Mean dynamic ocean topography determination from recent GOCE/GRACE geopotential models and satellite altimetry data

A. Katsadourou, G.S. Vergos and I.N. Tziavos

Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Univ. Box 440, 54 124, Greece

Introduction

The evolution of space geodesy led to the establishment of modern satellite missions and new methods of determining and tracking homogeneously the Earth's gravity field, thus providing a unique outlook of its spectrum and components, both in continental and marine areas, with increased accuracy at a global scale.

The satellite missions of CHAMP, GRACE and GOCE, have as their main objectives the high accuracy and global representation of the Earth's gravity field. Sea level variations and the determination of the sea surface topography outline in effect the interrelation of Geodesy and Oceanography. The latter is to be modeled in this study with the combination of satellite altimetry and GOCE data.

For the determination of the Dynamic Ocean Topography (DOT) in two study areas, located in the North Atlantic Ocean and the Mediterranean Sea, the GOCE/GRACE GOCO02S GGM and the MSS from DTU10 were combined. Furthermore, in order to evaluate the estimated MDOTC field the differences with the MDOT from DTU10 are determined.

The combination of models with different spatial resolution and accuracy requires the application of statistical tests as well as linear filters. Two statistical tests were applied (2σ and 3σ test) in order to account for blunders. In all such applications, filtering is needed in order to account for the observation noise, as well as the geoid omission and commission errors. Therefore, linear isotropic, filters have been applied namely boxcar, cosine arch and Gaussian filter.

The best solutions refer to filters with spatial wavelengths set to 400km and 550km (200km and 275km half wavelength, respectively) for the North Atlantic and 600km and 780km (300km and 390km half wavelength, respectively) for the Mediterranean Sea. From the so-determined MDOT models the surface geostrophic current velocities and the ocean circulation are studied for both areas.

Objectives

The main objective of this work was to determine a DOT model named herein MDOTC (Mean Dynamic Ocean Topography Combined) by combining the MSS from DTU10 and the geoid heights from GOCO02S for the North Atlantic Ocean and the Mediterranean basin.

The data processing aimed to the optimization of the solution through the implementation of statistical tests and linear filters. The filtering operations were carried out at various cut-off wavelengths (filter widths), so that the filter performance could be tested in the resulting DOT model. The validation is performed through comparisons with the DTU2010 DOT model.

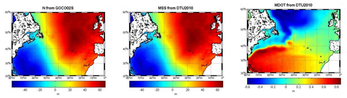
Finally, an estimation of the surface geostrophic currents, calculated according to the steady-state geostrophic equations, is presented describing the ocean circulation and known ocean currents in both study areas.

GOCO02S and DTU10 data

GOCO02s presents a spherical harmonics expansion of the Earth's potential to a maximum degree $n_{max}=250$ employing (a) *7-years ITG-Grace2010s data (d/o 180), (b) 8-months of GOCE Satellite Gravity Gradiometry (SGG) observations, (d/o 250), (c) 12-months of GOCE satellite-to-satellite tracking in high-low mode (SST-hl), (d/o 110), (d) 8-years of CHAMP data, and (d/o 120) and (f) 5-years of SLR data from 5 satellites (d/o 5).*

DTU10MSS is an improvement of the DNSC08 model determined by the DTU Space Institute. This estimation was derived from 17 years of altimetry data (1993 to 2009) and has been mapped with a spatial resolution of 1'x1'. The accumulation of more and better data, the improvement of the prediction methods, the filtering and sophisticated data processing as well as the use of a high-resolution and high-accuracy reference model (EGM08) lead to the determination of DTU10MSS. Correspondingly, the **DTU10MDOT** model arising from the difference between the DTU10MSS and the EGM08 geoid model resulted with a spatial resolution of 1'x1' .

N, MSS and MDOT in North Atlantic Ocean



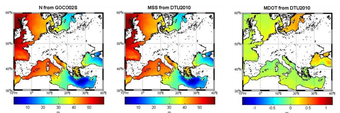
The **geoid** from GOCO02S in the of the **North Atlantic** Ocean [m]

The **MSS** from DTU10 in the of the **North Atlantic** Ocean [m]

The **MDOT** from DTU10 in the of the **North Atlantic** Ocean [m]

	max	min	mean	std
$N_{GOCO02S}$ [m]	66.895	-58.391	14.926	±37.840
$MSS_{DTU2010}$[m]	66.735	-57.494	15.029	±37.619
$MDOT_{DTU2010}$[m]	0.862	-0.614	0.146	±0.333

N, MSS and MDOT in Europe and the Mediterranean basin



The **geoid** from GOCO02S in **Europe and the Mediterranean basin** [m]

The **MSS** from DTU10 in **Europe and the Mediterranean basin** [m]

The **MDOT** from DTU10 in **Europe and the Mediterranean basin** [m]

	max	min	mean	std
$N_{GOCO02S}$ [m]	59.433	0.888	36.691	±13.198
$MSS_{DTU2010}$[m]	59.702	0.923	36.873	±13.032
$MDOT_{DTU2010}$[m]	1.174	-1.367	0.071	±0.156

MDOTC estimation and statistical tests results

The DOT can then be estimated as: $\zeta = \tilde{h}_{DTU2010-MSS} - N_{GOCO02S}$

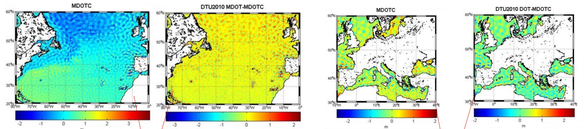
where, ζ is the DOT, N denotes the GOCO02s derived geoid height and $\tilde{h}$ the MSS. If in the above equation we consider: *(a) the geoid omission error (δN_L), arising from the fact that the used GGM to derive the geoid represents the geoid spectrum only up to some maximum degree and order $L=n_{max}$ and not to ∞, and (b) the geoid commission error (δ_L), arising from the propagation of the spherical harmonics errors to the geoid defined*, then we can re-write it as (N_L denoting the truncated contribution of the GGM):

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

Therefore, the estimation of the DOT needs to account for the unmodeled parts of the geoid still remaining in the DOT due to the limited representation offered by the GGM.

Having estimated this initial DOT, and in order to remove, or at least reduce, the influence of the δN_L and δ_L terms, some spatial filtering is needed. Moreover, in order to reduce blunders, mainly across the coastline from the such derived DOT, 2σ and 3σ tests are performed.

Initial results



The **MDOTC** in **North Atlantic** Ocean [m]

The **differences with the MDOT from DTU** in **North Atlantic** Ocean [m]

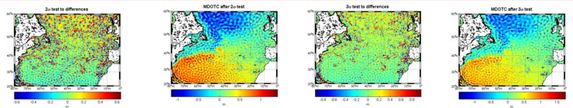
The **MDOTC** in **Europe and the Mediterranean basin** [m]

The **differences with the MDOT from DTU** in **Europe and the Mediterranean basin** [m]

	max	min	mean	std
$MDOT_{DTU2010}$ [m]	0.862	-0.614	0.146	±0.333
MDOTC [m]	3.957	-2.235	0.080	±0.529
$MDOT_{DTU2010}$-MDOTC [m]	2.280	-3.408	0.072	**±0.320**

	max	min	mean	std
$MDOT_{DTU2010}$ [m]	1.174	-1.367	0.071	±0.156
MDOTC [m]	2.061	-2.565	-0.015	±0.407
$MDOT_{DTU2010}$-MDOTC [m]	2.457	-2.084	0.099	**±0.307**

2σ and 3σ tests in differences and the new MDOTC field

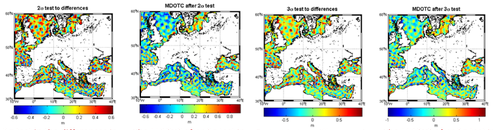


2σ test in the differences in **North Atlantic** Ocean [m]

The **MDOTC after 2σ** test in **North Atlantic** Ocean [m]

3σ test in the differences in **North Atlantic** Ocean [m]

The MDOTC after 3σ test in **North Atlantic** Ocean [m]



2σ test in the differences in **Europe and the Mediterranean basin** [m]

The MDOTC after 2σ test in **Europe and the Mediterranean basin** [m]

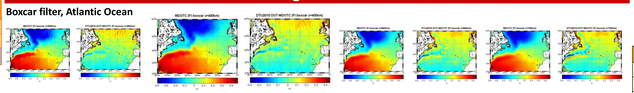
3σ test in the differences in **Europe and the Mediterranean basin** [m]

The MDOTC after 3σ test in **Europe and the Mediterranean basin** [m]

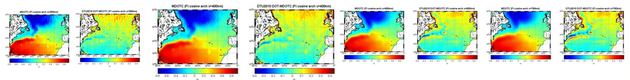
	Atlantic Ocean				Europe and Mediterranean Basin			
	max	min	mean	std	max	min	mean	std
$MDOT_{DTU2010}$ [m]	**0.862**	**-0.614**	**0.146**	**±0.333**	**1.174**	**-1.367**	**0.071**	**±0.156**
MDOTC [m]	**3.957**	**-2.235**	**0.080**	**±0.529**	**2.061**	**-2.565**	**-0.015**	**±0.407**
($MDOT_{DTU2010}$-MDOTC)[m]	**2.280**	**-3.408**	**0.072**	**±0.320**	**2.457**	**-2.084**	**0.099**	**±0.307**
2s test to ($MDOT_{DTU2010}$-MDOTC)[m]	0.640	-0.640	0.029	±0.238	0.612	-0.614	0.065	±0.268
MDTOC after 2s test [m]	**1.407**	**-1.173**	**0.152**	**±0.479**	**0.969**	**-0.713**	**0.023**	**±0.290**
($MDOT_{DTU2010}$-MDOTC) after 2s test [m]	**0.790**	**-0.727**	**0.055**	**±0.044**	**1.252**	**-1.381**	**0.039**	**±0.057**
3σ test to ($MDOT_{DTU2010}$-MDOTC)[m]	0.960	-0.957	0.037	±0.273	0.921	-0.917	0.084	±0.323
MDTOC after 3s test[m]	**1.753**	**-1.494**	**0.141**	**±0.501**	**1.127**	**-1.004**	**0.002**	**±0.342**
($MDOT_{DTU2010}$-MDOTC) after 3s test [m]	**1.029**	**-0.957**	**0.066**	**±0.063**	**1.315**	**-1.381**	**0.055**	**±0.064**

Atlantic Ocean—Filtering the MDOTC after 2σ test field

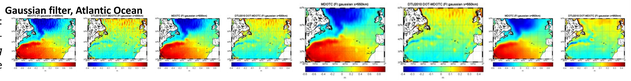
Boxcar filter, Atlantic Ocean



Cosine arch filter, Atlantic Ocean



Gaussian filter, Atlantic Ocean

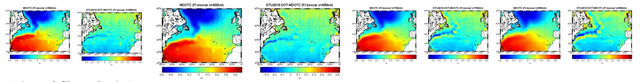


Boxcar (MDOTC) [m]						Cosine arch (MDOTC)[m]						Gaussian (MDOTC)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
300	0.946	-0.820	0.154	±0.419		300	0.946	-0.820	0.154	±0.419		400	1.022	-0.861	0.155	±0.421	
400	0.884	-0.769	0.154	±0.416		400	0.884	-0.769	0.154	±0.416		500	0.934	-0.800	0.154	±0.418	
550	0.848	-0.754	0.153	±0.412		600	0.844	-0.740	0.152	±0.411		550	0.904	-0.782	0.154	±0.417	
700	0.837	-0.737	0.152	±0.408		750	0.830	-0.741	0.151	±0.407		950	0.838	-0.729	0.153	±0.411	

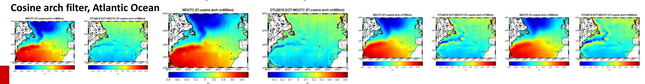
Boxcar (differences)[m]						Cosine arch (differences)[m]						Gaussian (differences)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
300	0.448	-0.226	0.026	±0.083	0.674	300	0.448	-0.226	0.026	±0.083	0.674	400	0.453	-0.278	0.026	±0.088	0.731
400	**0.469**	**-0.251**	**0.027**	**±0.081**	**0.720**	**400**	**0.469**	**-0.251**	**0.027**	**±0.081**	**0.720**	500	0.447	-0.203	0.026	±0.081	0.650
550	0.437	-0.299	0.028	±0.083	0.736	600	0.426	-0.309	0.028	±0.084	0.735	**550**	**0.447**	**-0.199**	**0.027**	**±0.080**	**0.646**
700	0.410	-0.326	0.029	±0.087	0.736	750	0.400	-0.342	0.029	±0.089	0.742	950	0.425	-0.273	0.028	±0.081	0.698

Atlantic Ocean—Filtering the MDOTC after 3σ test field

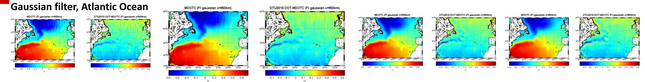
Boxcar filter, Atlantic Ocean



Cosine arch filter, Atlantic Ocean



Gaussian filter, Atlantic Ocean

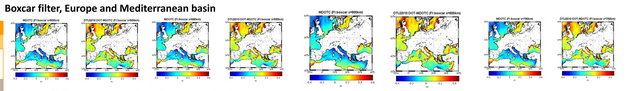


Boxcar (MDOTC) [m]						Cosine arch (MDOTC)[m]						Gaussian (MDOTC)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
350	0.940	-0.795	0.149	±0.423		350	0.940	-0.795	0.149	±0.423		500	1.153	-0.800	0.149	0.423	
400	0.929	-0.779	0.149	±0.421		400	0.929	-0.779	0.149	±0.421		650	1.013	-0.758	0.149	0.420	
700	0.863	-0.747	0.146	±0.414		700	0.863	-0.747	0.146	±0.414		800	0.939	-0.742	0.148	0.418	
900	0.831	-0.733	0.144	±0.409		900	0.831	-0.733	0.144	±0.409		950	0.895	-0.735	0.147	0.416	

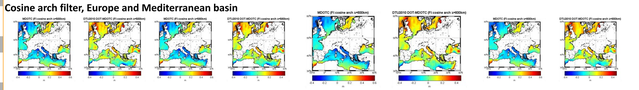
Boxcar (differences)[m]						Cosine arch (differences)[m]						Gaussian (differences)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
350	0.687	-0.280	0.031	±0.089	0.967	350	0.687	-0.280	0.031	±0.089	0.967	500	0.694	-0.438	0.031	0.089	1.132
400	**0.677**	**-0.256**	**0.032**	**±0.088**	**0.933**	**400**	**0.677**	**-0.256**	**0.032**	**±0.088**	**0.933**	**650**	**0.646**	**-0.298**	**0.032**	**0.086**	**0.944**
700	0.531	-0.333	0.035	±0.095	0.864	700	0.531	-0.333	0.035	±0.095	0.864	800	0.617	-0.243	0.033	0.087	0.860
900	0.456	-0.355	0.036	±0.101	0.811	900	0.456	-0.355	0.036	±0.101	0.811	950	0.582	-0.272	0.034	0.089	0.854

Europe and Mediterranean basin—Filtering the MDOTC after 2σ test field

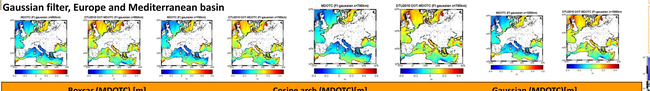
Boxcar filter, Europe and Mediterranean basin



Cosine arch filter, Europe and Mediterranean basin



Gaussian filter, Europe and Mediterranean basin

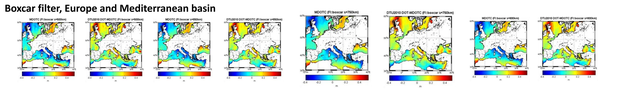


Boxcar (MDOTC) [m]						Cosine arch (MDOTC)[m]						Gaussian (MDOTC)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
500	0.495	-0.32	-0.002	±0.134		500	0.495	-0.32	-0.002	±0.134		650	0.520	-0.339	0.000	0.133	
580	0.467	-0.295	-0.003	±0.132		580	0.467	-0.295	-0.003	±0.132		700	0.495	-0.329	0.000	0.133	
600	0.461	-0.286	-0.004	±0.131		600	0.461	-0.286	-0.004	±0.131		780	0.470	-0.314	-0.001	0.131	
780	0.472	-0.258	-0.006	±0.128		800	0.480	-0.260	-0.006	0.128		1000	0.460	-0.280	-0.003	0.129	

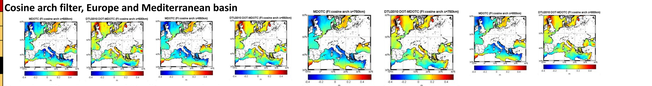
Boxcar (differences)[m]						Cosine arch (differences)[m]						Gaussian (differences)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
500	0.387	-0.333	0.086	0.098	0.720	500	0.387	-0.333	0.086	0.098	0.720	650	0.413	-0.318	0.084	0.094	0.731
580	0.374	-0.308	0.087	0.098	0.682	580	0.374	-0.308	0.087	0.098	0.682	700	0.403	0.311	0.084	0.094	0.714
600	**0.374**	**-0.302**	**0.088**	**0.098**	**0.676**	**600**	**0.374**	**-0.302**	**0.088**	**0.098**	**0.676**	**780**	0.394	-0.311	0.085	0.093	0.705
780	0.405	-0.336	0.090	0.099	0.741	800	0.408	-0.344	0.090	0.099	0.752	1000	0.386	-0.301	0.087	0.094	0.687

Europe and Mediterranean basin—Filtering the MDOTC after 3σ test field

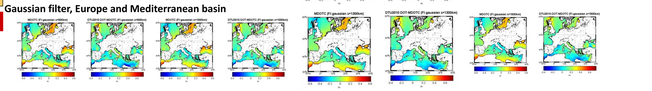
Boxcar filter, Europe and Mediterranean basin



Cosine arch filter, Europe and Mediterranean basin



Gaussian filter, Europe and Mediterranean basin



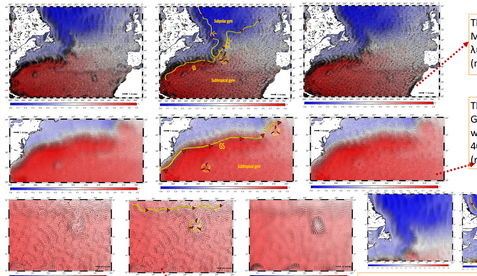
Boxcar (MDOTC) [m]						Cosine arch (MDOTC)[m]						Gaussian (MDOTC)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
500	0.495	-0.32	-0.002	±0.134		500	0.495	-0.32	-0.002	±0.134		650	0.520	-0.339	0.000	0.133	
580	0.467	-0.295	-0.003	±0.132		580	0.467	-0.295	-0.003	±0.132		700	0.495	-0.329	0.000	0.133	
600	0.461	-0.286	-0.004	±0.131		600	0.461	-0.286	-0.004	±0.131		780	0.470	-0.314	-0.001	0.131	
780	0.472	-0.258	-0.006	±0.128		800	0.480	-0.260	-0.006	0.128		1000	0.460	-0.280	-0.003	0.129	

Boxcar (differences)[m]						Cosine arch (differences)[m]						Gaussian (differences)[m]					
λ(km)	max	min	mean	std		λ(km)	max	min	mean	std		λ(km)	max	min	mean	std	
500	0.387	-0.333	0.086	0.098	0.720	500	0.387	-0.333	0.086	0.098	0.720	650	0.413	-0.318	0.084	0.094	0.731
580	0.374	-0.308	0.087	0.098	0.682	580	0.374	-0.308	0.087	0.098	0.682	700	0.403	0.311	0.084	0.094	0.714
600	**0.374**	**-0.302**	**0.088**	**0.098**	**0.676**	**600**	**0.374**	**-0.302**	**0.088**	**0.098**	**0.676**	**780**	0.394	-0.311	0.085	0.093	0.705
780	0.405	-0.336	0.090	0.099	0.741	800	0.408	-0.344	0.090	0.099	0.752	1000	0.386	-0.301	0.087	0.094	0.687

Surface ocean circulation in the areas

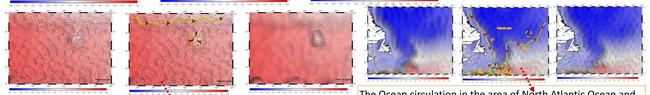
Having estimated the best filtered MDOTC after 2σ test, then, under the assumption of geostrophic flow the two components of the surface geostrophic currents can be determined in terms of the DOT as:

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



The ocean Circulation in North Atlantic. MDOTC field after filtering with boxcar λ=400km (left), cosine arch λ=400km (middle) and Gaussian λ=550km (right).

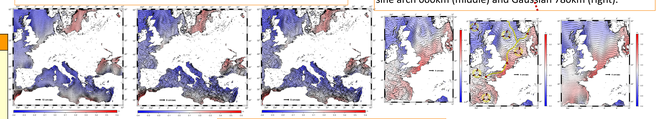
The Ocean circulation in the area of the Gulf Stream. MDOTC field after filtering with boxcar 400km (left), cosine arch 400km (middle) and Gaussian 550km (right).



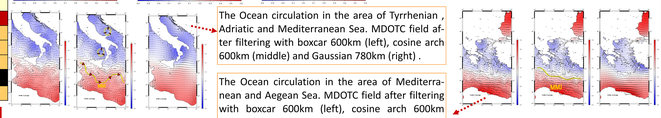
The Ocean circulation in a part of the Subtropical gyre. MDOTC field after filtering with boxcar 400km (left), cosine arch 400km (middle) and Gaussian 550km (right).

The Ocean circulation in the area of North Atlantic Ocean and the Subpolar gyre. MDOTC field after filtering with boxcar 400km (left), cosine arch 400km (middle) and Gaussian 550km (right).

The Ocean circulation in the area of Mediterranean and Europe. MDOTC field after filtering with boxcar 600km (left), cosine arch 600km (middle) and Gaussian 780km (right).



The Ocean circulation in the area of North Sea and Bay of Biscay. MDOTC field after filtering with boxcar 600km (left), cosine arch 600km (middle) and Gaussian 780km (right).



The Ocean circulation in the area of Tyrrhenian , Adriatic and Mediterranean Sea. MDOTC field after filtering with boxcar 600km (left), cosine arch 600km (middle) and Gaussian 780km (right) .

The Ocean circulation in the area of Mediterranean and Aegean Sea. MDOTC field after filtering with boxcar 600km (left), cosine arch 600km (middle) and Gaussian 780km (right) .

As indicated in the above Figures, the boxcar and cosine arch filtered MDOTC fields depict, with more detail, the ocean circulation compared to the Gaussian one. Although the latter represents the general information of ocean circulation it does not however show the same detail as the other two filters for both areas under study. This is mostly due to the removal of signal after the filtering process with the Gaussian filter .

Conclusions

A method to estimate the MDOTC based on an MSS model and a geoid model is presented. From the initial results obtained, of main importance is the implementation of statistical tests and filters in order to reduce blunders as well as white noise, omission and commission errors. By evaluating the results acquired, it can be concluded that the procedure followed provides good MDOT estimates as far as the differences to available MDOT global models are concerned. Furthermore, by using this MDOT estimation it was possible to study the ocean circulation and the current velocities of the two areas under study and identify the most important currents but also eddies and small cyclones and anticyclones for both regions.

EGU General Assembly, Session G4.2 – "Satellite Gravimetry: GOCE, GRACE and Future Gravity Missions" – EGU2013-2288 – Z45
April 07-12 2013, Vienna – Austria

The GOCESeaComb Project is funded by the European Space Agency within its Scientific Experiment Development Program (PRODEX) (Contract 4000106380).