fact that it can be computed as the difference between the MSS and the geoid, taking into account that both are available for the area under study. Two points that need attention are that both the MSS and geoid fields should refer to the same reference ellipsoid and the same tidal system.

Within GOCE+++, and in order to be compatible with the conventions in the satellite altimetry and oceanographic community, the T/P ellipsoid with equatorial radius of 6378.1363 km and a flattening of 1/298.257 and the mean-tide system will be used.

Data used and methodology

Given the availability of recent GGMs from of GOCE, the latest GGMs from GOCE and GRACE data, GOCO05c will be used to determine mean DOT models for the entire Mediterranean Sea.

The raw data used are Sea Level Anomaly (SLA) values from the Cryosat2 satellite for a period of 6 consecutive years 2010-2015 within the entire Mediterranean Basin (30° ≤ φ ≤ 50° and -10° ≤ λ ≤ 40°).

By simply restoring the effect of EGM2008 to the SLAs, sea surface heights (SSHs) from Cryosat2 have been generated for the area under study. Apart from the GOCE GGMs, the estimation will be based on the DTU2015 MSS model. Given the above, the DOT can be then determined as:

$$\zeta = \tilde{h} - N \qquad \tilde{\zeta} = \tilde{h} - N_L = \zeta + N - N_L + \delta_L = \zeta + \delta N_L + \delta_L$$

The spatial resolution that can be represented corresponds to ~70 km for GOCO05s which is far less than that of the DTU2015 MSS to be used, since the latter is derived from multi-mission altimetry data and has a resolution of 1 arcmin (~2 km). Having estimated this initial DOT, and in order to remove, or at least reduce, the influence of the δNL and δL terms, some filtering is needed.

DOT filtering

$$\zeta = \{\quad + \delta N_L + \delta_L\}$$

For the filtering, GOCE+++ will employ both spatial as well as spectral filtering. The spatial filters will be boxcar, cosine arch, Gaussian and Wiener-type of filters while various filter widths will be tested. For spectral filtering, WL MRA and FIR filters are examined.

$$h(x,y) = 2\lambda_c sinc\left(2\lambda_c\left(x^2+y^2\right)\right) \qquad h(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

$$x[n] = \sum_{i=0}^{N} a_i w[n-1] \qquad h(x,y) = sinc\left(\frac{x^2+y^2}{\lambda_c}\right) \frac{\cos\left(\frac{\theta\pi\left(x^2+y^2\right)}{\lambda_c}\right)}{1-\frac{4\theta^2\left(x^2+y^2\right)^2}{\lambda_c^2}}$$

$$\varphi_{(j,m,n)}(x) = 2^{(j/2)}\varphi\left(2^j x - m, 2^j y - n\right)$$

$$\psi^i_{(j,m,n)}(x,y) = 2^{(j/2)}\psi\left(2^j x - m, 2^j y - n\right), i = H,V,D$$

$$w(n) = \alpha - \beta\left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right), 0 \le n \le N-1$$

DOT determination

The initial DOT field results as the simple difference between the DTU2015 MSS and GOCO05c geoid heights. It is obvious that in the initial unfiltered field there are many blunders especially close to the coastline, while the un-modeled parts of the geoid omission and commission error are still present in the determined field. In order to remove the blunders and avoid over-smoothing at the next processing phase, a simple 3σ test has been applied .

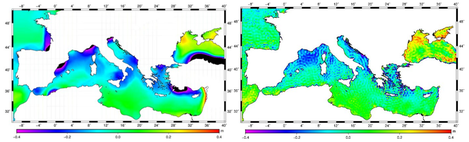


Figure 1: Initial field of DOT in the Mediterranean (left) and after the application of 3σ test (right).

DOT	min	max	std	mean
Initial field	-2.157	0.763	±0.142	0.018
After 3σ test	-0.428	0.428	±0.122	0.006

Table 1: Statistics of the DOT of the initial and the 3σ test field (m).

For all spatial filters five different widths have been tested corresponding to spatial scales of 50, 100, 200, 400 and 600 km full wavelength. These filters have been applied to the whole Mediterranean basin and the components of geostrophic circulation velocity *u,v* have been estimated.

$$u_s = -\frac{\gamma}{fR}\frac{\partial\hat{\zeta}}{\partial\varphi} \qquad v_s = -\frac{\gamma}{fR\cos\varphi}\frac{\partial\hat{\zeta}}{\partial\lambda}$$

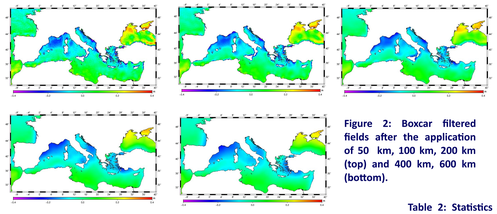


Figure 2: Boxcar filtered fields after the application of 50 km, 100 km, 200 km (top) and 400 km, 600 km (bottom).

MODEL		max	min	mean	rms	std
boxcar_50	DOT (m)	0.394	-0.473	0.003	0.109	0.109
	vel (m/s)	1.975	0.000	0.206	0.296	0.213
	v (m/s)	1.395	-1.787	0.01	0.194	0.193
	u (m/s)	1.601	-1.757	0.007	0.224	0.224
boxcar_100	DOT (m)	0.345	-0.445	0.000	0.105	0.105
	vel (m/s)	0.916	0.000	0.121	0.168	0.117
	v (m/s)	0.614	-0.802	0.008	0.108	0.107
	u (m/s)	0.575	-0.916	0.011	0.129	0.129
boxcar_200	DOT (m)	0.301	-0.305	-0.006	0.101	0.100
	vel (m/s)	0.432	0.000	0.069	0.09	0.058
	v (m/s)	0.292	-0.286	0.005	0.054	0.054
	u (m/s)	0.258	-0.418	0.012	0.072	0.071
boxcar_400	DOT (m)	0.288	-0.232	-0.015	0.096	0.094
	vel (m/s)	0.258	0.000	0.044	0.053	0.03
	v (m/s)	0.258	-0.105	0.004	0.03	0.03
	u (m/s)	0.122	-0.174	0.01	0.044	0.043
boxcar_600	DOT (m)	0.275	-0.234	-0.021	0.091	0.088
	vel (m/s)	0.196	0.000	0.036	0.042	0.022
	v (m/s)	0.199	-0.07	0.003	0.022	0.022
	u (m/s)	0.082	-0.115	0.008	0.036	0.035

Table 2: Statistics after the application of Boxcar filters.

Generally, the application of Boxcar filter in short wavelengths depicts the ocean circulation and filters the initial field, while as the cut-off increases, the field is getting oversmoothed so that not only noise, but also signal is removed.

After the application of Boxcar 50 km, although a large part of the noise is removed, the large DOT values close to the coastline are persisting.

Moreover, the geostrophic currents are still affected by the presence of land especially in the Greek region.

In the case of 100 km filter width, the velocity is reduced by 1 m/s compared to that of 50 km while the DOT does not alter since the mean value and the std are reduced only by ~3 mm.

Increasing the wavelength to 200, 400 and 600 km, not only the noise but also the signal are removed. The min value is reduced by 14 cm and 20 cm for the 200 and 400 km filters, compared to the 100 km one. The application of 600km filter reduces the std by 3.5 cm compared to the value of the initial field.

Table 3: Statistics after the application of Cosine arc filters.

MODEL		max	min	mean	rms	std
cosine_50	DOT (m)	0.41	-0.482	0.004	0.114	0.114
	vel (m/s)	3.128	0	0.349	0.468	0.312
	v (m/s)	2.496	-3.071	0.01	0.323	0.323
	u (m/s)	2.467	-2.654	0.005	0.338	0.338
cosine_100	DOT (m)	0.375	-0.462	0.002	0.107	0.107
	vel (m/s)	1.463	0.000	0.151	0.228	0.171
	v (m/s)	1.008	-1.407	0.009	0.148	0.148
	u (m/s)	1.078	-1.374	0.008	0.173	0.173
cosine_200	DOT (m)	0.329	-0.394	-0.002	0.103	0.103
	vel (m/s)	0.685	0.000	0.089	0.129	0.089
	v (m/s)	0.482	-0.469	0.007	0.077	0.077
	u (m/s)	0.387	-0.638	0.011	0.1	0.099
cosine_400	DOT (m)	0.285	-0.279	-0.009	0.098	0.098
	vel (m/s)	0.302	0.000	0.053	0.068	0.043
	v (m/s)	0.283	-0.188	0.005	0.039	0.039
	u (m/s)	0.175	-0.298	0.011	0.055	0.054
cosine_600	DOT (m)	0.281	-0.227	-0.014	0.095	0.094
	vel (m/s)	0.251	0.000	0.041	0.05	0.029
	v (m/s)	0.251	-0.101	0.004	0.027	0.027
	u (m/s)	0.251	0.000	0.041	0.05	0.029

Table 4: Statistics after the application of Gaussian filters.

MODEL		max	min	mean	rms	std
gaussian_50	DOT (m)	0.412	-0.483	0.004	0.115	0.115
	vel (m/s)	3.333	0.000	0.368	0.492	0.327
	v (m/s)	2.675	-3.281	0.01	0.34	0.34
	u (m/s)	2.600	-2.845	0.005	0.356	0.356
gaussian_100	DOT (m)	0.379	-0.465	0.002	0.108	0.108
	vel (m/s)	1.695	0.000	0.169	0.25	0.184
	v (m/s)	1.145	-1.634	0.009	0.164	0.164
	u (m/s)	1.243	-1.520	0.008	0.188	0.188
gaussian_200	DOT (m)	0.331	-0.404	-0.002	0.103	0.103
	vel (m/s)	0.776	0.000	0.094	0.136	0.097
	v (m/s)	0.535	-0.572	0.007	0.084	0.083
	u (m/s)	0.439	-0.725	0.011	0.107	0.106
gaussian_400	DOT (m)	0.291	-0.285	-0.008	0.098	0.098
	vel (m/s)	0.346	0.000	0.055	0.072	0.047
	v (m/s)	0.283	-0.214	0.005	0.042	0.041
	u (m/s)	0.191	-0.342	0.011	0.059	0.058
gaussian_600	DOT (m)	0.280	-0.238	-0.013	0.095	0.094
	vel (m/s)	0.256	0.000	0.043	0.053	0.031
	v (m/s)	0.256	-0.111	0.004	0.029	0.029
	u (m/s)	0.124	-0.194	0.01	0.044	0.043

Table 5: Statistics after the application of Wiener filters.

MODEL		max	min	mean	rms	std
wiener_50	DOT (m)	0.4	-0.420	0.025	0.108	0.105
	vel (m/s)	1.851	0.000	0.19	0.266	0.186
	v (m/s)	1.23	-1.637	0.005	0.183	0.182
	u (m/s)	1.263	-1.265	0.007	0.193	0.193
wiener_100	DOT (m)	0.350	-0.350	0.021	0.101	0.099
	vel (m/s)	0.958	0.000	0.107	0.160	0.118
	v (m/s)	0.618	-0.810	0.004	0.110	0.110
	u (m/s)	0.609	-0.881	0.009	0.115	0.115
wiener_200	DOT (m)	0.310	-0.250	0.014	0.094	0.093
	vel (m/s)	0.516	0.000	0.066	0.105	0.082
	v (m/s)	0.321	-0.496	0.003	0.073	0.073
	u (m/s)	0.255	-0.443	0.008	0.076	0.076
wiener_400	DOT (m)	0.260	-0.190	0.007	0.083	0.083
	vel (m/s)	0.360	0.000	0.043	0.078	0.065
	v (m/s)	0.168	-0.330	0.003	0.052	0.052
	u (m/s)	0.145	-0.224	0.007	0.059	0.058
wiener_600	DOT (m)	0.230	-0.160	0.003	0.073	0.073
	vel (m/s)	0.221	0.000	0.032	0.067	0.059
	v (m/s)	0.168	-0.168	0.002	0.043	0.043
	u (m/s)	0.145	-0.144	0.006	0.052	0.052

MRA-WL filtering

WL MRA allows the decomposition of the signal in distinct levels, each corresponding to a different spectral range. In the present scenario, Level 1 corresponds to spatial scales between 9 km and 18 km,. Through the synthesis process various DOT models can be determined, since each level can be represented by a different model, based on the data performance at each specific level of analysis. Each level is analysed in an approximation coefficient and three detail coefficient.

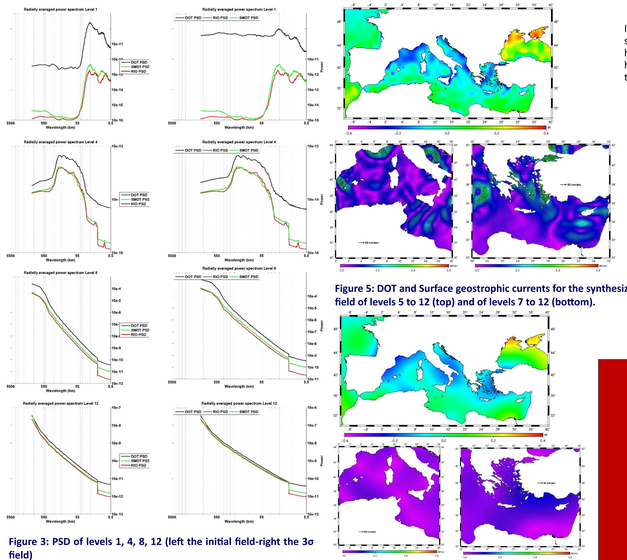


Figure 3: PSD of levels 1, 4, 8, 12 (left the initial field-right the 3σ field)

Figure 5: DOT and Surface geostrophic currents for the synthesized field of levels 5 to 12 (top) and of levels 7 to 12 (bottom).

Table 6: Statistics of the synthesized MRA-WL fields

MODEL		max	min	mean	rms	std
2_12	DOT (m)	0.42	-0.45	-0.003	0.119	0.119
	vel (m/s)	3.239	0.000	0.328	0.473	0.341
	v (m/s)	2.696	-3.202	-0.001	0.356	0.356
	u (m/s)	2.334	-2.269	0.000	0.311	0.311
3_12	DOT (m)	0.417	-0.423	-0.003	0.114	0.114
	vel (m/s)	3.078	0.000	0.229	0.324	0.229
	v (m/s)	3.071	-2.404	-0.001	0.259	0.259
	u (m/s)	1.618	-1.556	0.001	0.194	0.194
4_12	DOT (m)	0.397	-0.436	-0.005	0.110	0.110
	vel (m/s)	1.054	0.000	0.14	0.185	0.121
	v (m/s)	0.991	-1.053	-0.002	0.147	0.147
	u (m/s)	0.703	-0.601	0.000	0.113	0.113
5_12	DOT (m)	0.358	-0.325	-0.009	0.107	0.107
	vel (m/s)	0.553	0.000	0.097	0.119	0.069
	v (m/s)	0.329	-0.529	-0.004	0.093	0.092
	u (m/s)	0.293	-0.326	0.001	0.075	0.075
6_12	DOT (m)	0.316	-0.251	-0.016	0.105	0.104
	vel (m/s)	0.228	0.000	0.064	0.074	0.038
	v (m/s)	0.222	-0.227	-0.004	0.057	0.057
	u (m/s)	0.141	-0.147	0.000	0.047	0.047
7_12	DOT (m)	0.314	-0.027	-0.025	0.097	0.094
	vel (m/s)	0.116	0.000	0.038	0.043	0.02
	v (m/s)	0.103	-0.061	-0.005	0.026	0.026
	u (m/s)	0.107	-0.054	0.005	0.034	0.034

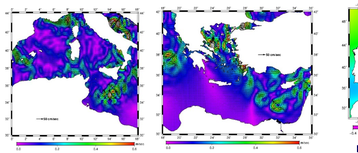


Figure 5: Surface geostrophic currents in Eastern and Western Mediterranean Sea for the synthesized field of levels 4 to 12.

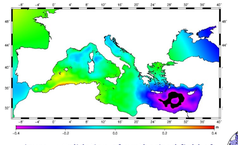
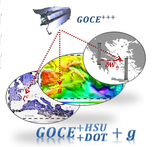


Figure 7: Validation of synthesized field of levels 7_12 with SMDT model.

Table 7: Statistics of validation of synthesized fields with Rio model.

RIO_validation	max	min	mean	rms	std
Lvl 2_12	0.55	-0.519	0.016	0.187	0.186
Lvl 3_12	0.498	-0.517	0.016	0.185	0.185
Lvl 4_12	0.458	-0.517	0.017	0.184	0.183
Lvl 5_12	0.456	-0.484	0.016	0.181	0.18
Lvl 6_12	0.463	-0.436	0.018	0.18	0.179
Lvl 7_12	0.432	-0.427	0.012	0.177	0.177



Spectral FIR test

In case of the FIR test the one that has given the best results in previous tests (Natsiopoulos et al. 2016) has been chosen. It is one band bass filter with two cut off frequencies, the lower at 0.35 Hz and the upper one at 0.65 Hz. This filter has been applied on along track data (on every pass of each cycle) of the year 2014 (cycles 49 to 61). Two different tests have been made. On first one all data have been used while on the second one the data within a distance of 20 km from the coastline has been omitted as the altimetry data close to the land have lower accuracy.

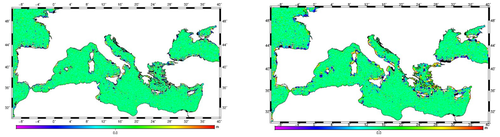


Figure 6: DOT in the Mediterranean after the application of FIR filter (all data-left), omit data (20km from coast-right)

Validation with Rio model and SMDT model

In case of FIR test the one that has given the best results in previous tests (Natsiopoulos et al. 2016) has been chosen. It is one band bass filter with two cut off frequencies the lower at 0.35 Hz and the upper one at 0.65 Hz. This filter has been applied on along track data (on every pass of each cycle) of the year 2014 (cycles 49 to 61). Two different tests have been made. On first one all data have been used while on the second one the data within a distance of 20 km from the coastline has been omitted as the altimetry data close to the land have lower accuracy.

RIO_validation	max	min	mean	rms	std
Boxcar_50	0.426	-0.189	0.039	0.082	0.072
Boxcar_100	0.373	-0.177	0.042	0.081	0.069
Boxcar_200	0.363	-0.177	0.048	0.083	0.068
Boxcar_400	0.357	-0.149	0.054	0.087	0.068
Boxcar_600	0.366	-0.174	0.044	0.081	0.068
Wiener_50	0.371	-0.213	0.016	0.072	0.070
Wiener_100	0.337	-0.196	0.02	0.07	0.067
Wiener_200	0.329	-0.187	0.026	0.07	0.065
Wiener_400	0.319	-0.177	0.031	0.072	0.065
Wiener_600	0.311	-0.177	0.032	0.072	0.065
Gaussian_50	0.44	-0.234	0.038	0.087	0.078
Gaussian_100	0.41	-0.183	0.04	0.081	0.071
Gaussian_200	0.362	-0.174	0.044	0.081	0.068
Gaussian_400	0.358	-0.167	0.049	0.083	0.067
Gaussian_600	0.356	-0.156	0.053	0.085	0.067
Cosine_50	0.439	-0.229	0.038	0.086	0.077
Cosine_100	0.405	-0.179	0.04	0.081	0.07
Cosine_200	0.356	-0.153	0.054	0.086	0.067
Cosine_400	0.356	-0.153	0.054	0.086	0.067
Cosine_600	0.356	-0.153	0.054	0.086	0.067

Table 6: Statistics of the validation of spatial filter with Rio model.

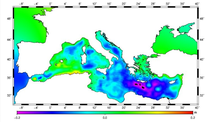


Figure 6: Validation of Wiener 600 km field with SMDT model

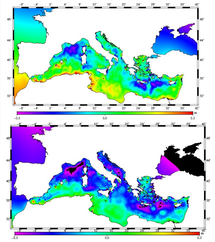


Figure 8: Validation of FIR filtered field from WL levels 7_12 with Rio (top) and SMDT (bottom).

Table 8: Statistics of validation of FIR field with Rio and SMDT model.

MODEL	max	min	mean	rms	std
RIO	0.332	-0.701	0.007	0.076	0.076
SMDT	0.261	-0.838	-0.071	0.1	0.07

Conclusions

- Four spatial filters corresponding to five spatial scales, six DOT models through WL-MRA and one spectral bandpass FIR filter have been tested for the determination of mean DOT.
- All the aforementioned models have been validated against the Rio and SMDT model in the Mediterranean Sea.
- For the spatial filters, the Wiener 600 km filtered field presents the best results with the Rio DOT, with a std of 6.5 cm and 5.8 cm against the SMDT DOT. A good agreement with both models has been achieved with the FIR along-track filter, giving a std of 7.0 cm with SMDT and 7.6 cm with Rio. Spectral filtering with WL-MRA provides worse results with a std of 17 cm with the SMDT model and 17.7 cm with Rio.

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