External calibration/validation of ESA' s GOCE mission and contribution to DOT and SLA determination using a stochastic approach - The GOCESeaComb Project

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Introduction and Problems

Monitoring the Earth's gravity field both over marine and continental regions has been the focus of extensive geodetic research during the past decades and in the recent years has considerably increased due to the recent gravity-field dedicated satellite missions. With the missions of CHAMP and GRACE setting the path, the latest ESA mission of GOCE is offering new opportunities for improved insights into the Earth's gravity field and geoid, while the synergistic use of geodetic and oceanographic data are promising improved representations of the ocean circulation and the sea level variations mechanisms.

Moreover, the combination of GOCE-type high-quality and accuracy gravity field models with altimetric observations from ENVISAT, ERS1/2 and Jason1/2 missions, offer new opportunities for the determination of the marine geoid, vertical datum unification, as well as the introduction of a global vertical datum and the determination of dynamic ocean topography (DOT) modeling in different scales.

The present work summarizes the objectives of the **GOCESeaComb** project funded by ESA in the frame of the PRODEX program and the work carried out thus far. The key points in studies to determine rigorously stationary components of the gravity field (e.g., geoid) and quasi- or non-stationary constituents (e.g., DOT, time-varying DOT and steric and eustatic sea level variations), are:

a) the utilization of calibrated and validated input data,

b) the investigation of the spectral content of the input data, and

c) the development of data optimal combination methods, considering the statistical behavior of the input observations, towards the achievement of high-quality and accuracy predictions.

Given the above, we outline the initial processing strategy to be followed, the GOCE/GRACE Global Geopotential Models (GGMs) to be used along with their pre-processing, and, finally, the local gravity and GPS/Leveling data that will be employed for validation.

Moreover, the DOT and SLA determination methodologies are outlined along with the heterogeneous data combination strategy.

Some first results on the investigation of the GOCE/GRACE GGM spectral content are reported as well as their validation against the local data. To this respect, the GGM absolute and relative accuracies on geoid heights are determined in order to investigate the accuracy achieved by the GGMs, the improvement brought by GOCE data in modelling the long- and medium-wavelengths of the gravity field spectrum and, finally, the accuracy that can be reached when GPS/Levelling is utilized for the determination of orthometric heights.

GOCESeaComb Objectives

The main objective of the **GOCESeaComb** project is related to the exploitation of data from ESA's GOCE, ENVISAT and ERS1/2 missions towards the modeling and improved understanding of Earth Observations parameters as the geoid, sea level and DOT in the Mediterranean Sea.

To reach the main goal of the project, several sub-objectives have been identified, given that the entire study can be broken-down in the following three major steps:

- *Study of data prerequisites and methodologies development*,
- *collection, validation and processing of heterogeneous data and*
- *optimal combination of the afore mentioned data for gravity field multi-resolution representation, ocean circulation modeling and sea level variations determination.*

Data prerequisites and area under study

The entire Mediterranean Basin has been selected for the project experiments. The Mediterranean Sea may be characterized as a "natural laboratory" for geosciences, which is justified by the plurality of phenomena and processes, the alternating morphology and the temporal variations found.

The data collected and to be used for GOCE validation, DOT and SLA determination have already been pre-processed and refer to:

a) Local gravity anomalies and collocated GPS/Leveling observations over Greece.

All gravity data have been referred to GRS80/IGSN71 and refer to the geoid (free-air reduced). A collocation-based blunder detection and removal test has been applied to remove blunders.

The GPS/Leveling data refer to observations over trigonometric BMs covering continental Greece and the islands. All data refer to GRS80 and the TF system.

b) Satellite altimetry data from ERS1, ERS2, Jason-1, Jason-2 and ENVISAT missions

Uniform geophysical corrections, all orbits readjusted to GDR-D Jason-2 orbital altitude.

c) GOCE, GRACE, GOCE/GRACE and combined static GGMs

All have been referred to the TF system while the GRS80 ellipsoid has been used as a normal field.

d) GRACE monthly gravity fields in the form of GGMs

GFZ R5 monthly models have been used with the DDK1 smoothing filter applied.

GOCE GGM validation

The first methodology aims to study the spectral content of the GOCE-based GGMs through their *a) degree and error degree variances and b) the evaluation of anomaly differences w.r.t. EGM2008.*

The second approach will be based on the evaluation of the GOCE-based GGM contribution to gravity anomalies and geoid heights through comparisons with *a) local gravity data and b) local GPS/Leveling geoid heights at collocated BMs.*

The third approach will be based on the spectral evaluation of the GGM content on gravity anomalies employing *a) 2D-FFT transforms and b) wavelet transforms*

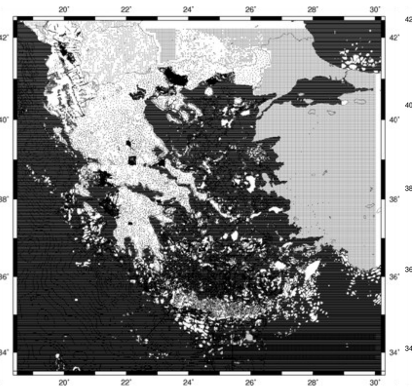
All approaches aim to come to some conclusions on the power of the specific bands that GOCE aims at, i.e., those between d/o 60 and 250. The tentative list of GOCE, GOCE/GRACE and combined GGMs is provided in the Table, while new releases that will emerge during the progress of the project will be incorporated as well.

As far as the degree-variances and error degree-variances concept is concerned, two approaches will be followed. The first one will use degree variances and error degree variances from the CHAMP-only, GRACE-only and GOCE-only GGMs in order to determine the GGM signal power, error, rms signal power and rms signal error by degree and cumulatively. The second approach will focus on the determination of the differences between coefficients from CHAMP-only, GRACE-only and GOCE-only GGMs to the coefficients provided by EGM008 as reference.

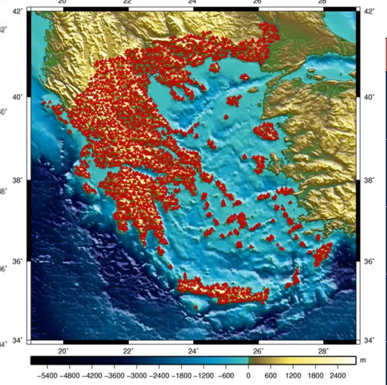
For the comparison with local data, analytic evaluation of various GGM cut-off frequencies will be performed in order to investigate their agreement with the available GPS/Levelling geoid heights. The evaluation with local gravity data refers to the reduction the GGMs provide in order to assess their performance in a scenario that a remove-compute-restore procedure would be followed for geoid determination.

As far as the validation of the spectral content of GOCE data is concerned, this will be investigated via a wavelet-based and FFT-based multi-resolution analysis of GOCE GGMs.

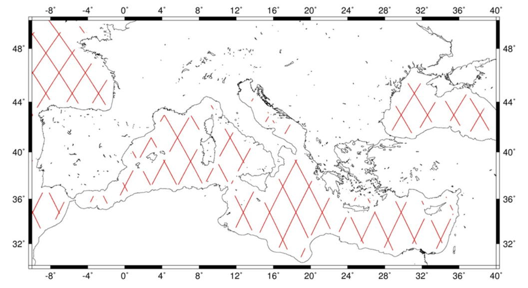
The spectral content of the GOCE-only, GOCE/GRACE, combined GGMs and the local gravity data, will be analyzed both with wavelet-based techniques at various levels of decomposition, and classic FFT-based techniques by employing 2D-wavelet and 2D-FFT transforms, respectively.



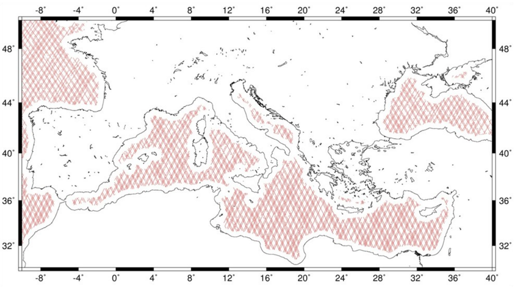
Local gravity data to be used for GOCE validation



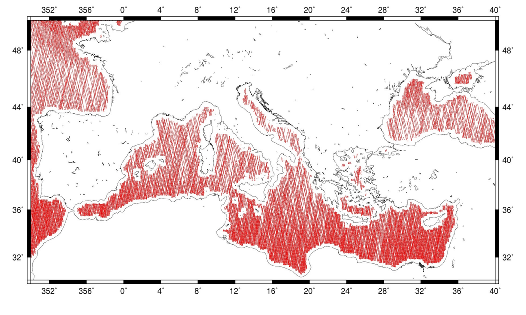
GPS/Leveling data to be used for GOCE validation



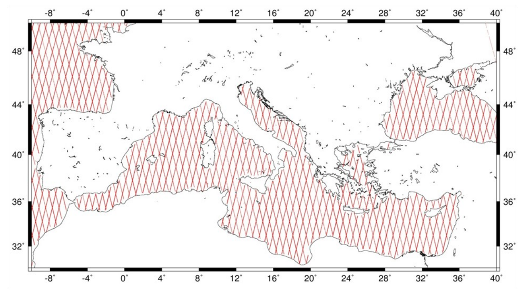
Jason1/2 ERM data in the area under study



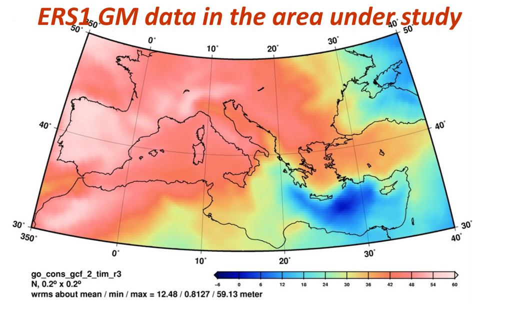
Jason-1 GM data in the area under study



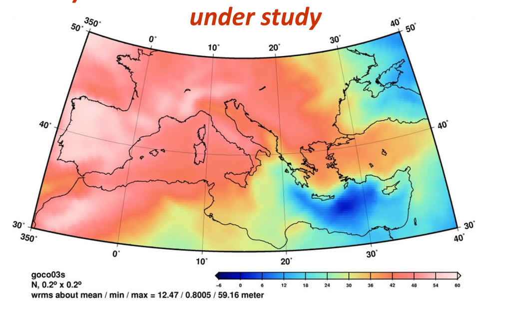
ERS1 GM data in the area under study



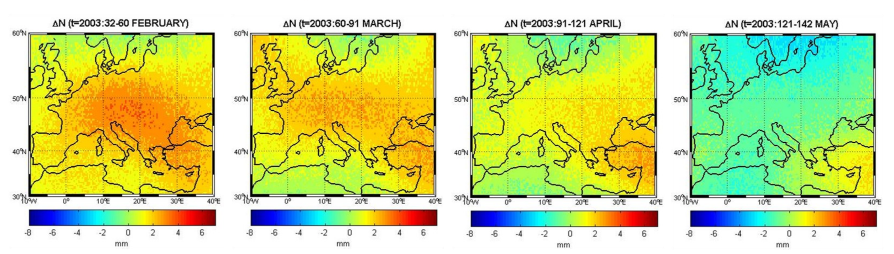
ERS1/2 and ENVISAT ERM data in the area under study



Geoid heights from GO-TIM-T3 (n_{max}=250) in the area under study



Geoid heights from GOCO03s (n_{max}=250) in the area under study



Geoid height variations for four consecutive months form the monthly GRACE models

Models	n_{max}	*Data*	*Reference*
EGM2008	2190	S(GRACE), G, A	Pavlis et al., 2008
EIGEN-51C	359	S(GRACE, CHAMP), G, A	Bruinsma et al, 2010
EIGEN-6C	1420	S(GOCE, GRACE, LAGEOS), G, A	Förste et al, 2011
EIGEN-6S	240	S(GOCE, GRACE, LAGEOS)	Förste et al, 2011
EIGEN-6C2	1949	S(GOCE, GRACE, LAGEOS), G, A	Förste et al, 2012
GOCO01S	224	S(GOCE, GRACE)	Pail et al., 2010
GOCO02S	250	S(GOCE, GRACE, CHAMP, SLR)	Goiginger et al., 2011
GOCO03S	250	S(GOCE, GRACE, CHAMP, SLR)	Mayer-Gürr, et al. 2012
ITG-GRACE2010S	180	S(GRACE)	Mayer-Gürr et al., 2010
GIF48A	360	S(GRACE), G, A	Ries, et al. 2011
DIR_R1	240	S(GOCE + background model EIGEN-51C)	Bruinsma et al., 2010
DIR_R2	240	S(GOCE+ background model ITG-GRACE2010S)	Bruinsma et al., 2010
DIR_R3	240	S(GOCE, GRACE, LAGEOS)	Bruinsma et al., 2010
TIM_R1	224	S(GOCE)	Pail et al., 2010
TIM_R2	250	S(GOCE)	Pail et al., 2011
TIM_R3	250	S(GOCE)	Pail et al., 2011
SPW_R1	210	S(GOCE)	Migliaccio et al., 2010
SPW_R2	240	S(GOCE)	Migliaccio et al, 2011
DGM-1S	250	S(GRACE, GOCE)	Hashemi et al., 2012

(Data: S = Satellite Tracking Data, G = Gravity Data, A = Altimetry Data
GRACE (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment)
CHAMP (**CHA**llenging **M**ini-satellite **P**ayload)
GOCE (**G**ravity field and steady state **O**cean **C**irculation **E**xplorer)
LAGEOS (**La**ser G**EO**dynamics **S**atellite)
SLR (**S**atellite **L**aser **R**anking)

GPS/Leveling geoid height differences at the network of 1542 BMs over Greece for the various GGMs. Unit [m].

MODEL		60	80	140	160	180	220	240	250	360	1420	1949	2159
EGM08	mean	0.349	0.036	-0.297	-0.284	-0.288	-0.318	-0.332	-0.343	-0.331	-0.375	-0.374	-0.374
	std	1.733	1.387	0.724	0.724	0.642	0.529	0.497	0.472	0.369	0.152	0.142	0.141
EIGEN-51C	mean	0.351	0.045	-0.292	-0.273	-0.275	-0.308			0.309			
(n_{max}=359)	std	1.734	1.388	0.709	0.724	0.644	0.537			0.403			
EIGEN-6C	mean	0.350	0.042	-0.304	-0.298	-0.303	-0.337		-0.361	-0.349	-0.394		
	std	1.733	1.386	0.714	0.727	0.651	0.524		0.478	0.379	0.161		
EIGEN-6C2	mean	0.350	0.041	-0.303	-0.296	-0.302	-0.356		-0.356	-0.344	-0.389	-0.388	
	std	1.733	1.386	0.715	0.727	0.651	0.525		0.475	0.374	0.149	0.137	
EIGEN-6S	mean	0.350	0.042	-0.302	-0.300	-0.307	-0.344	-0.358					
	std	1.733	1.386	0.716	0.722	0.646	0.508	0.512					
ITG-GRACE	mean	0.349	0.041	-0.304	-0.308	-0.299							
2010S	std	1.734	1.386	0.716	0.692	0.690							
DGM-1S	mean	0.349	0.041	-0.304	-0.298	-0.303	-0.341	-0.363					
	std	1.734	1.386	0.716	0.720	0.647	0.527	0.515					
GOCO01S	mean	0.349	0.041	-0.303	-0.301	-0.305	-0.341						
(n_{max}=224)	std	1.734	1.386	0.716	0.714	0.661	0.547						
GOCO02S	mean	0.349	0.041	-0.305	-0.300	-0.305	-0.341		-0.358				
	std	1.734	1.386	0.716	0.718	0.643	0.522		0.501				
GOCO03S	mean	0.349	0.041	-0.304	-0.299	-0.303	-0.335		-0.353				
	std	1.733	1.386	0.717	0.717	0.645	0.510		0.496				

MODEL		60	80	140	160	180	220	240	250	360	1420	1949	2159
GO-DIR-R1	mean	0.347	0.042	-0.297	-0.292	-0.298	-0.330	-0.344					
	std	1.733	1.385	0.714	0.725	0.656	0.535	0.507					
GO-DIR-R2	mean	0.351	0.043	-0.302	-0.298	-0.306	-0.347	-0.357					
	std	1.734	1.386	0.713	0.719	0.644	0.505	0.510					
GO-DIR-R3	mean	0.350	0.042	-0.302	-0.295	-0.301	-0.341	-0.352					
	std	1.734	1.386	0.716	0.722	0.645	0.496	0.482					
GO-TIM-R1	mean	0.343	0.037	-0.307	-0.305	-0.310	0.348						
(n_{max}=224)	std	1.734	1.383	0.716	0.720	0.663	0.544						
GO-TIM-R2	mean	0.345	0.038	-0.305	-0.301	-0.306	-0.345		-0.360				
	std	1.733	1.384	0.716	0.720	0.644	0.525		0.502				
GO-TIM-R3	mean	0.347	0.010	-0.304	-0.298	-0.303	-0.337		-0.356				
	std	1.734	1.386	0.718	0.720	0.647	0.516		0.494				
GO-SPW-R1	mean	0.345	0.042	-0.300	-0.297	-0.303	-0.371						
(n_{max}=210)	std	1.735	1.388	0.714	0.725	0.675	0.586						
GO-SPW-R2	mean	0.338	0.029	-0.312	-0.309	-0.315	-0.347	-0.345					
	std	1.732	1.384	0.716	0.719	0.642	0.539	0.537					

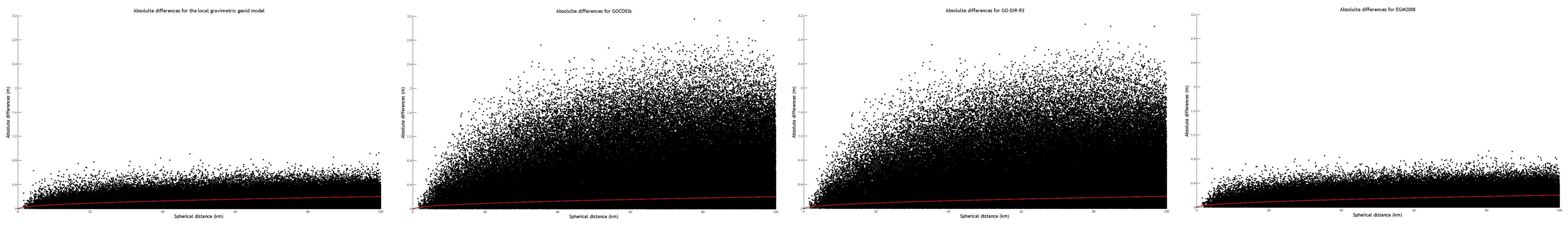
N^{LSC}	max	min	mean	rms	std
	0.119	-1.033	-0.392	±0.416	0.140

From the GPS/Leveling geoid height differences with the available GGMs, the improvement offered by the GOCE-based Release3 modes, w.r.t. the earlier releases is evident. For the GOCO models, the std of the differences drops by ~5 cm between R1 and R3, while the improvement is at the same level for the TIM models. The improvement for the DIR is marginal, at the 2 cm level, given that its R1 model provided an accuracy equal to that of the R2 for GOCO and TIM. This is due to the a-priori information from EIGEN-5C used in the development of GO-DIR-R1.

The performance of the GOCE/GRACE models is equivalent to that of EGM2008, when truncated to a d/o 250, being inferior by just 1-2 cm for the latest, R3, releases. This shows the great improvement offered by the inclusion of more GOCE data, especially in view of the fact that EGM2008 contains detailed local gravity data over Greece even at that d/o.

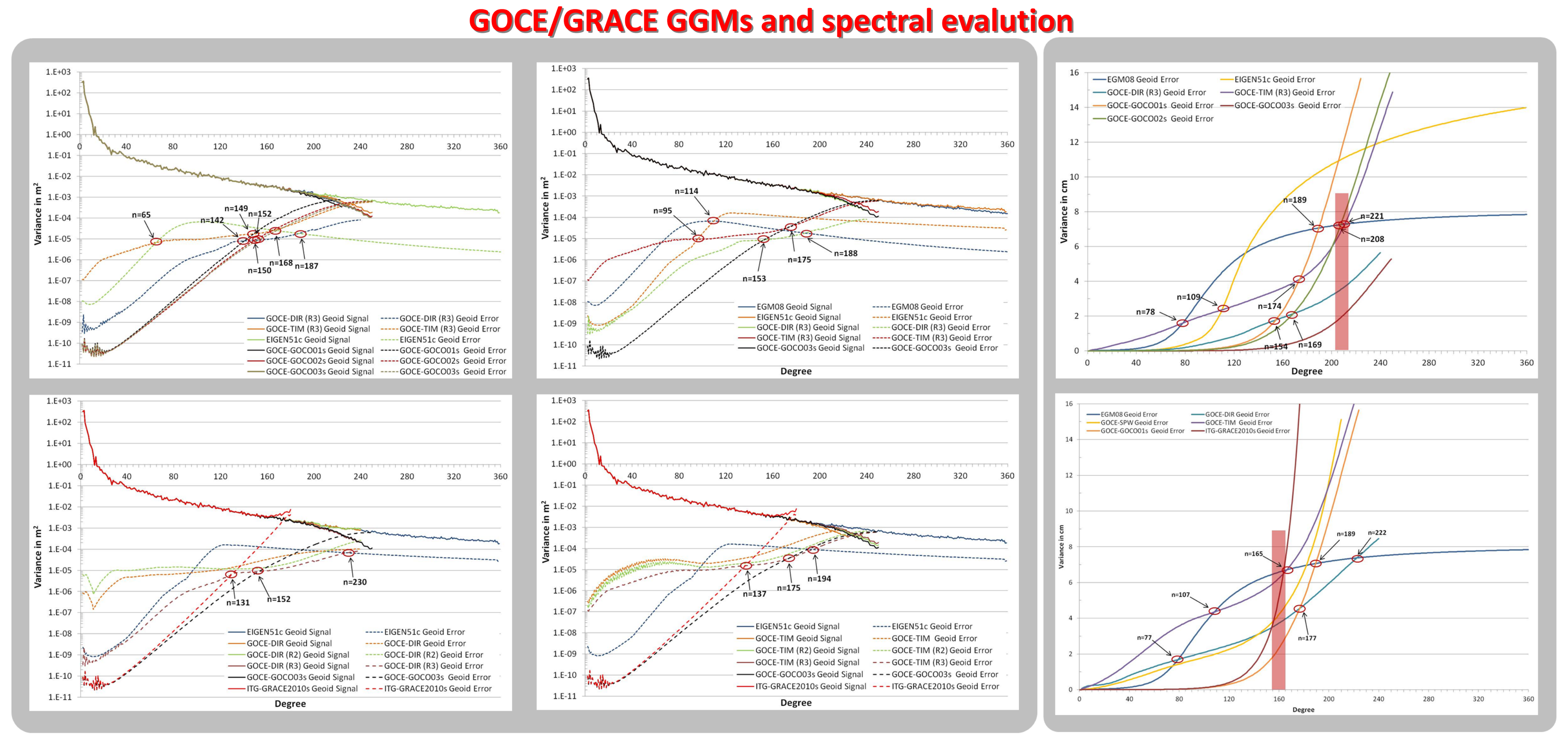
GOCO03s has a std of 49.6 cm to d/o 250, so considering the geoid omission error of 30.3 cm and the GOCO03s cumulative geoid error of 15.5 cm an un-modeled error of ~36 cm remains. This may stem from the quality of, mainly, the orthometric heights within the HVD, which are known to be of low, yet unknown, accuracy. The same results are derived for the other combined GGMs, such as GO-DIR-R3 which has a std with the GPS/Leveling geoid heights at 48.2 cm (d/o 240), with a geoid omission error of 32.1 and a formal cumulative geoid error of only 5.6 cm. The latter signals that the formal error degree variances are quite optimistic, so that proper error modeling would require external information for validation.

From the relative differences and short baselines, up to 10 km, the contribution of local gravity data to the LSC-based geoid is clear, since it is better by 2 ppm compared to EGM2008, EIGEN6C and EIGEN6C2. As expected the GOCE and GOCE/GRACE GGMs have inferior performance by as much as 13-15 ppm compared to the local model and high degree GGMs. This is resolved for longer baselines, e.g., greater than 40-50 km, where the satellite only GGMs provide an error close to the 1 cm level, in the relative sense.



Absolute differences ΔN^{GPS}-ΔN^{grav} and ΔN^{GPS}-ΔN^{GGM} for baselines up to 100 km (200,000 baselines). The red curved line in all figures represents the error model $\sigma_{\Delta N}=\sigma_0 S^{1/2}$ with σ_0=2cm/km$^{1/2}$ and S the spherical distance. The (%) denote the number of baselines with errors smaller than $\sigma_{\Delta N}$.

GOCE/GRACE GGMs and spectral evalution



Degree and error degree variances of the TIM, DIR and GOCO models (R1, R2, R3) (left) and the respective cumulative geoid errors (right)

In terms of the cumulative geoid errors, the improvement of the rel. 3 models is evident. Comparing GOCO-01S, 02S, and 03S, each reaches the 1 cm geoid error to d/o 143, 159 and 190 respectively. It is clear that the inclusion of more GOCE data in the rel. 3 models, offers a significant boost to the reduction of the formal geoid errors. On the other hand, this improvement by 3 orders in the total cumulative geoid error of the GGMs to their maximum d/o of expansion, e.g., from 15.6 cm 5.4 cm between GOCO01S and GOCO03S, is

GOCO03s provides the overall best results with smaller errors up to degree n~175 compared to the EGM08 and n~175 compared to EGM08. Its predecessors GOCO01S and GOCO02S were better than EGM08 to degree n~153 and n~166 respectively.

The strong V-shape in both the GOCE-DIR and GOCE-DIR-R2 models is due to GRACE-GOCE combination. This is not shown in the rel. 3 DIR model, which has smaller formal errors, compared to the earlier releases, by 2-3 orders of magnitude. GOCE-DIR-R3 is better than EGM08 to degree n~188.

The R1 and R2 GOCE-only GGMs are better than GRACE-based ones above n~140 due to the few GOCE observations used. Note that most models are based on a few months of GOCE data contrary to ~7 years of GRACE observations. This situation changes completely with the R3 models which incorporate about 1.5 yrs of GOCE data. The DIR-R3 error spectrum is improved by ~4 order of magnitude compared to R1 and R2, while the TIM-R3 one by about 1-2 order of magnitude.

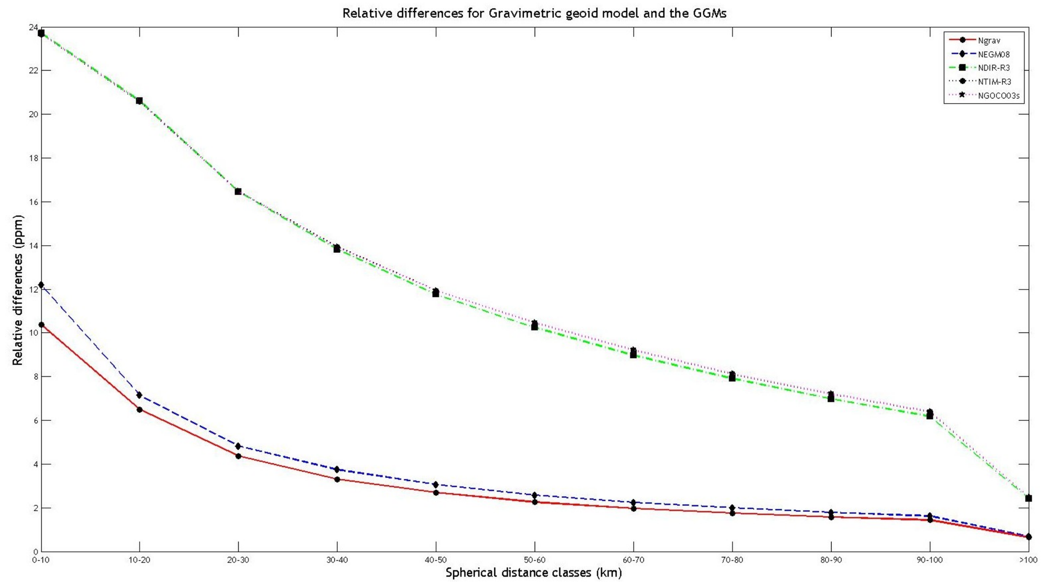
With more GOCE observations used, their influence is significant especially when combined with GRACE data. This is evident when comparing the ITG-GRACE2010s model and GOCO02s, where GOCE data in the latter boost its error degree variances to be smaller than those of EGM08 up to degree n=175 contrary to n=142 for the former.

From the GOCE-only GGMs, it is concluded that the R3 versions of GOCE-TIM, GOCE-DIR and GOCO are better than the first and second releases, since they have smaller errors to higher degrees. This is due to the use of more GOCE data (~1.5 yrs) in the R3 releases and as far as the DIR models are concerned, the use of ITG-GRACE2010s as a reference for the R3 model contrary to EIGEN-51c for the R1 one.

Statistics of the original free-air gravity anomalies over Greece, contribution of the various GGMs (normal lettering) and reduced fields (italics). Unit [mGal]

GOCE/GRACE GGMs effects on local gravity data [mGal]					
max	min	mean	rms	std	
269.927	-236.099	-22.731	77.522	74.114	Δgf (original)
213.982	-236.870	-22.451	77.582	74.263	EGM08 (2159)
92.084	*-147.407*	*-0.280*	*5.871*	*5.864*	Δg red EGM2008
117.056	-192.911	-18.461	73.346	70.985	EGM08 (250)
210.259	*-138.388*	*-4.270*	*27.074*	*26.735*	Δg red EGM2008
117.929	-189.708	-18.594	73.385	70.991	EIGEN-51C (250)
210.370	*-139.195*	*-4.136*	*27.054*	*26.736*	Δg red EIGEN51c
98.953	-180.089	-17.373	71.843	69.710	ITG-GRACE2010S (180)
251.906	*-147.804*	*-5.358*	*30.889*	*30.421*	Δg red ITG-GRACE2010s
97.867	-190.283	-17.821	72.728	70.511	GOCO01S (224)
228.526	*-137.327*	*-4.909*	*29.146*	*28.730*	Δg red GOCO01s
107.419	-193.351	-18.314	72.979	70.644	GOCO02S (250)
223.161	*-132.429*	*-4.416*	*27.869*	*27.517*	Δg red GOCO02s
107.499	-191.915	-18.312	73.027	70.694	GOCO03S (250)
224.651	*-132.057*	*-4.419*	*27.779*	*27.425*	Δg red GOCO03s

GOCE/GRACE GGMs effects on local gravity data [mGal]					
max	min	mean	rms	std	
113.186	-196.837	-18.479	73.373	71.008	GO-DIR (240)
216.119	*-136.974*	*-4.251*	*27.601*	*27.217*	Δg red GO-DIR
104.643	-193.634	-18.088	73.104	70.831	GO-DIR-R2 (220)
226.427	*-132.401*	*-4.463*	*28.755*	*28.378*	Δg red GO-DIR-R2
106.050	-190.976	-18.387	73.143	70.795	GO-DIR-R3 (240)
223.690	*-129.921*	*-4.344*	*28.096*	*27.758*	Δg red GO-DIR-R3
98.634	-190.849	-17.815	72.792	70.579	GO-TIM (224)
227.824	*-138.574*	*-4.915*	*29.148*	*28.731*	Δg red GO-TIM
107.867	-193.859	-18.333	73.032	70.694	GO-TIM-R2 (250)
222.635	*-132.988*	*-4.937*	*27.831*	*27.482*	Δg red GO-TIM-R2
109.486	-192.800	-18.385	73.158	70.810	GO-TIM-R3 (250)
223.574	*-133.430*	*-4.346*	*27.680*	*27.337*	Δg red GO-TIM-R3



Relative differences ΔN^{GPS}-ΔN^{grav} and ΔN^{GPS}-ΔN^{GGM} for baselines up to 100 km.

Conclusions

GOCESeaComb aims to evaluate the internal and external accuracy of GOCE, GOCE/GRACE and combined products in the form of GGMs.

The methodologies proposed will focus both in the space and the frequency domain in order to conclude on the improvement brought by GOCE to the medium frequencies of the gravity field spectrum.

The results from a first evaluation of the recent GOCE/GRACE GGMs has been presented, using collocated GPS and Levelling data for 1542 BMs and 294777 irregularly distributed free-air gravity anomalies.

From the results acquired, the improvement of incorporating more GOCE data in the GGMs is evident, ranging from 2 to 6 cm in terms of geoid height differences w.r.t. the GPS/Levelling data and the few mGal level when compared with the free-air gravity anomaly field. The latest (Release3) versions of the GOCE/GRACE GGMs manage to provide a 1 cm relative accuracy for baselines larger than 40-50 km.

The latest combined GGMs EIGEN6C and especially EIGEN6C2 provide slightly better results compared to EGM2008 even for lower maximum degrees of expansion. Therefore, the crucial point is that combined GGMs, employing all available GOCE, GRACE, gravity and altimetry observations can now be determined with increased accuracy, compared to older models, in the medium wavelengths.

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