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The Evaluation of Sea Surface Topography Models based on the Combination of the Satellite altimetry and the Global Geoid Models in the Persian Gulf

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ABSTRACT: One of the difficulties in using absolute altitudes is the separation between the mean open sea level and geoid. Theoretically, geoid is the base level in absolute altitudes, but practically, the mean open sea level is used as a base level for absolute altitudes. The difference between these two levels is called as the sea surface topography. In this research, it is dealt the mean sea level modeling by using the observations of three altimeter satellites (i.e. Topex/Poseidon, Jason-1 and GFO) in Persian Gulf and then it is dealt with the evaluation of existing models of the sea surface topography based on the altimeter satellites data and the global geopotential geoid models (i.e. European Improved Gravity model of the Earth by New techniques, Gravity field and steady-state Ocean Circulation Explorer, Earth Gravitational Model 2008. The results of this research indicate that the sea surface topographical model resulting from the EIGEN06C geoid is the most precise model with changes range between -2.482 m and -1.511 m and mean -0.23 m.

Key words: Satellite, Sea surface, Persian Gulf, Gravity model

INTRODUCTION

One of the common parameters in geodetic sciences and oceanography is the study of the sea level. The relation between these two sciences is revealed in this fact that geodesies require oceanographical observations to determine a precise marine geoid model and oceanographists also need marine geoid to determine the absolute quantities of the sea streams velocity in various depths (Ross, 1995). The opposite point between these two sciences is the separation of geoid and the mean sea level (MSL) which is called as “dynamic sea surface topography”or “pseudo-static sea surface topography” (Knudsen, 1992b).

For all determined geoid, it is normally assumed that geoid is equipotential surface the same as gravity centre of the earth which is best coincided with the MSL. With a little attention. it is clear that the separation of the geoid from the MSL for a precise geoid specially in open oceans is between -2.2 m and 70 cm with standard deviation $\pm$ 62 in global scale (Engelis, 1985; Engelis, 1987); this big separation is normally due to the oceanic streams resulting from some factors such as wind, salinity changes, temperature and pressure which are directly related to the earth.

Given the geoid and the MSL, there are some problems in determining the altitude reference of the countries; so it is better to determine the sea surface topography (SST) values in tidal reference stations and to use it for the zero height level in that region (Ardalan and Mosaiebzade 2003). Now, finding the SST requires calculating the geoid which is the desired base level. In this article, the global models “EGM2008, GOCE and EIGEN06C” are used to calculate this level. In addition, we also examine how to determine the MSL and how to calculate this level. In this regard, Fourier analysis and the least squares methods are used to eliminate the periodic disturbances and anomalies.

MATERIAL & METHODS

The mean sea level (MSL) is one of the important and fundamental elements in geodesy and hydrography. MSL is a level on which the open seas level will be coincided if no turbulences and

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disturbances exist. This level altitude is normally calculated from the instantaneous mean of the water. The MSL is normally calculated from the observations of the points in an arranged (regular) network. These point observations are obtained from the tidal stations (tide gage) throughout the world or they are obtained by using satellite altimetry method.

The MSL is traditionally considered as "zero height point and balance sea level in the coast; in order to obtain the, level we should omit the tidal frequencies in limited time openings and consider the remaining level as the MSL after omitting the periodic changes. By connecting this level to the coastal benchmarks, the zero height will move to the land. Determining this level is very important in topography. Determination of geoid is one of the most important uses of the MSL. In order to obtain the geoid, we should use an equipotential surface which its difference from the MSL is minimum. Using this level as the base level in navigation purposes is the other uses of this level. In this research, it is dealt with the MSL modeling by using the altimeter observations of the satellites "Topex/Poseidon, Jason-1 and GFO" in a point form. To achieve this goal, data from the altimeter satellites Topex/Poseidon, Jason -1 and GFO containing the collected information during years 1992 to 2008 were firstly used which time series were made from the sea level changes in satellite passes in Persian Gulf. Then tidal constituents could be obtained in observation points by performing the Fourier spectral analysis and the least squares method on these time series. Fig.1. shows the passes of the satellites Topex/Poseidon, Jason-1 and GFO. Accordingly, we can see in this map that these satellites have provided a relatively good coverage. It is necessary to note that the passages of the satellites Topex/Poseidon and Jason-1 are exactly placed on each other which are shown in blue and the passages of the satellite GFO are illustrated in red (Beckley *et al.*, 2007).

In order to determine the sea surface height (SSH) in observation point as compared with reference ellipsoid, we should firstly correct the systematic errors relating to satellite distance from the sea level which is measured by altimeter. All of these corrections are available in information files known as MGDR-B files. These corrections are provided for each point separately.

After correcting the distance between the satellite and instantaneous sea surface (corrected Range), SSH could be obtained on the same point in regard to reference ellipsoid by having determined satellite altitude (H_{sat}) from the ellipsoid. One point should be considered here is that, as our goal is to make time series from the instantaneous SSH and to analyze these

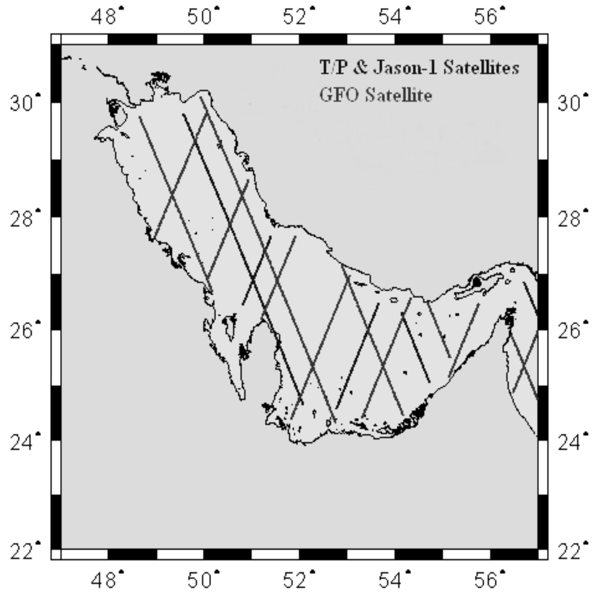

Fig. 1. the passes of the Topex/Poseidon, Jason-1 and GFO satellites over the Persian Gulf

series to find the MSL; then the corrections resulting from the tide should not be used for observations (Marsh, J. G., *et al.*, 1990).

$$SSH(\lambda,\varphi,t) = H_{sat}(\lambda,\varphi,t) - Corrected\ Range \qquad (1)$$

As our goal is to find the MSL Height in satellite passes in which time series are made, so we first determine MSL and its time changes and then we estimate the periodic constituents. Therefore, assume that the time series $h\{(t_i)\}\ i = 1,2,\ldots,n$ are the observations relating to the instantaneous SSH of the sea surface in a known point, so the appropriate model for tidal modeling is shown below (Yu Wang, 2004):

$$h(\varphi,\lambda,t) = a_0(\varphi,\lambda) + b_0(\varphi,\lambda)t + \sum_{i=n}^{n}[a_i(\varphi,\lambda)Cos(2\pi f_i t) + b_i(\varphi,\lambda)Sin(2\pi f_i t)] \qquad (2)$$

In the above-mentioned formula, a_0 denotes the MSL and a_i, b_i denotes the tidal waves amplitude which should be determined as Fourier coefficients; b_0 denotes permanent increase in the seas water level which is considered constant in all of the sea levels due to the pole ices melting and f_i denotes the used frequencies. Determination of the Fourier coefficients in the above-mentioned extension, in fact, led to the determination of a model for a phenomenon behavior. These coefficients are determined by using a sample and providing a parametric equations system. The least squares method is used to solve this parametric equation system.

Choosing the number of constituent depends on different factors such as observations duration. After solving the least squares in equation2, the amplitude and the tidal i.th phase are calculated as follows (P.Vanicek, E.Krakiwsk 1986):

$$A_i = \sqrt{a_i^2 + b_i^2} \quad (3)$$

$$\Psi_i = 2tg^{-1}\left(\frac{a_i}{b_i + A_i}\right) \quad (4)$$

Table 1 shows four tidal Constituents parameters.

Nowadays it is possible to determine the MSL and geoid in seas with high precision by using satellite altimetry method. It is a common method for using global geopotential models. The long gravity field wavelength is shown well because satellite-based observations with monotonous coverage and high compression are used in the determination of the spherical harmonics coefficients. The global models are used in the determination of the satellite orbit, high wavelengths of geoid, tidal constituents of the earth, oceanography, oceanic permanent streams and estimating the earth rotation parameters and the pole movement parameters.Fig. 2. shows local mean sea level model based on the Topex/Poseidon, Jason-1 and GFO Data.

It is necessary to note that satellite-only observations are used in calculating some of these

Table 1. Name, frequency, period and amplitude of the four used tidal ConstituentsUnit: meter

Constituent Name	Mean value	Minimum Value	Maximum Value	frequency (cycle/day)	Period
M.S.L	-21.616	-34.557	-1.650	0	Extreme
O_1	0.172	0.007	0.300	0.9295	1.0758
K_1	0.274	0.011	0.507	1.0027	0.9973
M_2	0.331	0.008	0.885	1.9324	0.5175
S_2	0.120	0.002	0.342	2.0000	0.0005

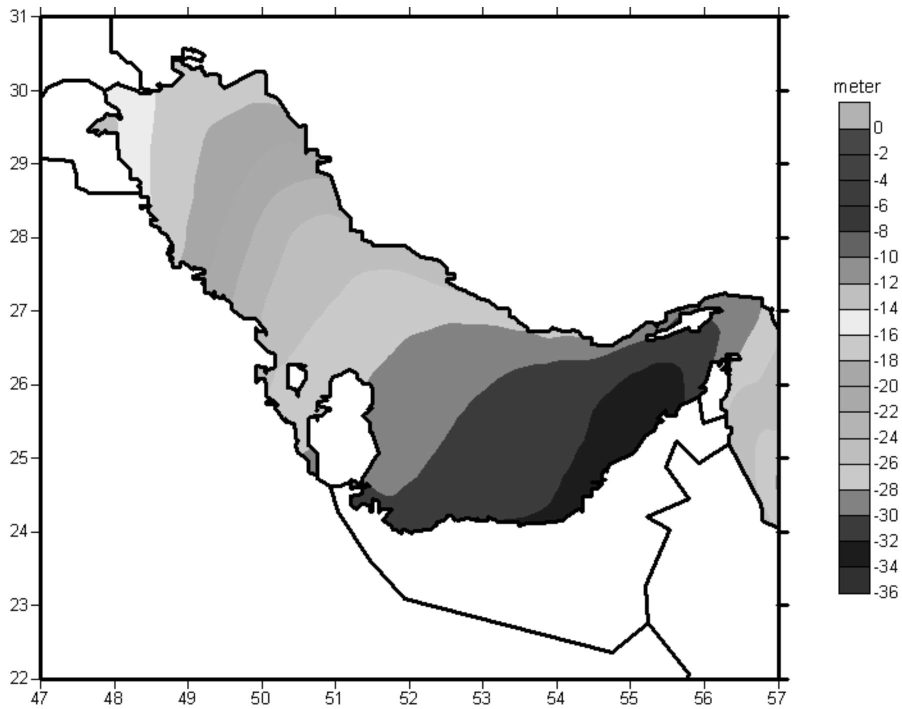

Fig. 2. Local mean sea level model on the Topex/Poseidon, Jason-1 and GFO Data. Contour line. Unit: meter

models and in other models combined satellite and ground observations are used. The former models are known as "satellite-only global gepoptential model" and the last models are known as "combined global geopotential model". By advancing the satellite-based gravitational methods and improving the compression and precision of the ground data nowadays, we can see so many geopotential models which are calculated and presented by diverse research institutions and universities throughout the world. The compression, precision and accuracy of the ground data used in combined models in different parts of the world are different, so the precisions of these models differ from each other and an appropriate model should be selected in accordance with the usage type and geographical position. We will present some new and precise global geoid models.

The EGM96 model was the last earth geopotential model which was provided in the middle1990 by National Geospatial-Intelligence Agency. This model has degree and order 360 which is made for marine regions by using the gravitational data 30 minute by 30 minute resolution, throughout the world, the long wavelength information of about forty satellites, height data extracted from twenty nine Sources and the altimeter data of satellites GEOSAT, ERS-1 and TOPEX. The root mean square (RMS) of model EGM96 is estimated about 0.5 to 1 meters which is approved by a group of experts in international association of geodesy (IAG) (Nikolaos *et al.* 2008).

After model EGM96, a global geopotential model known as "model EGM2008" was available for users in 2008 with degree and order 2160 (Pavlis *et al.* 2008). This model is formed based on using revised data of the gravitational Information 52 ×52 throughout the world and the geopotential models are formed based on the GRACE satellite (Gravity Recovery And Climate Experiment) information.

The expected accuracy of this new model EGM2008 was much exaggerated because the gravitational distributions 5'x5' mean resolution, degree and order 2160 and 15 cm for global geoid accuracy are considered. The new model EGM2008 found in National Geospatial-Intelligence Agency (NGA) institution requires gravitational data with global coverage and intervals 5'x5' mean resolution. This database is formed by using combined gravitational ground (geoid), marine and aerial data and gravity anomaly for the most of the oceanic regions using altimeter satellites. The long wavelength in EGM2008 is obtained by using satellite GRACE data which is more precise than data contained in prior EGM models. The most precise and newest model GRACE is used in model EGM2008. Fig. 3 and Table 2 show the geoidal height and its statistical values based on the EGM2008 model.

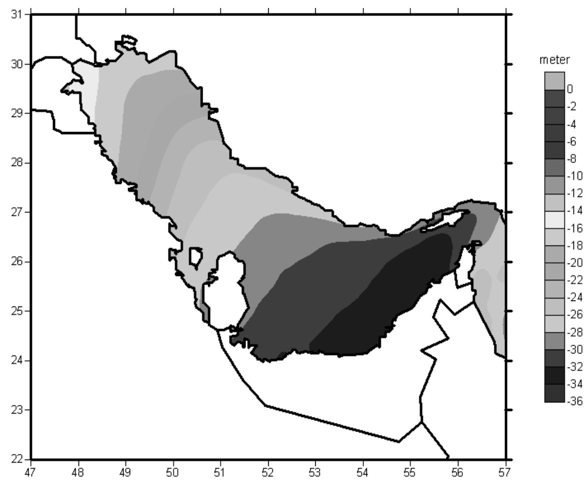

Fig. 3. EGM2008 global geoid model contour line. Unit: meter

Table 2. the statistics of the geoidal heights"EGM2008" Unit: meter

Maximum Value	Minimum Value	Mean Value	Standard deviation
-1.688	-34.872	-21.936	8.863

EIGEN06C model (Förste *et al.*, 2011), is complete to degree and order 1440 and was jointly elaborated by GFZ Potsdam (GeoForschungsZentrum) and CNES/ GRGS Toulouse) Groupe de Recherche de Geodesie Spatiale(. It is the first EIGEN model inferred from a combination of GRACE and GOCE data, enhanced with the DTU10 global gravity anomaly grid (Andersen, O. B., P. Knudsen and P. Berry). The combination of GRACE and GOCE (The Gravity Field and Steady-State Ocean Circulation Explorer) data allows the construction of an accurate satellite-only model to degree and order 240, the gradiometer data of the latter contributing only to degrees upwards of 100. This is achieved through filtering of the GOCE observation equations, which is necessary because of the degraded gradiometer performance outside the measurement bandwidth. Analyses of gradiometer residuals calculated with ITG-Grace2010s (Mayer-Gürr *et al.*, 2011), EIGEN-5C and EGM2008 as background models revealed considerable model errors in current combined gravity field models caused by the inclusion low-quality and/or low resolution surface data. Therefore, in EIGEN06C model the combination procedure of satellite and surface data was revisited in order to mitigate this error source. In particular, the surface data normal equations are combined with satellite normal equations at a higher degree than presently applied (for instance at degree 70 in EIGEN-5C). The comparison of test results (orbit computation, GPS/leveling) of this latest EIGEN model with a GOCE-only model, EGM2008 and ITG-Grace2010s demonstrates the gain in accuracy at high degrees, while its performance remains identical compared to a GRACE-only model for the low degrees.Fig. 4 and Table 3 show the geoidal height and its statistical values based on the EIGEN06C model.

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) is an ESA satellite that was launched on March 17, 2009. It is a satellite carrying a highly sensitive gravity gradiometer which detects fine density differences in the crust and oceans of the Earth.

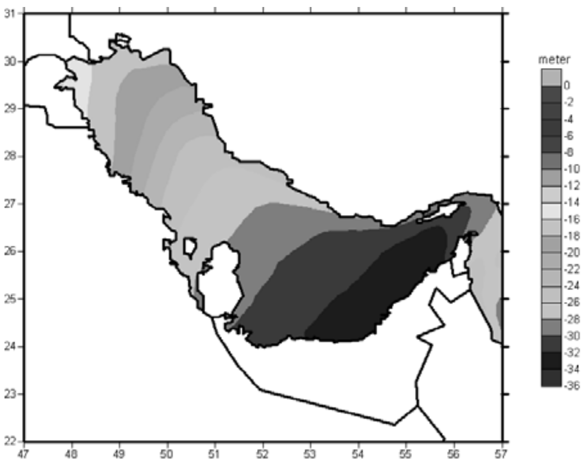

Fig. 4. EIGEN06C global geoid model contour line. Unit: meter

Table 3. the statistics of the geoidal heights” EIGEN06C” Unit: meter

Maximum Value	Minimum Value	Mean Value	Standard deviation
-1.114	-34.872	-22.845	8.993

GOCE data will have many uses, probing hazardous volcanic regions and bringing new insight into ocean behavior. The latter, in particular, is a major driver for the mission. By combining the gravity data with information about sea surface height gathered by other satellite altimeters, scientists will be able to track the direction and speed of geostrophic ocean currents. The low orbit and high accuracy of the system will greatly improve the known accuracy and spatial resolution of the geoid (the theoretical surface of equal gravitational potential on the Earth).

The satellite’s arrow shape and fins help keep the GOCE stable as it flies through the wisps of air still present at an altitude of 260 km. In addition, an ion propulsion system continuously compensates for the deceleration of air-drag without the vibration of a conventional chemically-powered rocket engine, thus restoring the path of the craft as closely as possible to a purely inertial trajectory. The craft’s primary instrument is three pairs of highly sensitive accelerometers which measure gravitational gradients along three different axes. In this article, the last accessible model of this one namely GO_CONS_GCF_2_DIR (Bruinsma *et al.*, 2010) was used in 2010 with degree and order 240 and without ground combined data. Fig.5.and Table 4 shows the geoid resulting from this model in region under study.

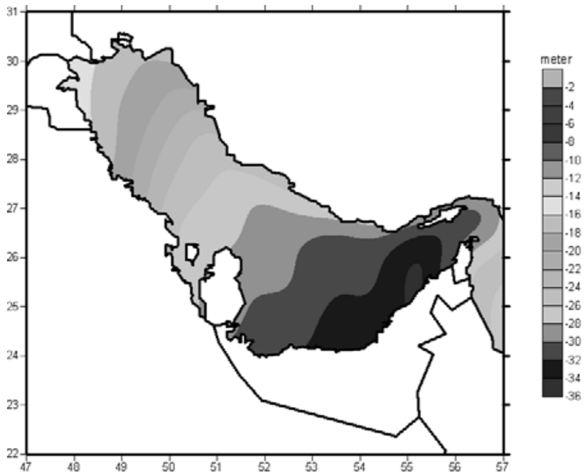

Fig. 5. GOCE global geoid model contour line. Unit: meter

Table 4. the statistics of the geoidal heights” GOCE” Unit: meter

Maximum Value	Minimum value	Mean Value	Standard deviation
-2.140	-34.688	-21.917	8.877

RESULTS & DISCUSSION

The distance between the instantaneous sea surface and the MSL is called as “mean sea surface topography” which results from some factors such as solid ground tide, oceanic streams and geology phenomena. The distance between geoid and the MSL is called as “sea surface pseudo-static topography” which results from diverse dynamic phenomena in oceans like temperature, salinity, unsolvable oxygen quantity in water. It is very important to measure the sea level specially the topographical sea surface because we can obtain the sea discharge with the help of measuring the geodesy, geoidal height and hydrology.

The SST consists of two parts: the pseudo-static part (unchangeable in time) and the changeable in time part. The pseudo-static topography is stable (unchangeable) as the SSH on time period and the changeable topography changes with the slight changes in time scale and seasonal phenomena. The relation between geoidal height and the sea surface topography is shown in fig.6. in which ζ_t is the changeable part and ζ_c is the pseudo-static topography part. Fig.6. shows the relation between the geoidal height, the SST and the instantaneous SSHs measured by altimeter.

$$SSH = N + SST \quad (5)$$

Equation5 is a simple equation which shows the relation between Earth's reference ellipsoid (h), orthometric height (H) and geoidal height (N).

$$h = N + H \quad (6)$$

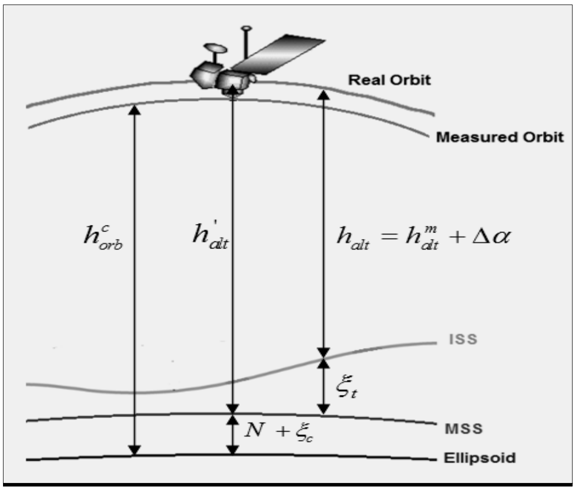

Fig. 6. The relation between orthometric height, reference ellipsoid and geoidal height

The SST term in equqtion5 shows the continental orthometric height, that's why it is called as the sea surface topography. The SST and the SFT (sea floor topography), of course, have many distinctions and there is relatively a relation between the SST and the SFT; this shows that these two levels are less in common. In addition to pseudo-static part which is stable on time period, the SST also has changeable dynamic part whereas the earth topography is always stable. The maximum and minimum value for the SST is about 2.2 meters whereas the maximum earth topography reaches to 8.5 km in Himalaya.

The SST modeling is done by geodetic and oceanic methods. The geodetic methods use the earth gravity centre observations related to some quantities such as geoidal height, geoid anomaly, gravity anomaly, vertical deflections and gravity undulations. The oceanic methods are based on the observations of salinity, temperature, pressure and unsolvable oxygen contents in oceans water and they are written based on the complicated differential equations. Generally, more precise modeling is performed by geodetic techniques of the SST. In all usages of physical geodesy which aim to determine the geoid, it is assumed that geoids don't change in a specific time period. Therefore, only pseudo-static part of the SST is needed. The time changeable part of the SST could be calculated by analyzing the satellites crossover points during the repetitive altimeter mission period and it also could be omitted during the altimeter data processing and then it could be filtered by the momentary sea observations as parameters "bias and tilt ".

The geodetic modeling methods for the SST are classified in three classes. The first method is based on the spherical harmonics extension which is offered by (Engelis, 1987). In this method, the satellite altimetry observations and the geopotential model with low degrees have been used. The shortcoming of this method is that the whole sphere function and the whole earth observations should be covered in order to extend to a spherical harmonic series. Unfortunately, part of the earth is covered by land and so the altimeters can't observe some parts of oceans in high latitudes. In the second method, we use orthonormal functions instead of spherical harmonics. In this sense, high latitudes are not considered. The intentioned functions are defined in specific regions in the earth, and they aren't considered in high latitudes regions and marine zones such as Mediterranean Sea, Black Sea and so on. This method is offered by Rapp. Third method, extending the frequency space, is offered by Anderson in 2000 and it modulates the SST in remote marine zones with good results. The precise determination of the SST depends on the precise determination of the MSL and geoid.

$$SST\big|_{(\varphi,\lambda)} = MSL\big|_{(\varphi,\lambda)} - N_{geoid}\big|_{(\varphi,\lambda)} \quad (7)$$

Fig.7. and Table.5. Show the SST map based on the global geoid models "EGM2008, GOCE and EIGEN06C" and comparing the statistical results of the models.

Table 5. comparing the statistical results of the sea surface topography based on the global geoid models "EGM2008, GOCE AND EIGEN06C" Unit: meter

Geoid Models	Maximum value	Minimum value	Mean value	Root Mean Squares
EGM2008	1.848	-1.687	-0.319	-0.501
GOCE	1.219	-1.609	-0.301	-0.500
EIGEN06C	2.482	-1.511	-0.229	-0.467

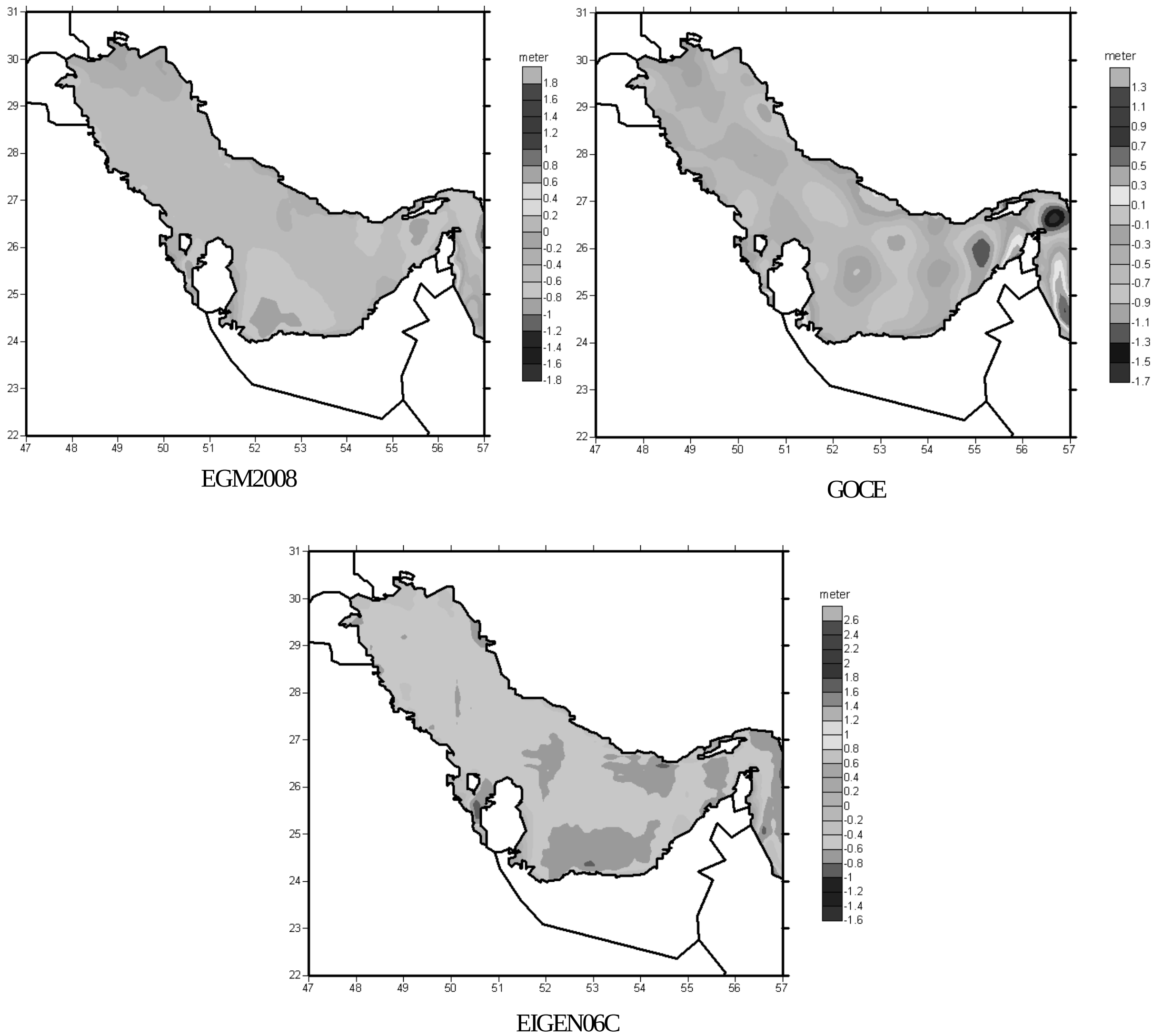

Fig. 7. The sea surface topography based on the global geoid models "EGM2008, GOCE AND EIGEN06C" Unit: meter

CONCLUSION

The measuring base of the absolute altitude in every country is resulted from the tide gage information measurements. The existence of the SST leads to the separation between the geoid and the MSL. The altitudes measurement base differs in different countries. As a result, the altitudes base difference should be determined in different countries in order to relate the geodesy researches and mapping projects together in different countries so that they relate to the points absolute altitudes. In order to find the difference between the absolute altitudes base levels, only the SST of the countries latitude base points should be determined. In order to determine the SST, the geoid model which is the desired base level requires to be calculated. Different global geoid models are used to calculate the SST. In addition, in this article the MSL is calculated and it is determined in detail how to determine this level. For this purpose, the Fourier analysis method and the least squares method are used to remove the periodic anomalies. By comparing the pictures in fig.7, we can see an appropriate conformity between models "EIGEN06C and EGM2008". In comparison with two other models, the model resulting from GOCE has more details about the SST. Table.5. also shows that the model "EIGEN06C" has the Root mean Squares with about 8cm more than other models. Meanwhile, the models "EIGEN06C and EIGEN06C" have the least (about 2.82 m) and the most (about 4 m) range for the SST changes respectively. The existence of the more details for the SST of the model "GOCE" could be very important from the viewpoint of the oceanography studies specially the marine streams studies. By comparing the squares sum parameter of the mean sea surface topography in different geopotential models, it is evident that the geopotential model "EIGEN06C" which contains a combination of the ground and satellite-based data has the nearest distance from the MSL among the other models.

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