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Detection of Systematic Error in Mean Dynamic Topography Model DTU10MDT on the Territorial Waters of Vietnam

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Abstract: In the sea bordering countries, a mean dynamic topography (MDT) model, that in Geodesy is called as mean sea surface topography model (MSST), is a very important source of data for creation of a different types of marine thematic maps and research on ocean dynamical processes. However, a majority of the permanent tide gauge stations with water level measurement period more 18.6 years are located at the some onshore islands. So the mean sea levels (MSL) determined at the onshore permanent tide gauge stations don't permit to construct MSST covering the entire national waters. Over the past decade many international techno-scientific organizations had constructed a global highly accurate mean dynamic topography (MDT) models based on the global Earth's Gravity models (EGM) and the MSS models determined from altimetric data and had supplied users with these models. These valuable models with the MSL determined at the onshore permanent tide gauge stations fully allow to construct the MSST model on the entire national waters.

The MSST model had been constructed based on the corresponding mean sea surface (MSS) model, whose accuracy depends on many factors, especially on an accuracy of the used global tide model. In practice, complicated hydro-meteorological conditions in shallow water area near the coast don't permit to construct the highly accurate global tide model in the inshore *shallow water regions. That may be a potential cause of presence of a systematic error in the* MSST model.

This scientific article will present a research results for construction of the mean sea surface topography model MDTVN2015 on national waters of Vietnam based on the international DTU10MDT model created by the National Space Institute (NSI) belonged to the Technical University of Denmark (DTU). The main focus of this article is a detection of potential systematic error in the DTU10MDT model on national waters of Vietnam based on the national normal heights of the local mean sea surfaces at the onshore permanent tide gauge stations.

Key words: Mean Dynamic Topography (MDT), Mean Sea Surface Topography (MSST), Mean Sea Surface (MSS), systematic error, Mean Sea Level (MSL)

1. Introduction

The MSST model on national waters in reality is the digital elevation model of the national mean sea surface topography according to the local geoid with gravity potential W_0 in addition the geoid is the best fitted to the mean sea surface at the national zero tide gauge station and used for the initial surface of the national hight system. In Vietnam the national zero tide gauge station is the Hon Dau tide gauge station. The construction of the MSST on national waters has many important significations for Oceanography and Geodesy. In Oceanography field the MSST model is used to study impacts of ocean curents, sea water temperature and salinity, ocean tides, ocean waves during typhoon, tsunami et cetera. For Geodesy, the mean sea surface and continental surfaces are components of the Earth's physical surface — object of surveying and mapping. The MSST model is used not

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only to create geographic background for marine geographic information system, but also to separate the mean sea surface from the geoid for study of the Earth's gravity field.

The mean sea levels (MSL) determined at the onshore permanent tide gauge stations have an accuracy at level of ±0.1 m [1], but they don't permit to construct MSST covering the entire national waters. In the meantime by research results in Ref. [2], the accuracy of the mean sea surface height above the geoid, which is symbolized as MDT, from the DNSC08MDT model can be obtained at level of ±6.8 cm. So the international MDT model guaranteis not only coverage, but also accuracy for creation of the MSST model on national waters. At present based on the global Earth's Gravity models (EGM) and the MSS models determined from altimetric data, many international techno-scientific organizations had constructed the global highly accurate MDT models according to the global geoid with a gravity potential $\overline{W}_0$. The gravity potential $\overline{W}_0$ is equal to $\overline{W}_0$ = 62636856.0 m^2.s^{-2} [3, 4].

By IAG resolution No.16 (June 1983) in Hamburg (Germany) [5], all geodetic data must be processed in the zero tide system. We symbolize $\overline{MDTn}$ as the height of point with geodetic latitude $\overline{B}$ on the mean sea surface determined from the international MDT model in the non-tide system. For the national waters of Vietnam with purpose to convert the $\overline{MDTn}$ of given point from the DTU10MDT model to the $MDTVN_z$ of that point in the zero tide system in national MSST model according to the local geoid with gravity potential W_0 at the Hon Dau tide gauge station, we use following formula [6]:

$$MDTVN_z = \overline{MDT_n} - H_0 + \delta MDT_{n-z}, \quad (1)$$

where δMDT_{n-z} is the corection for conversion of the $\overline{MDT}_n$ from the non-tide system to the zero tide system and determined by formula [7]:

$$\delta MDT_{n-z} = 0.033 - 0.0998x\sin^2 \overline{B} \quad <m>,$$

H_0 is the height of the Hon Dau local geoid above the global geoid and calculated by following formula:

$$H_0 = \frac{\overline{W_0} - W_0}{\bar{\gamma}}. \quad (2)$$

On an account of coincidence of the geoid and quasigeoid on the sea, H_0 (2) is also the height of the Hon Dau local quasigeoid above the global quasigeoid. The gravity potential of the HON DAU local geoid is equal to W_0 = 62636847.2911 m^2.s^{-2} [8]. The height H_0 (2) is equal to 0.890 m. The normal height system is used in Vietnam. Because the local and global quasigeoids aren't equipotential surfaces in the normal gravity field of the reference ellipsoid WGS-84, height H_0 (2) is a constant value on a world scale [9].

Based on formulas (1), (2) and mô hình DTU10MDT model, in Ref. [10] had been proposed the national MSST model on the entire national waters of Vietnam which is symbolized as MDTVN2015 model.

In process of construction of the MDTVN2015 model, we had performed a detection of systematic error in the DTU10MDT model on national waters of Vietnam based on the national normal heights of local mean sea surfaces at the tide gauge stations. The *cause of presence of the systematic error in the* international MDT model may be impact of different seasonal wind regime on the coastal areas which causes seasonal changes of the sea surface [11]. Apart from that, a change of regimes of tide in different sea zones leads to erroneous estimation of the mean sea surface by altimetric data.

The international MDT model had been constructed based on the global tide model. For examples, the DTU10MDT model had been constructed based on the global tide model FES2004 (Finite Element Solution 2004) [1]. As for it, the accuracy of the global tide model very much depends on the accuracy of depth measurement results and the shape of the continental shelf [1, 12]. In coastal shallow water areas, the ocean waves not only have changed their speed of movement and amplitudes, but also have been influenced by complicated hydro-meteorological conditions. From these causes, in the global tide model in shallow water zones many tidal constituents have large amplitudes and have been determined with low accuracy [12]. In altimetric data processing, the global tide model is used to decrease large tidal effects. However the global tide model doesn't have enough accuracy to decrease complicated and large tidal effects in shallow water zones [13]. From limitations of the satellite altimetry method and incompleteness of global modelling for tidal prediction in shallow water zones, it isn't realistic for the ocean tide model to completely represent a coastal tide state [14]. The low accuracy of the global tide model in shallow water zones can cause the systematic error in the international MDT model. So the detection of *presence of the systematic error in the* DTU10MDT model is one of important tasks for construction of the national MSST model based on the DTU10MDT model.

In process of construction of the MDTVN2015 model based on the DTU10MDT model, we had discovered *presence of the constant systematic error in the* DTU10MDT model on sea zone Nga Son (province Thanh Hoa). In this article will be represented results of detection of the constant systematic error in the DTU10MDT model based on the normal heights of the mean sea surfaces at the onshore permanent tige gauge stations on national waters of Vietnam.

2. Data

The Danish National Space Center (DNSC, at present NSI) had constructed the DNSC08MDT model based on the DNSC08MSS model and the EGM2008. The DNSC08MSS model in the mean tide system had been constructed from satellite missions as TOPEX/Poseidon, JASON-1, GEOSAT GM, GFO ERM, ERS-1 GM, ERS-2 ERM, ENVISAT ERM, ICESAT in period 1993 - 2004 [15].

The DTU10MDT model with resolution 1' x 1' had been constructed based on the DTU10MSS model and the EGM2008, in addition the DTU10MSS had been developed from the DNSC08MSS model with supplemented altimetric data at the Arctic region [12].

The database of the DTU10MDT model had been supplied by the DTU in website "DTU Space National Space Institute" by address:

http://www.space.dtu.dk/english/Research/Scientific_data_and_models/Global_Mean_Dynamic_topography

The mean sea levels of the 05 coastal permanent tide gauge stations as Hon Dau, Tien Sa, Quy Nhon, Nha Trang, Vung Tau and the 09 permanent tide gauge stations at the islands as Co To, Bach Long Vy, Cua Ong, Hon Ngu, Con Co, Phu Quy, Con Đao, Phu Quoc, Tho Chu had been determined based on the water measurement results from June 1994 to June 2014. The national normal heights of the mean sea surfaces of the 05 coastal permanent tide gauge stations had been calculated based on the second order levelling results from the first and second orders benchmarks by the method of river crossing levelling. The national normal heights of the mean sea surfaces of the 09 permanent tide gauge stations at the islands had been obtained by the method of GPS/quasigeoid levelling based on the GPS technology and mixed quasigeoid model VIGAC2014, where the VIGAC2014 model is the Hon Dau local quasigeoid model in the zero tide system according to the international WGS-84 ellipsoid and had been constructed based on conversion of the global geoid model EGM2008 to the Hon Dau local quasigeoid surface.

3. Applied Methods

At the every permanent tide gauge station had been deternined two sequences of heights of the local mean sea surface in the zero tide system: H^{γ} from the method of river crossing levelling or the method of GPS/quasigeoid levelling and $MDTVN_z$ from the DTU10MDT model by formula (1). As a consequense, for the n permanent tide gauge stations we have the two independent sequences of heights of the local mean sea surfaces in following form:

$$H_1^{\gamma} \qquad H_2^{\gamma} \ldots\ldots\ldots\ldots H_n^{\gamma},$$
$$MDTVN_1 \quad MDTVN_2 \ldots\ldots MDTVN_n. \tag{3}$$

It's necessary to underline that the both sequences of heights in (3) don't contain the same constant systemetic error, because they had been obtained by different methods and from different sources of data.

The first problem that we must resolve is to detect the presence of constant systemetic error in one of two sequences of heights in (3). In order to perform this detection, we will use a processing method for double sequences of measured values proposed in Ref. [16].

It is assumed that for n different quantities *Xi* (*i* = 1,2,…n) an every quantity had been measured two times. As a result we get two sequences of independent, equally accurate measured values in following form:

$$y_1 \quad y_2 \quad \cdots \quad y_n;$$
$$y_1' \quad y_2' \quad \cdots \quad y_n'. \tag{4}$$

When assume that the first sequence y in (4) doesn't contain the constant systemetic error S, meanwhile the second sequence contains this systemetic error, we calculate following differences:

$$d_i = y_i - y_i' \quad (i = 1,2,..,n) \tag{5}$$

and quantity

$$C = \frac{\sum_{i=1}^{n} d_i}{n}. \tag{6}$$

If following condition will be satisfied:

$$A > 0.25 \times \mathrm{B}, \tag{7}$$

where $A = \left|\sum_{i=1}^{n} d_i\right|$, $B = \sum_{i=1}^{n} |d_i|$, then we can assert that above mentioned assumption fully is accepted, i.e., the second sequence contains the constant systemetic error S.

In this case quantity C (6) is equal to –S and is the correction to measured values y_i', $(i = 1,2,..,n)$ in the second sequense in (4).

On the contrary, if following condition will be satisfied:

$$A \le 0.25 \times \mathrm{B} \tag{8}$$

then the both sequences in (4) don't contain the any constant systemetic error S.

By such way the first problem will be resolved. In the case of discovery of the presence of constant systematic error in sequences (4), the next second important problem is to determine: what sequence will contain this systematic error. This problem will only be resolved on base of data analysis in the both sequences (4), which will be represented in Section 4.

4. Results

Based on the national normal heights of the 164 first and second orders benchmarks, which are the most stable and relatively regularly distributed on land territory of Vietnam, in addition co-located GPS observations had been processed in ITRF according to the international reference ellipsoid WGS84 and transfered to the zero tide system, in Ref. [17] had been represented results of orientation of the international reference ellipsoid WGS84 under the condition of best it's fitting to the Hon Dau national quasigeoid.Apart from getting the national reference ellipsoid WGS84, we had got the sequence of national quasigeoid heights on the 164 first and second orders benchmarks. Results of conversion of the mixed quasigeoid heights from the mixed quasigeoid model VIGAC2014 to the national reference ellipsoid WGS-84 and their comparison with the national quasigeoid heights obtained from the above mentioned results of orientation of the ellipsoid showed that the most differences between above mentioned quasigeoid heights are at level of cm, 160 (97.56%) differences are less than 0.175 m by absolute values, remaining 4 differences less than 0.2 m by absolute values. These differences don't contain any constant systematic error. The above mentioned research results had proved that not only the national normal heights, but also the quasigeoid heights from the mixed quasigeoid model VIGAC2014 on the 164 first and second orders bencmarks don't contain any constant systematic error. The determination of the national normal height of the mean sea surface at the coastal tide gauge station had been performed by method of river crossing levelling from the nearest first or second orders benchmarks. On the other hand, the coastal permanent tide gauge stations are located at different geographic positions along the coastlines. So it can't happen that the national normal heights of the coast permanent tide gauge stations similtaneously contain the same constant systematic error, i.e., the sequence of the national normal heights H^{γ} in (3) can't contain any constant systemetic error. The national normal heights of the local mean sea surfaces at the permanent tide gauge stations in the zero tide system on national waters of Vietnam have accuracy at level of ±(6-7) cm [10].

Now we will continue to analyse a sequence of quantities $\overline{MDTn}$ determined from the DTU10MDT model at the permanent tide gauge stations on national waters of Vietnam. From schema of a contours lines of the quantities $\overline{MDTn}$ in part of the national waters of Vietnam represented in Fig. 1, we saw that the contours lines of the quantities $\overline{MDTn}$ suddenly become more and more near to each other from the parallel of latitude 19°57' to the parallel of latitude 18°48' and the quantities $\overline{MDTn}$ start to increase from 0.9 m to 1.2 m. Moving down the South, the contour lines had been stretched, but the quantities $\overline{MDTn}$ still are at level of 1.2-1.3 m.

Analysing sudden increase in the quantities $\overline{MDTn}$ by a tilts of the mean sea surface topography along 3 meridians 106°00', 107°00', 108°00' in intervals of different latitude changes (see Table 1) we saw that the tilts of the mean sea surface topography had very small changes from the parallel of latitude 22°11' to the parallel of latitude 19°57'. After that the tilts suddenly had been changed from the parallel of latitude 19°57' to the the parallel of latitude 18°48'. Moving down the South from the parallel of latitude 18°48' on national waters of Vietnam, the tilts of the mean sea surface topography had started having very small changes.

From above mentioned analysis we can accept an assumption that in the Gulf of Tonkin to the parallel of latitude 19°57', the quantities $\overline{MDTn}$ don't contain any constant systematic error. From the parallel of latitude 19°57' going down the South, the quantities $\overline{MDTn}$ had started containing the constant systematic error.

For proving of the accepted assumption, we willl perform the detection of presence of the constant systematic error in 04 quantities $MDTVN_z$ determined by formula (1) at the 04 permanent tide gauge stations in the Gulf of Tonkin (see Table 2).

Calculated values: A = 0.014 m, B = 0.150 m. Because A = 0.014 m < 0.25×B = 0.038 m, i.e., the condition (8) had been satisfied, we can conclude that there isn't any presence of the constant systematic error in 4 quantities $MDTVN_z$ at the 4 permanent tide gauge stations in the Gulf of Tonkin.

We continue to perform the detection of the presence of constant systematic error in DTU10MDT model for national waters of Vietnam from the parallel of latitude 19°57' to the South based on the state normal heights of

Table 1 Changes of tilt of the $\overline{MDT_n}$ by meridians.

Intervals of latitude changes	Changes of tilt of the mean surface topography along some meridians (mm/km)		
	Meridian 106°	Meridian 107°	Meridian 108°
22°11'-21°00'	-0.42	-1.44	-0.61
21°00'-20°40'	-0.04	0	-0.03
20°40'-19°57'	0.83	0.5	0.94
19°57'-18°48'	2.61	1.94	0.61
18°48'-16°06'	-0.61	-0.50	-0.50
16°06'-13°46'			0.67
13°46'-12°12'			0.22

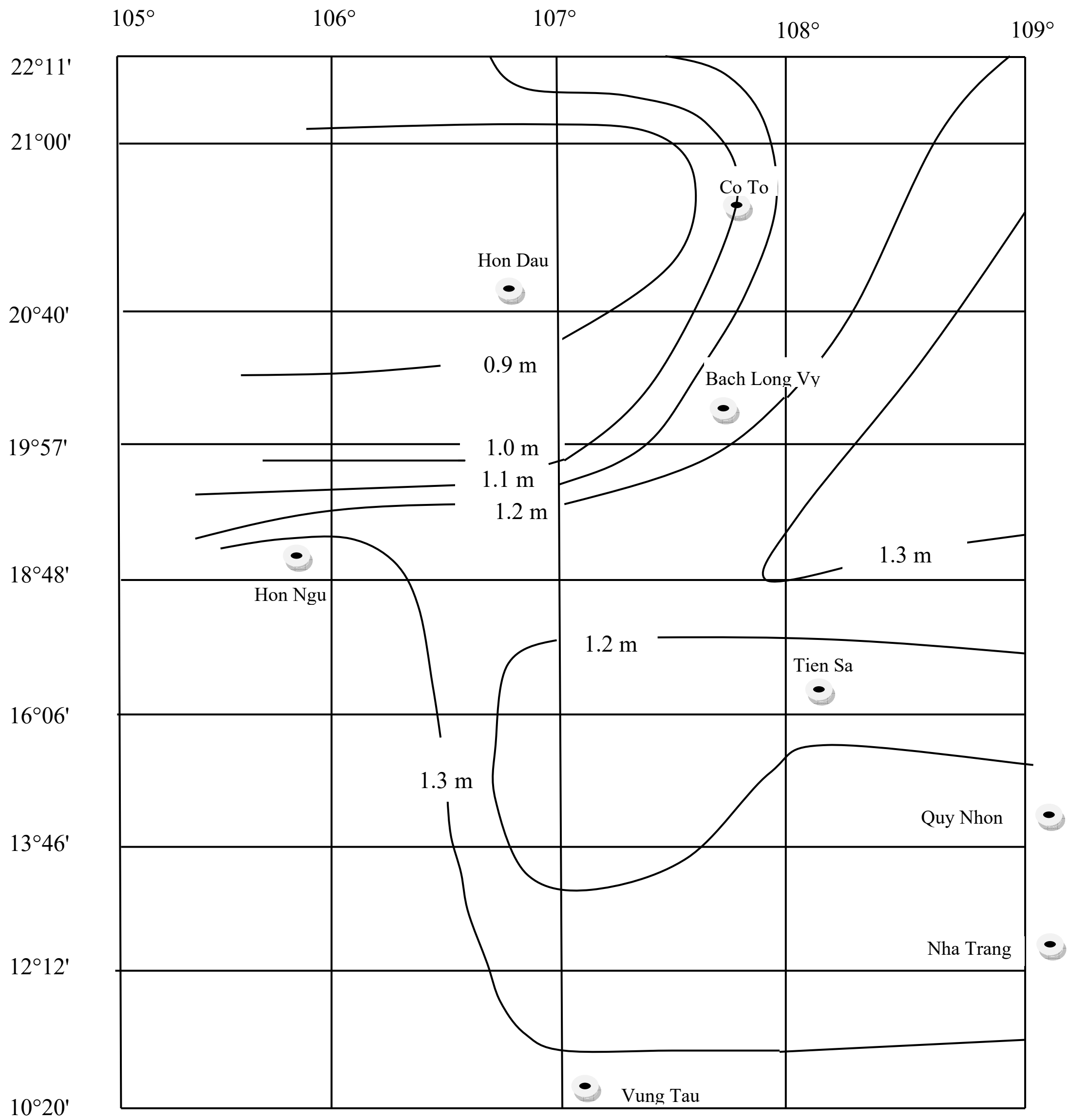

Fig. 1 Schema of contours lines of quantities $\overline{MDTn}$ in part of the national waters of Vietnam.

Table 2 The detection of the presence of constant systematic error in DTU10MDT model at the 4 permanent tide gauge stations in the Gulf of Tonkin.

No i	Permanent tide gauge stations	Quantities $\overline{MDTz}$ according to the global quasigeoid in the zero tide system (m)	Quantities $MDTVN_z$ according to the Hon Dau quasigeoid in the zero tide system (m)	State normal heights H_z^{γ} of the mean sea surfaces (m)	Differences d_i (m)
1	Co To	1.095	0.205	0.174	0.031
2	Hon Dau	0.895	0.005	0.000	0.005
3	Bach Long Vy	0.812	-0.078	0.004	-0.082
4	Cua Ong	0.978	0.088	0.056	0.032

the local mean sea surfaces at the 07 coastal and onshore permanent tide gauge stations as Hon Ngu, Tien Sa, Quy Nhon, Nha Trang, Vung Tau, Con Đao, Phu Quoc. The state normal heights of the local mean sea surfaces at the remaining 03 onshore permanent tide gauge stations as Con Co, Phu Quy, Tho Chu will be used for a control of results of the performed detection of the constant systematic error.

In Table 3, the quantities $MDTVN_z$ at the 07 coastal and onshore permanent tide gauge stations had been determined by formula (1) from the DTU10MDT model and had been accepted as sequence $y_1' \; y_2' \; \cdots \; y_7'$, the state normal heights H_z^{γ} of the local mean sea surfaces had been accepted as sequence $y_1 \; y_2 \; \cdots \; y_n$ in (4). Differences d_i had been calculated by formula (5).

Calculated values: A = 2.228 m, B = 2.228 m. Because A = 2.228 m > 0.25 × 2.228 m = 0.557 m, i.e., the condition (7) had been satisfied, we can conclude that the quantities $MDTVN_z$ contain the constant systemetic error, which is equal to $S = \frac{2.228}{7} = 0.318 \; m.$ The correction to the quantities $MDTVN_z$ is calculated by formula (6) and equal to $C = -\frac{2.228}{7} = -0.318 \; m.$

Table 3 The detection of the presence of systematic error in DTU10MDT model at the 7 coastal and onshore permanent tide gauge stations along the national waters of Vietnam.

No	Permanent tide gauge stations	The state normal heights H_z^{γ} of the mean sea surfaces (m)	The quantities $MDTVN_z$ according to the Hon Dau quasigeoid in the zero tide system (m)	Differences d_i (m)
1	Hon Ngu	0.085	0.420	-0.335
2	Tien Sa	0.103	0.266	-0.163
3	Quy Nhon	0.076	0.348	-0.272
4	Nha Trang	0.050	0.368	-0.318
5	Vung Tau	-0.030	0.436	-0.466
6	Con Đao	0.044	0.289	-0.245
7	Phu Quoc	-0.098	0.331	-0.429
Total sum				-2.228

With purpose of determination of the presence of the constant systematic error in the quantities $MDTVN_z$ at the permanent tide gauge stations located at the parallels of latitudes lower than latitude 19°57', we will analyse the hydro-meteorological conditions in a coastal sea zone of district Nga Son (province Thanh Hoa), in addition the parallel of latitude 19°57' passes through this sea zone. By hydro-meteorological data of the Vietnam Department of Meteorology and Hydrology, in sea region from Do Son to Nga Son, a tide regime has been changed from diurnal tides to semi-diurnal tides. Apart from that a wind direction has been changed from the Northeast to the North in period from November to April of the next year and from the Southwest to the South regime North in period from May to October. In this sea region speed of tide currents is at level of 10-30 cm/s in coastal sea zone and can reach up to 90-150 cm/s at river mouths. In off-shore sea zone of this region exists a stable tide current, which flows in counterclockwise direction with speed of 20-30 cm/s. In other sea regions of Vietnam speeds of tide currents are much less.

The presence of the constant systematic error in the DTU10MDT model in the Nga Son sea zone could be caused by the complicated hydro-meteorological conditions in this sea zone, in addition this constant systematic error could be accumulated and transmitted to calculational results of other quatities $\overline{MDTn}$ of the

DTU10MDT model in sea region on the parallels of latitudes less 19°57' on national waters of Vietnam.

It is true that the constant systematic error exists in the quatities $\overline{MDTn}$ of the DTU10MDT model in sea region on the parallels of latitudes less 19°57' on national waters of Vietnam, although the causes of presence of the constant systematic error could be explained by many different ways. So with purpose of construction of the MDTVN2015 model on national water of Vietnam based on the DTU10MDT model, instead of formula (1) we will use following formula:

$$MDTVN_z = \overline{MDT}_n - 0{,}890 \quad m + \delta MDT_{n-z} + \begin{cases} 0 & with \;\; B \geq 19^0 57' \\ -0{,}318 \;\; m & with \;\; B < 19^0 57'. \end{cases} \qquad (9)$$

Based on formula (9) had been constructed the MDTVN2015 model with resolution 1' x 1' in the WGS-84. In order to estimate the MDTVN2015 model we had used the national normal heights of local mean sea surfaces at the all 14 permanent tide gauge stations on national waters of Vietnam. A estimation results have been represented in Table 4.

Table 4 Control of results of the detection of the presence of systematic error in DTU10MDT model at 14 coastal and onshore permanent tide gauge stations along the national waters of Vietnam.

SNo	Tide gauge stations	State normal heights of the mean local sea surfaces (m)	Corrected quantities $MDTVN_z$ (m)	Differences d_i (m)
1	Co To	0.174	0.205	0.031
2	Hon Dau	0.000	0.005	0.005
3	Bach Long Vy	0.004	-0.078	-0.082
4	Cua Ong	0.056	0.088	0.032
5	Hon Ngu	0.085	0.102	0.017
6	Tien Sa	0.103	-0.052	-0.155
7	Quy Nhon	0.076	0.030	-0.046
8	Nha Trang	0.050	0.050	0.000
9	Vung Tau	-0.030	0.118	0.148
10	Con Đao	0.044	-0.029	-0.071
11	Phu Quoc	-0.098	0.013	0.111
12	Phu Quy	0.101	0.019	-0.082
13	Tho Chu	0.114	0.046	-0.068
14	Con Co	0.072	-0.028	-0.100
Total sum				-0.260

Calculated values: A = 0.260 m, B = 0.948 m. Because A = 0.260 m > 0.25×B = 0.237 m, in the sequence of the quatities $MDTVN_z$ exists remaining systematic error, which is equal to $\frac{0.260}{14} = 0.02 \;\; m = 2 \;\; cm.$ The remaining systematic error is considered to be negligible.

The accuracy of the quatities $MDTVN_z$ in MDTVN2015 model is established by following formula:

$$m_{MDTVN} = \pm \sqrt{\frac{\sum_{i=1}^{14} d_i^2}{2x14}} = \pm \sqrt{\frac{0.095778}{28}} = \pm \; 0.058 \;\; m.$$

5. Discussions

The construction and perfection of the international MDT models create favourable conditions for the sea bordering countries in the construction of the national MDT models according to the national waters. However, from the complicated hydro-meteorological conditions in the coastal shallow water zones of every country the used international MDT model could contain systematic errors. So a task of the detection of systematic error in the used international MDT model has greate important signification in the construction of the highly accurate national MDT model.

The method used in this article for the detection of systematic error in the international MDT model may be effective for accomplishing above mentioned task.

6. Conclusions

The research results represented in this article had shown that the national MDTVN2015 model constructed based on the DTU10MDT model on national waters of Vietnam has the high accuracy. One of key problems is the detection of systematic error in the quatities $\overline{MDTn}$ of the DTU10MDT model in coastal shallow water zones based on the national normal hights of the local mean sea surfaces at the permanent tide gauge stations. Method used in this article for performing of the detection of systematic error has a high confidence. However for effective usage of this method we must guarantee that the national normal hights of the local mean sea surfaces at the permanent tide gauge stations had been determined with high accuracy and confidence.

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