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Fitting the Global Digital Elevation Models into the Local Height System

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Abstract: Satellite mapping enabled obtaining Global Digital Elevation Models (GDEMs) to wide areas of the earth surface. Those DEMs have low accuracy, so they need to be evaluated and improved. In this paper, ground orthometric and GPS heights have been used to evaluate two GDEMs: Shuttle Radar Topography Mission (SRTM) with 30 m resolution; and ALOS Phased Array type L-band Synthetic Aperture Radar (ALOS/PALSAR) with 12.5 m resolution. Toshka in the south of Egypt and another site in the southwest of Egypt were both available for the study. The evaluation technique involved comparing the ellipsoidal and orthometric heights of the two GDEMs with the corresponding GPS and orthometric terrestrial data. The GDEMs have been through three steps of improvement. The first step includes converting the ellipsoidal heights of the used GDEMs to orthometric ones by using the High-Resolution Earth's Gravity Field Model (SGG-UGM-2) instead of the Earth Gravitational Model 1996 (EGM96). The second step has been performed by shifting the model heights using one point in the middle of the study area. The third step compromises shifting the model heights using the average value of well distributed five ground control points (GCPs). The results proved that the proposed simple shifting process is effective in improving the performance of the used GDEM. On the other hand, using GDEMs ellipsoidal heights is much better than using their orthometric heights. As well, using an accurate geoid model, instead of EGM96, in converting the ellipsoidal heights into orthometric heights can improve the GDEM performance.

Keywords: Global Digital Elevation Models (GDEMs), DEM evaluation, DEM improving, Shifting process, Global geoid models.

1. INTRODUCTION

Many applications and uses require the representation of the earth's surface. Using ground-based instruments would take time and effort, but the revolution of satellite mapping, made it possible to obtain DEMs of large portions of the earth's surface. The portrayal of the earth's surface is now simple, time and effort efficient. Unfortunately, the major issue with this approach is the low accuracy and precision of these DEMs in many locations due to the characteristics of the earth's topography and the lack of data in other locations, voids. The GCPs were used to validate the vertical accuracy of the GDEMs [1].The vertical accuracy of GDEMs can be improved by using terrestrial GPS data and applying the regression model-ling method and the kriging geostatistical approach [2], by substituting more exact Global Geopotential Model (GGM) for such geoidal undulation values [3]. The polynomial model and cubic convention resampling were used to modify the method based on merging the GPS ground control points with the SRTM3 surface [4]. This polynomial model is examined using a variety of data points and various data point spacings. The proposed empirical surface subtraction approach and the linear regression analysis approach were employed by [5] to assess and enhance the vertical accuracy of SRTM1 global digital elevation model. The available released DEMs are misleading the users when using them as they are. Trusted data from ground surveying, such as levelling, tacheometric surveying, total station, GPS, and laser scanning, can be added to the GDEM to improve the precision, accuracy and resolution. In the absence of ground data for enhancing the DEMs, simple suggestions could be introduced to guide the users to improve the performance of the existing DEMs, which is the main motivation behind this research

2.STUDY AREA AND DATA SOURCES

Data used in this study contains:

a) Test area 1: A grid of 239 fixed points cover an area of 18.85 km by 12.15 km in Toshka south of Egypt, about 55,000 Fedan, as shown in figure 1. The ellipsoidal coordinates of those points are obtained using GPS relative positioning. One of the High Accurate Reference Network (HARN) points was used as a reference station for the GPS work. Dual frequency receivers were used. The precision of the GPS results was within few centimeters. The orthometric heights of those fixed points are obtained by traditional surveying methods related to the Egyptian Surveying Authority (ESA) Benchmarks. Ordinary levelling has been performed, and the precision of the obtained height differences were within few centimeters. The maximum effect of using orthometric correction in the levelling process in such areas is within few centimeters, so it is not considered [6] [7]. The ellipsoidal heights of test area 1 range from 234 to 280 m with moderate slopes as shown in figure 1.

b) Test area 2: a grid of 2722 points in the southwest of Egypt cover an area of 210 km by 120 km, about 6 million Fedan, as shown in figure 1. GPS ellipsoidal heights of those points are available, while orthometric heights are not available. Test area 2 is introduced by ESA. The ellipsoidal heights of test area 2 range from 347 m to 707 m with rough slopes, figure 1. The terrain roughness is significant factor for the quality of products obtained from DEM [8].

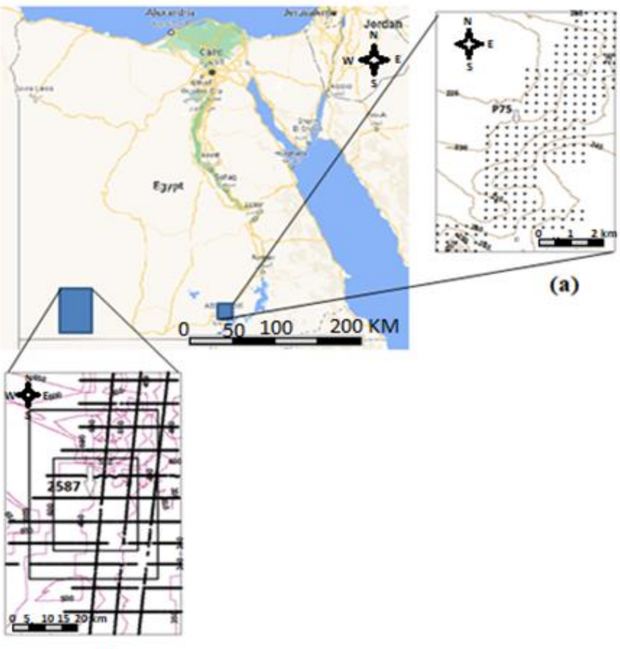

Fig 1. Test area 1, Toshka south of Egypt and test area 2, southwest desert of Egypt. (a) Study area 1, 239 points, about 19 km length by 12 km width; (b) Test area 2 and its two subzones, 2722 points, 1532 points, then 534 points respectively.

c) SRTM1 global DEM: It became available in year 2000 with 30 m resolution and ±16 m vertical precision [9]. It is downloaded from Earth Explorer (https://earthexplorer.usgs.gov). All of the released products' original SRTM1 elevations are calculated according to the WGS84 ellipsoid, and then heights relative to the geoid were obtained by adding the EGM96 geoid separation values [10].

d) ALOS/PALSAR global DEM: It became available in year 2014 with 12.5 m resolution and produced different residual topography values of almost -20.5 m with a standard deviation of 33.24 m [11]. Orthometric heights with the EGM96 vertical datum were provided for several DEMs by NASA. The Alaska Satellite Facility (ASF) MapReady geoid adjust tool was used to convert them to ellipsoid heights [12]. SRTM1 and ALOS/PALSAR are chosen for this research because of their common usage among the users. As well, they have good resolution among other available models.

e) Geoidal undulations from EGM96 and SGG-UGM-2: global gravity models were obtained from the official site of ICGEM, with 360˚ for EGM96 and 2190˚ for (SGG-UGM 2). Reference system is WGS84 for the two geoid models with resolutions of about 55 km and 9 km respectively. They have been downloaded from ICGEM International Center for Global Gravity Field Models (icgem.gfz-potsdam.de). SGG-UGM 2 is one of the best recent global gravitational models [13].

3. METHODOLOGY

For both areas the following steps have been followed by first validating the data and then enhancing it as follows:

3.1 Validation process

Step a: Compares SRTM1 and ALOS/PALSAR orthometric heights with the corresponding field values based on EGM96. The differences and their statistics are computed as follows:

$$\Delta H_{\text{SRTM1 or ALOS/PALSAR}} = H_{\text{field}} - H_{\text{SRTM1 or ALOS/PALSAR}} \quad (1)$$

Where H_{field} is the orthometric height of the field data.

Step b: Converts the orthometric height of SRTM1 and ALOS-POLSAR to ellipsoidal heights using the geoid undulations of EGM96 as stated in equation (2). Ellipsoidal heights of SRTM1 and ALOS/PALSAR are compared with their corresponding GPS field values. The differences are obtained, and their statistics are computed.

$$h_{\text{SRTM1 or ALOS/PALSAR}} = H_{\text{SRTM1 or ALOS/PALSAR}} + N_{\text{EGM96}} \quad (2)$$

Where h is the ellipsoidal height

Step c: Computes the new modified Orthometric height for SRTM1 and ALOS/PALSAR by subtracting the geoid undulations of SGG-UGM-2 from both global DEM's ellipsoidal heights as in equation (3).

$$H_{SRTM1\ or\ ALOS/PALSAR} = h_{SRTM1\ or\ ALOS/PALSAR} - N_{SGG\text{-}UGM\text{-}2} \quad (3)$$

The new modified orthometric heights are tested against their corresponding field values, the differences are computed, and their statistics are also computed.

3.2 Enhancement process

The enhancement process is done using three different trials as follows.

- Shifting the orthometric heights of SRTM1 and ALOS/PALSAR by using one intermediate point.
- Shifting once more but using the average of five well-distributed points over the study area using equation (4).

The shifted model orthometric heights are compared with their corresponding field values, and the differences are computed, and their statistics also computed.

$$H_{modified} = H_{model} + S \quad (4)$$

Where H_{model} is the orthometric height of model data and S is the shift value.

- Least squares fitting polynomial is applied using the well-distributed five points as:

$$\Delta h = h_{model} - h_{field} = a_o + a_1 * \varphi + a_2 * \lambda \quad (5)$$

Where:

- h_{model} is the ellipsoidal height obtained from the model.
- h_{field} is the ellipsoidal height obtained from GPS.
- φ, λ are the latitude and longitude of the point.

Solving equation 5 for well distributed five points in the study area, the three unknown coefficients (a_o, a_1, and a_2) can be obtained.

The obtained coefficients will be applied to each station within the test area to obtain the corresponding Δh values. These differences will then be deducted from the model ellipsoidal heights to estimate the corresponding ellipsoidal heights, and the statistics of the differences will then be computed.

4. RESULTS AND ANALYSIS

4.1 Validation of SRTM and ALOS-PALSAR in both test areas.

For the two GDEMs (SRTM1 and ALOS/PALSAR) in test area 1, a validation process has been done by comparing SRTM1 and ALOS/PALSAR orthometric heights with their corresponding field values. The differences and their statistics are computed and illustrated as shown in figure 2, followed by a comparison of SRTM1 and ALOS/PALSAR ellipsoidal heights with their corresponding field values. SRTM1 ellipsoidal heights are obtained by adding the geoidal undulations of EGM96 to SRTM1 orthometric heights as stated in equation 2. The differences and their statistics are computed and illustrated in Figure 3.

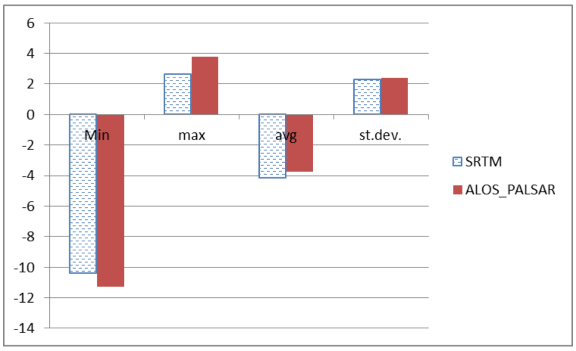

Fig 2. ($H_{field} - H_{SRTM1,\ ALOS/PALSAR}$)

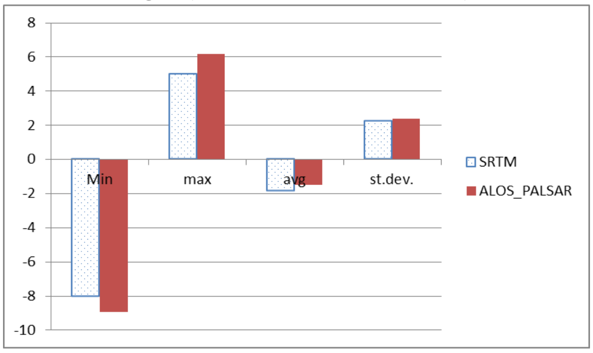

Fig 3. ($h_{field} - h_{SRTM1,\ ALOS/PALSAR}$)

TABLE 1. ($H_{field} - H_{SRTM1,\ ALOS/PALSAR}$)

	SRTM	ALOS_PALSAR
Min	-10.38	-11.28
max	2.63	3.78
avg	-4.15	- 3.75
st.dev.	2.28	2.39

TABLE 2. ($h_{field} - h_{SRTM1,\ ALOS/PALSAR}$)

	SRTM	ALOS_PALSAR
Min	-8.04	-8.94
max	5.00	6.16
avg	-1.87	-1.47
st.dev.	2.27	2.38

- In figure (2), the range and standard deviation of ALOS/PALSAR are bigger than the corresponding values of SRTM1, but the average of ALOS/PALSAR is smaller than the average of SRTM1. Standard deviations (st.dev.) of the SRTM1 are better than those of the ALOS/PALSAR.
- In figure (3), the average values of ALOS/PALSAR are less than those of SRTM1. The st.dev. of SRTM1 are slightly better than those of ALOS/PALSAR.

Excluding the geoid undulations, of EGM96, improved the average values from -4.15m for orthometric case to -1.87m for ellipsoidal case using SRTM1. It also improved the average values from -3.75 m to -1.47 m using ALOS/PALSAR.

For clarity, using ellipsoidal heights of DEMs is more reliable than using their orthometric heights and then a trustable geoid model can be used to convert the heights to orthometric ones.

Test area 2 will be divided into three zones with different radii, as shown in figure 1.

Both SRTM1 and ALOS/PALSAR GDEMs, in test area 2, will undergo validation by comparing ellipsoidal heights from SRTM1 and ALOS/PALSAR to the corresponding data from the field. Figures 4, 5, and 6 show the obtained differences for each of the three zones along with their data.

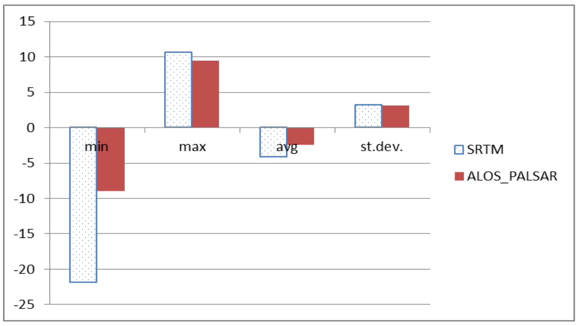

Fig 4. Zone 1-test area 2, 2722 points: ($h_{field} - h_{SRTM1, ALOS/PALSAR}$), R=125 km, units in meters.

TABLE 3. Zone 1-test area 2, 2722 points: ($h_{field} - h_{SRTM1, ALOS/PALSAR}$), R=125 km, units in meters.

	SRTM	ALOS_PALSAR
min	-21.84	-8.97
max	10.66	9.45
avg	-4.17	-2.40
st.dev.	3.17	3.14

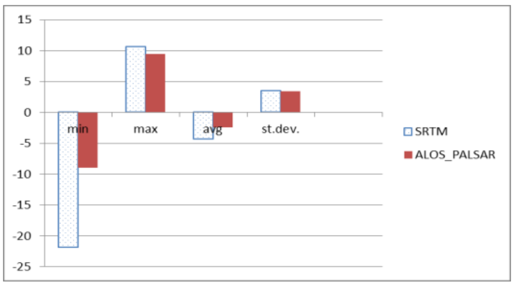

Fig 5. Zone 2-test area 2, 1532 points: ($h_{field} - h_{SRTM1, ALOS-PASSAR}$), R=89 km, units in meters.

TABLE 4. Zone 2-test area 2, 1532 points: ($h_{field} - h_{SRTM1, ALOS-PASSAR}$), R=89 km, units in meters.

	SRTM	ALOS_PALSAR
min	-21.84	-8.97
max	10.66	9.44
avg	-4.27	-2.42
st.dev.	3.54	3.38

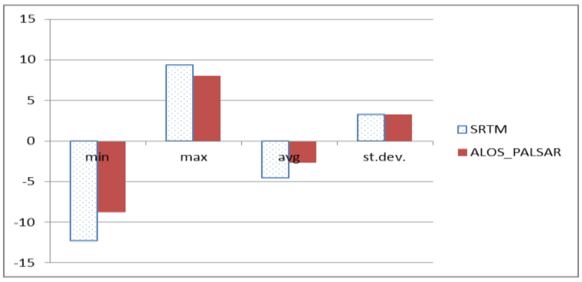

Fig 6. Zone 3-test area 2, 534 points: ($h_{field} - h_{SRTM1, ALOS/PALSAR}$), R=50 km, units in meters.

TABLE 5. Zone 3-test area 2, 534 points: ($h_{field} - h_{SRTM1, ALOS/PALSAR}$), R=50 km, units in meters.

	SRTM	ALOS_PALSAR
min	-12.29	-8.80
max	9.38	7.99
avg	-4.56	-2.64
st.dev.	3.28	3.26

For all three cases, range values of SRTM1 are larger than those of ALOS PALSAR and are generally getting smaller as the test area getting smaller. The average values of ALOS/PALSAR are much smaller than those of SRTM1. st.dev. of both models are close to each other.

Compared with the similar case in test area 1, the range in test area 2 is much larger than that of test area1 when using SRTM1 and it is not far from its value in test area1 when using ALOS/PALSAR. For both models, the average and st.dev. values are much larger in test area 2 than those of test area1. A possible reason is that test area 2 is much bigger than test area 1 and it has irregular topography compared to test area 1. The precision of the two models in test area 2 are close to each other unlike in the case of test area 1.

4.2 Enhancing the performance of SRTM1 and ALOS/PALSAR for both test areas

The enhancement procedure, as stated before, has been performed in three scenarios: first using one intermediate point; second by using the mean of five points; and lastly by using polynomial solution as stated in section 4.2.

4.2.1 Enhancing the performance of SRTM1 and ALOS/PALSAR, test area 1

The enhancement process has been performed as follow:

4.2.1.1 Testing shifted H SRTM1, ALOS/PALSAR using one point against field orthometric heights

All points were shifted by a value of -4.12 m for SRTM1 and -3.95 m for ALOS/PALSAR, which corresponds to the difference between intermediate point's observed orthometric height and the corresponding model one.

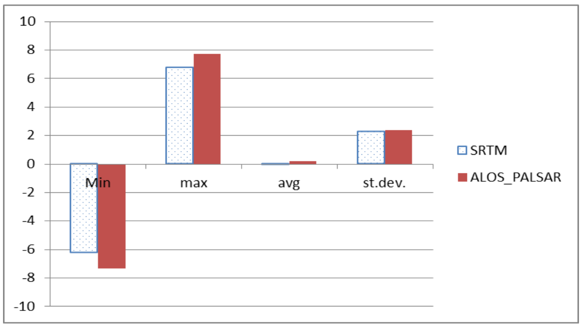

Fig 7. (H_{field} – shifted $H_{SRTM1,\ ALOS/PALSAR}$) EGM96, R = 11.72 km, units in meters.

TABLE 6. (H_{field} – shifted $H_{SRTM1,\ ALOS/PALSAR}$) EGM96, R = 11.72 km, units in meters.

	SRTM	ALOS_PALSAR
Min	-6.25	-7.33
max	6.76	7.73
avg	-0.03	0.19
st.dev.	2.27	2.37

The differences range for ALOS/PALSAR are always larger than those for SRTM1. The st.dev. of ALOS/PALSAR are larger than those of SRTM1. Once again, SRTM1 is more precise than ALOS/PALSAR. Comparing the shift results with the orthometric heights without shift, the average values are reduced dramatically after shift. In case of SRTM1, they reduced from -4.15 m before shift to -0.03 m after shift. In case of ALOS/PALSAR, they changed from -3.75 m to 0.19 m after shift. Shift process does not affect the st.dev. because the internal relation between the values still the same. In this regard, shifting process improves the average, but does not affect the precision of the model.

4.2.1.2 Testing shifted h SRTM1, ALOS/PALSAR against GPS ellipsoidal heights

All points have been shifted by a value of -1.89 m for SRTM1 and -1.71 m for ALOS/PALSAR, which corresponds to the difference between intermediate point's GPS ellipsoidal height and its model ellipsoidal height.

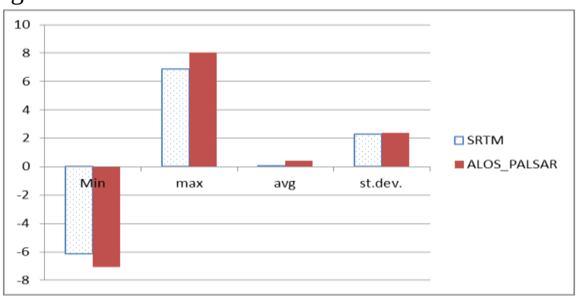

Fig 8. (h_{field} – shifted h_{model}), shifted by one point, R = 11.72 km, units in meters.

TABLE 7. (h_{field} – shifted h_{model}), shifted by one point, R = 11.72 km, units in meters.

	SRTM	ALOS_PALSAR
Min	-6.15	-7.05
max	6.89	8.05
avg	0.02	0.42
st.dev.	2.27	2.38

The range and st.dev. values of ALOS/PALSAR are larger than those of SRTM1, while the average values of ALOS/PALSAR are smaller than those of SRTM1. The Shift process improved the average values from -1.87 m to 0.02 m for SRTM1 and from -1.47 m to 0.42 m for ALOS/PALSAR. Shifting the ellipsoidal heights of the DEMs showed similar results as shifting their orthometric heights.

4.2.1.3 Testing shifted h SRTM1, ALOS/PALSAR, using one point and five points

For SRTM1, the shift values by using one point and five points were -1.89 and 0.05 m respectively. For ALOS/PALSAR, the shift values by using one point and five points were -1.71 m and 0.30 m respectively.

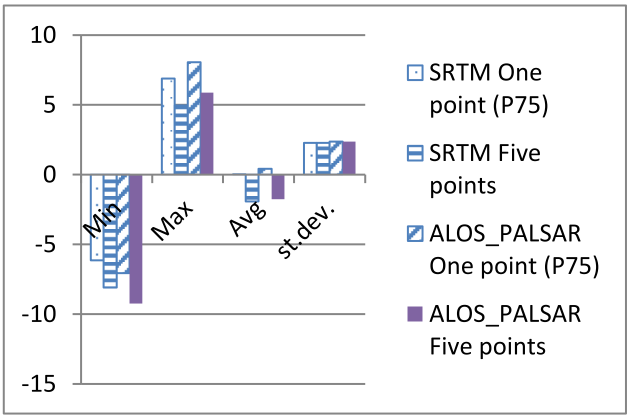

Fig 9. SRTM1 and ALOS/PALSAR ellipsoidal heights, shifted by one-point and by average of 5 points, R = 11.72 km, units in meters.

TABLE 8. SRTM1 and ALOS/PALSAR ellipsoidal heights, shifted by one-point and by average of 5 points, R = 11.72 km, units in meters.

	SRTM		ALOS_PALSAR	
	One point (P75)	Five points	One point (P75)	Five points
Min	-6.15	-8.08	-7.05	-9.23
Max	6.89	4.95	8.05	5.87
Avg	0.02	-1.91	0.42	-1.76
st.dev.	2.27	2.27	2.38	2.38

The average of the differences in case of using one point for shift is much better than that of using 5 points. The probability that at least one point among the used five will be erroneous is present. In the case of SRTM1, the average values are 0.02 and -1.91 m for one point and five points respectively. On the other hand, the average values for ALOS/PALSAR were 0.42 and -1.76 m respectively.

Referring to average values, still using the ellipsoidal heights of DEM is better than using the corresponding orthometric heights. In case of SRTM1, Using ellipsoidal heights resulted in average value of -1.87 m, while using orthometric heights resulted in average value of -2.87 m in case of SRTM1. In case of ALOS/PALSAR, using ellipsoidal heights resulted in average value of -1.47 m while using the orthometric heights resulted in average value of -2.47 m.

4.2.1.4 Testing modified H SRTM1 , ALOS/PALSAR orthometric heights

The ellipsoidal heights of SRTM1 and ALOS/PALSAR are transformed into their corresponding orthometric heights by subtracting the undulation values of one of the recent Earth-Geoid-Models (SGG-UGM 2). The new obtained orthometric heights of SRTM1 and ALOS/PALSAR are then compared to the field orthometric heights.

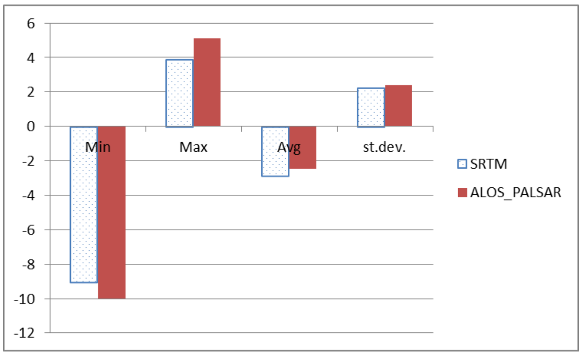

Fig10. Zone 1.1, 239 points, ($H_{field} - H_{SRTM1\ SGG\text{-}UGM\text{-}2}$), ($H_{field} - H_{ALOS/PALSAR\ SGG\text{-}UGM\text{-}2}$), units in meters.

TABLE 9. Zone 1.1, 239 points, ($H_{field} - H_{SRTM1\ SGG\text{-}UGM\text{-}2}$), ($H_{field} - H_{ALOS/PALSAR\ SGG\text{-}UGM\text{-}2}$), units in meters.

	SRTM	ALOS_PALSAR
Min	-9.08	-10.00
Max	3.91	5.096
Avg	-2.87	-2.47
st.dev.	2.27	2.38

The average value of ALOS/PALSAR is smaller than that of SRTM1. st.dev. value of SRTM1 is smaller than that of ALOS/PALSAR. Again, it means that SRTM1 is more precise than ALOS/PALSAR.

Using SGG-UGG 2 instead of EGM96 changed the average value from -4.25 to -2.87 m in case of SRTM1, while they changed from -3.75 to -2.47 m in case of ALOS/PALSAR. The st.dev. values did not change due to changing the used geoid model.

4.2.1.5 Testing shifted modified H SRTM1 , ALOS/PALSAR using one point

All points were shifted by a value of -2.84 m for SRTM1 and -2.66 m for ALOS/PALSAR, which corresponds to the difference between the intermediate point's observed orthometric height and its corresponding modified model orthometric height

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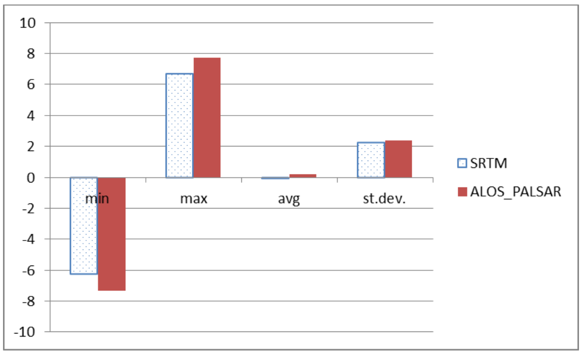

Fig 11. ($H_{field} - H_{SRTM1\ SGG\text{-}UGM\text{-}2}$), shifted by one-point, units in meters.

TABLE 10. ($H_{field} - H_{SRTM1\ SGG\text{-}UGM\text{-}2}$), shifted by one-point, units in meters.

	SRTM	ALOS_PALSAR
min	-6.24	-7.34
max	6.75	7.75
avg	-0.03	0.19
st.dev.	2.27	2.38

The range, average, and st.dev. values of ALOS/PALSAR are larger than those of SRTM1. The same results have been obtained for shifting modified orthometric (SGG-UGG 2) heights and for shifting the orthometric heights (EGM96). Both cases are close to shifting the ellipsoidal heights.

4.2.1.6 Testing shifted modified H SRTM1 using one and five points

This test has been done only for shifted modified SRTM1 orthometric heights to study the effect of the shift using five points instead of using one point. Recalling that

ALOS/PALSAR is released only as ellipsoidal heights, all points were shifted by a value of -2.76 m for one point-shift and -0.95 m for five points-shift in case of SRTM1.

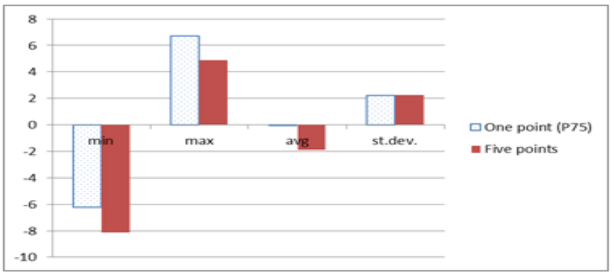

Fig 12. ($H_{field} - H_{SRTM1\ SGG-UGM-2}$), shifted by one-point, five points, R = 11.72 km, units in meters.

TABLE 11. ($H_{field} - H_{SRTM1\ SGG-UGM-2}$), shifted by one-point, five points, R = 11.72 km, units in meters.

	One point (P75)	Five points
min	-6.24	-8.12
max	6.75	4.87
avg	-0.03	-1.91
st.dev.	2.27	2.27

For both cases, the range and st.dev. are almost equal. However, the st.dev. in case of using one point (-0.03 m) is much better than that of using 5 points (-1.91 m).

4.2.1.7 First order polynomial improvement

Recalling that by applying a first-order polynomial in latitude and longitude at the well distributed five points, equation (5):

$$\Delta h = h_{model} - h_{field} = a_o + a_1 * \varphi + a_2 * \lambda \quad (5)$$

The equation coefficients will be obtained and applied to each station within the test area to produce the corresponding values of Δh, which will then be deducted from the model ellipsoidal heights to obtain the corresponding estimated ellipsoidal heights. The statistics of the differences have been computed as shown in figure (13).

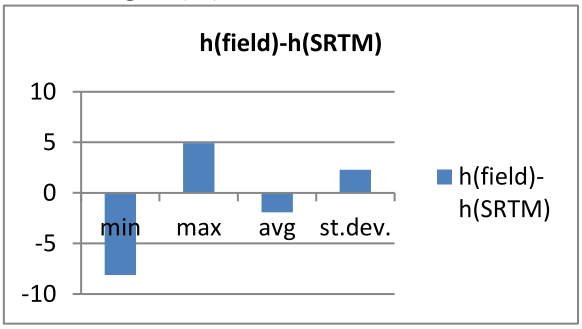

Fig 13. Zone 1, 239 points: SRTM1 ellipsoidal heights, improved by using first order polynomial, R = 11.72 km, units in meters.

TABLE 12. Zone 1, 239 points: SRTM1 ellipsoidal heights, improved by using first order polynomial, R = 11.72 km, units in meters.

	h(field)-h(SRTM)
min	-8.11
max	4.92
avg	-1.92
st.dev.	2.27

As can be observed, the results of using the polynomial in the improvement process are very close to those obtained for the shifting using the average of the same five points. It is worth mentioning that, the shifting process is much easier and practical than the polynomial-based enhancement.

4.2.2 Enhancing the performance of SRTM1 and ALOS/PALSAR, test area 2

The enhancement process has been done as follow:

4.2.2.1 Testing shifted ellipsoidal heights of SRTM1 and ALOS/PALSAR, using one intermediate point

The test has been done 3 times with 3 different radii. All points were shifted by a value of -3.96 m for SRTM1 and -2.27 m for ALOS/PALSAR.

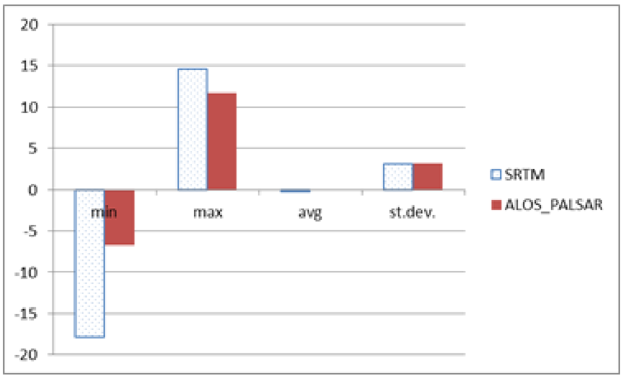

Fig 14. Zone 1, 2722 points: ellipsoidal heights, shifted by one-point, R = 125 km, units in meters.

TABLE 13. Zone 1, 2722 points: ellipsoidal heights, shifted by one-point, R = 125 km, units in meters.

	SRTM	ALOS_PALSAR
min	-17.88	-6.70
max	14.62	11.72
avg	-0.21	-0.13
st.dev.	3.17	3.14

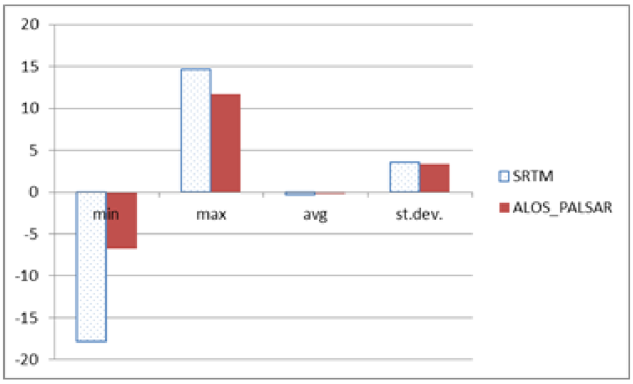

Fig 15. Zone 2, 1532 points, shifted by one-point, R = 89 km, units in meters.

TABLE 14. Zone 2, 1532 points, shifted by one-point, R = 89 km, units in meters.

	SRTM	ALOS_PALSAR
min	-17.88	-6.70
max	14.62	11.72
avg	-0.31	-0.16
st.dev.	3.54	3.38

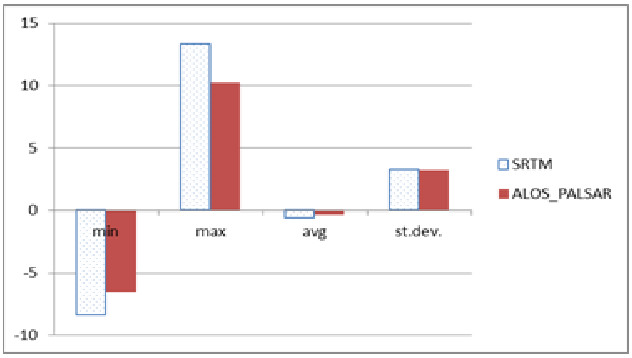

Fig 16. Zone 3, 534 points, shifted by one-point, R = 50 km, units in meters.

TABLE 15. Zone 3, 534 points, shifted by one-point, R = 50 km, units in meters.

	SRTM	ALOS_PALSAR
min	-8.33	-6.53
max	13.35	10.26
avg	-0.60	-0.37
st.dev.	3.28	3.26

For all three cases, range values of SRTM1 are larger than those of ALOS/PALSAR and they are generally getting smaller as the test area getting smaller. The average values of ALOS/PALSAR are smaller than those of SRTM1.
st.dev. of both models are close to each other. Shifting process reduced the average values from -4.17, -4.27, -4.56 to -0.21, -0.31, -0.60 m in case of SRTM1 and reduced them from -2.40, -2.42, -2.64 to -0.13, -0.16, -0.37 m in case of ALOS/PALSAR.

4.3 Comparing SRTM1 ellipsoidal heights with their corresponding values of ALOS/PALSAR.

The ellipsoidal heights of SRTM1 have been compared with their corresponding values from ALOS/PALSAR. The statistics of the differences have been computed and compared for both test areas 1 and 2 as presented in figure 17 and figure 18.

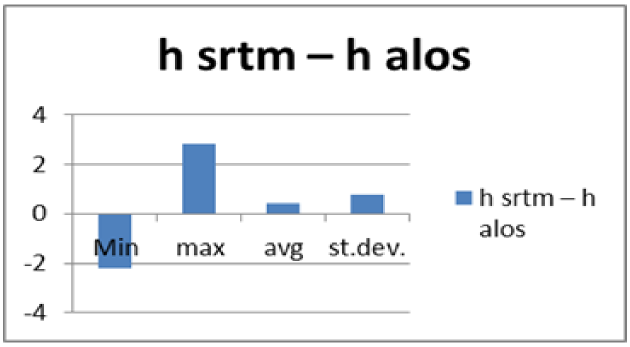

Fig 17. Test area 1, (h $_{SRTM1}$ – h $_{ALOS/PALSAR}$), units in meters.

TABLE 16. Test area 1, (h $_{SRTM1}$ – h $_{ALOS/PALSAR}$), units in meters.

min	**-2.20**
max	2.82
avg	0.40
st.dev.	0.77

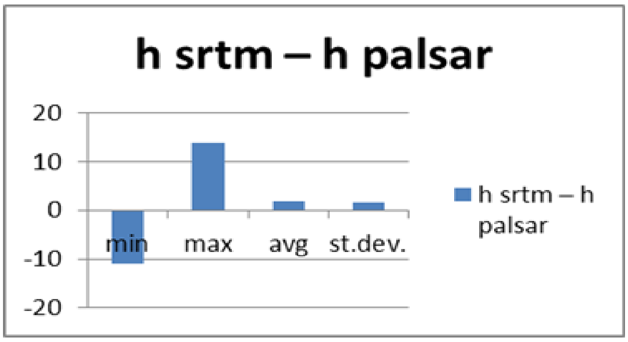

Fig 18. Test area 2, (h $_{SRTM1}$ – h $_{ALOS/PALSAR}$), units in meters.

TABLE 17. Test area 2, (h $_{SRTM1}$ – h $_{ALOS/PALSAR}$), units in meters.

min	**-10.96**
max	13.90
avg	1.77
st.dev.	1.63

The range of the differences between the two models in test area 1 is 5.02 m with average value of 0.40 m and st.dev. of 0.77 m. The range of the differences between the two models for test area 2 is larger than those of test area 1, 24.86 m, with average value of 1.77 m and st.dev. of 1.63 m.

5. CONCLUSIONS

Two GDEMs have been evaluated and improved in this research. The two models are SRTM1 and ALOS/PALSAR. The evaluation process has been carried out over two study areas: Toshka, at the south of Egypt, and the other one is located at the south-west desert of Egypt. 239 control points with measured GPS ellipsoidal heights and leveling orthometric heights in test area 1, and 2722 GPS ellipsoidal heights in test area 2 have been used. The adopted methods to evaluate the accuracy is the comparison between SRTM1 and ALOS/PALSAR orthometric heights with their field corresponding values in test area 1 and by comparing SRTM1 and ALOS/PALSAR ellipsoidal heights with their field corresponding GPS values in the two test areas. The adopted approaches to improve the performance of the two GDEMs were as follow: Both GDEMs' ellipsoidal heights are shifted once using an intermediate point and once more using the average of five well distributed points over the study area. The geoid undulations of SGG-UGM-2 are obtained from ICGEM, and they are subtracted from both global DEMs' ellipsoidal heights to obtain new (modified) orthometric heights which are then tested against their corresponding field values. The results showed that the st.dev. of SRTM1 data is equal to ±2.27m in moderate slopes and ±3.54m in rough slopes. For ALOS/PALSAR, the st.dev. values are ±2.38m and ±3.38m for moderate and rough slopes respectively. In most cases, SRTM1 is more precise than ALOS/PALSAR. Users are using global DEMs without verification while they are not very precise rather than accurate.

Using DEMs ellipsoidal heights is much better than using their orthometric heights. The averages of the differences are -1.87 and -1.47 m for ellipsoidal heights in cases of SRTM1 and ALOS/PALSAR respectively. The corresponding values are -4.15 and -3.75 m in the case of orthometric heights for SRTM1 and ALOS respectively. Using an accurate geoid model, instead of EGM96, in converting the ellipsoidal heights of the DEMs into orthometric heights, improves the DEM performance. The averages of the differences in case of using EGM96 were -4.25 and -3.75 m and in case of using SGG-UGM 2, they were -2.87 and -2.47 m for SRTM1 and ALOS/PALSAR respectively. The proposed simple shifting process is effective in improving the performance of the used DEM. However, it does not affect its precision. It makes the DEM surface simply near to the ground surface using one or few ground points. Shifting process improved the average values from -1.87 to 0.02 m for SRTM1 and from -1.47 to 0.42 m for ALOS/PALSAR. For large areas, shifting using one point is better than using 5 points. The situation is inverting while the area is getting smaller. Five points in large area may include one or more erroneous point because of the probable irregular topography, while the probability decreases in small area. The accomplished results showed that SRTM1 produced smaller differences (both in mean and st.dev. values), than ALOS/ PALSAR. The accomplished findings reveal that global DEMs perform better on moderate slopes than on rough slopes. To increase the accuracy of a GDEM in EGYPT, a precise Global Geopotential Model (GGM) is needed. The obtained results from the enhanced models presented here could be used for hydrologic research (hydrologic modelling), evaluation of natural hazards (tsunami and flooding), and vegetation surveys (3D urban structure characterization).

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