ASSESSMENT AND CORRECTION OF SRTM DEM WITH REFERENCE TO GEO-HAZARD IDENTIFICATION IN THE CAMERON HIGHLANDS, MALAYSIA.

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Abstract

This research assesses the accuracy of SRTM DEMs acquired over the mountainous-hillands of Cameron Highlands with DEMs generated from Digital Aerial Photograph (DAP) with a fine (2 m) spatial resolution and height resolution of about 0.5 m. The ground control points used for generating stereo models from the DAP were acquired during field work using GPS which achieved accuracy better than 2 cm in most cases.

To overcome the difficulty of overlaying the DEMs with the DAP DEM as no features can be easily identified on both the images, therefore a technique of using transects and contours generated from the DEMs were used to correct the horizontal displacement. These then allowed an analysis of the height accuracy to be undertaken.

The height of SRTM DEM was also corrected by applying Linear Regression Models. These models were produced by comparing pixels obtained from points, profiles and an area. Once again the corrected DEMs were assessed. Finally the extracted profiles and contours from the corrected SRTM DEM were compared with the reference DEM.

From the comparisons, the horizontal errors of the SRTM DEMs were found to be about one and the half pixels (≈140 m) to the east. The SD of height differences using 90% data were 9.2 m from the profile comparisons; 10.4 m from the pixel area comparisons and 10.8 m from GPS GCPs comparison. From the three comparisons, the means of the height differences were 5.2 m, 6.1 m and 15.2 m. When the corrections were applied the generated contours from the SRTM DEM were close to the DAP reference contours.

Using contour colours images and height modelling, the corrected DEM was found to have the potential to detect areas that prone to flash floods and mudslides.

Introduction

DEM stands for digital elevation models. Elevations are ground level heights above a given reference (Small, 1998). Digital terrain model (DTM) is another term that commonly used. The term DEM is preferred for models containing only elevation data. RADAR and aerial photogrammetry generated DEMs are examples of data capture for DEM, because in vegetated areas the height of the canopy rather than ground-level elevation represents the DEM. DEMs can be represented either by mathematically defined surface or by point or line images using image data (Burrough, 1990). In point models an altitude matrix or regular rectangular grid is the most common form of DEM. Various products can be generated from DEMs such as block diagram, aspect image, shaded relief image, slope image, contour maps and volume estimation.

DEM can be obtained from various sources and generated by various techniques. The most common form of DEM is the regular rectangular grid can be produced by interpolation of irregularly or regularly spaced elevation points. These elevation points of the earth's surface are usually obtained from stereoscopic aerial photographs, RADAR remote sensing, and stereoscopic optical remote sensing or from ground survey. Shuttle borne SRTM is example of system using single pass type of interferometry technique to generate DEM.

Environmentalist, geographers, surveyors and civil engineers uses DEMs of different sources for statistical analysis, mapping, thematic interpretation, comparison of terrain and volume calculation. Environmentalists, disaster monitoring teams together with other government and non-government agencies need DEMs for planning and to mitigate the effect of natural disaster like landslide, flash flooding and land subsidence. Environmentalist can use the contour map or DEM to map area that prone to flood, and can pin point area that need immediate attention such as to deepen shallow river or to taking remedial action to stabilize slope to prevent landslide and mitigate flash flooding. With a DEM, the volume of water received for a particular valley area can be computed and modelled. If the amount of rainfall in a particular period can be recorded, the consequence hazardous event such as flood can be predicted.

Accurate representation of topography is desirable because in modern work these representations such as DEM and other DEM products like profile (transect), contour lines map and etc. are important reference for the various applications mentioned. In statistical analysis, heights of transects and heights of DEM's area/patches are useful to provide reference heights in comparison of different kind of terrain that usually acquired from difference sources. For example, Rodridgues et al (2003) compared NASA/NIMA Shuttle Radar Topography Mission (SRTM) DEM with various reference DEMs.

It is a normal practice for the data provider to carry out research on the assessment and validation of RADAR DEM's generation in order to check the accuracy of the system. It is impossible however for the data provider to check the accuracy for every data set. Therefore, the user should make effort to check the accuracy of the data and eliminate errors. Errors may occur in processing and be due to the wrong coordinates of local reference points provided by local government being used, inaccurate parameters in coordinate conversion from a local system to a global system or reference or can be due to many other reasons. As a pre-emptive move, and before DEM can be used for mapping and other applications it is necessary to validate the data particularly the height accuracy and later correcting errors.

The assessment data was first need to be co-registered with the reference data to correct for horizontal error before the height assessment was carried out. With out co-registration the resultant height difference can be affected by errors. For flat areas or areas with uniform gradient, errors might not be too critical. However, in rugged and undulating areas, horizontal errors can cause severe errors in heights.

Co-registration is a process to match together two images/DEMs of the same area but acquired from different sources. The co-registration of DEMs can be done easily if it is accompanied by the brightness images. Because they are co-registered, then identical features such as corner reflectors, water bodies, coastal lines, buildings and road junctions can be used as tie points. If only DEMs are available, coastlines may be the only choice. Some RADAR DEM's products like coherence image and shaded relief image which are co-registered may provide alternative for co-registration if images have fine resolution so some features like top of the mountains may be identified. Unfortunately in many cases they may not be visible or available.

In this research SRTM DEM was to be used in geo-hazard applications. Check on the accuracy is important to make sure the results of the application are reliable. Before height assessment, co-registration is necessary for high relief terrain like Cameron Highlands. In this no coastlines are available in SRTM DEM or shaded relief and no brightness image accompanying the DEM. Therefore new techniques were employed for co-registration by comparing contours and profiles of SRTM DEM with DAP DEM. Together with pixels profiles and pixels Sample Area of DAP DEM and GPS GCPs were used in comparison with SRTM DEM for height assessment. Linear Regression models were derived from various height comparisons. Then the models were also applied to correct the SRTM DEM. Simultaneously the technique computes the

R-squared to check the relationship between the datasets. To show the graphical results, contours and profiles of SRTM DEM were compared with the DAP DEM together with AIRSAR DEM that was corrected using similar technique. Finally the corrected DEM was used in identifying geo-hazards prone areas.

Study site

Cameron Highlands is located in the main highland range of Malaysia about 150 km North of Kuala Lumpur. The Research Site is bounded by Longitudes 101 20 21E to 101 26 50E and Latitudes 4 24 37 N to 4 33 19 N (Geographic Lat/Lon WGS 84 Projection). It covers an approximate area of 16 km by 12 km. The smaller Sample Area covered by the aerial photography DEM is 1.7 km by 3.2 km area, situated within the Research Site. The physical topography of the Cameron Highlands is rough and hilly. Local relief ranges from 800 to 2200 m. Some areas are mountainous particularly along the western parts. The eastern part of the area is dominated by hillands. There are flat valleys, mixed with small hills, where small town settlements are located.

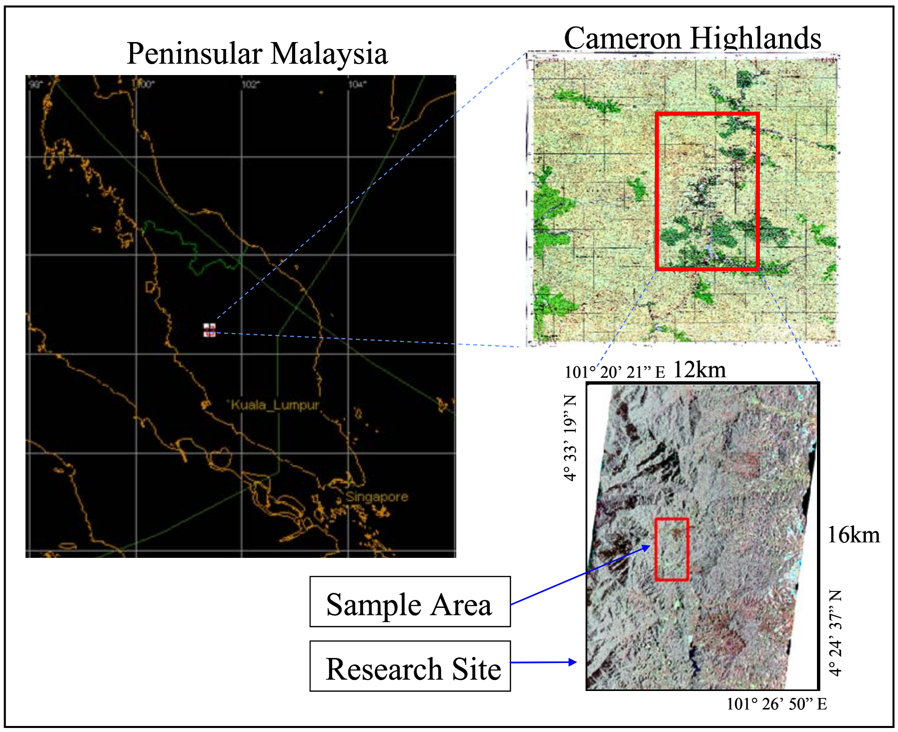


Figure 1: Location of the study area - Cameron Highlands, Malaysia, which consist of Research Site and Sample Area.

Data description and data acquisition

- *GPS Ground Control Point (GCP)*

To establish GCPs, two highly accurate GPS reference points that were acquired from a research team from UTM, Malaysia were used. One of the GCP was used as base for the measurement of the new 10 points using Global Positioning System (GPS). The other point was used as a check point. A pair of LEICA GPS System 500 units was used for these measurements.

- *Digital Aerial Photograph (DAP)*

Five 1997 DAP were acquired from the Malaysian Surveying and Mapping Department. These black and white digital images have resolution=0.54 m pixel. (1 image pixel represents 0.54 m on the ground).

- *Shuttle Radar Topographic Mapping (SRTM) SRTM DEM*

This data was collected during SRTM 2000 flown on board of Space Shuttle Endeavour. During this mission about 80% of the earth between the latitude of 60° degree North and 56° South was mapped. The DEM was acquired using relatively short wavelength of C-band (5.6 cm). For the Eurasia region and all part of the world except USA, data were released at a spacing of 3 second (i.e. about 90 m). The targeted accuracies for the mission was less than 16 and 10 m for absolute and relative vertical accuracy respectively (Kellndorfer, 2004; Rodriguez *et al*., 2005).

SRTM DEM file (N04E101.hgt) was downloaded from the EURASIA website. This is 1°x1° tile. The coverage is between Longitude 100° 59' 55.5" E to 101° 59' 55.5" E and Latitude 4° 00' 1.50" N to 5° 00' 1.50" N.

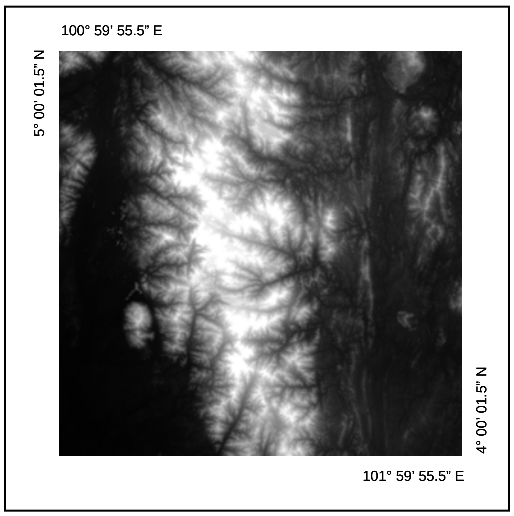


Figure 2: SRTM DEM original image.

For this research the size of the sub-area image coverage used is slightly larger than the Research Site that is from 763094.89 E to 764782.89 E and from 493805.19 N to 496919.19 N. The pixel resolution of this data is x=92.48 m and y= 92.15 m.

- *AIRSAR Data*

AIRSAR data were collected over the Cameron Highlands on 3rd December 1996, during the PacRim1 campaign. The flight line was oriented N7.7°, and covered an area of 41.32 km long and 11.09 km wide. The 40 MHz – 10 km swath bandwidth used for this data gives DEM resolution of 10 by 10 meters.

Methodology

i) Data post processing

- *GPS Ground Control Points (GCPs) processing*

For post-processing, Trimble Geographic Office (TGO) software was used in this project to compute baselines, coordinates and height. Three observation files were processed with an adjustment style setting of 95% confidence limit. Adjustments were performed in WGS 84. Calculation to determine the coordinates of the observed GPS ground control point was based on "single base-radial technique". In this technique, the known latitude, longitude and elevation of base point (HABU station) were fixed. The radial distant, azimuth and delta height from that base point to the observed points to be determined were then calculated. Finally, the coordinate of the observed point was determined by adding the calculated values to the fixed values. The final coordinates are given as Geodetic Coordinates (i.e. Geographic Latitude and Longitude).

The results of the derived GCP latitudes, longitudes and ellipsoidal heights and errors using 1.96σ show the accuracy achieved is better then 2 cm in most cases with a maximum error of 0.052 m. The different coordinates of check point (BM-C1032) between the given and the measured is latitude=0."0009 (0.03 m), longitude=0."0071 (0.22 m) and ellipsoidal height=0.04 m.

The 10 new GCPs together with the original 2 GCPs were used either as control points for aerial triangulation of the digital aerial photographs or as ground truth data for the validation of the SRTM DEM.

- *Digital Aerial Photograph (DAP) processing*

The images were first processed with various procedures on a Digital Photogrammetric Workstation (DPW) using Socet-Set software. The objective is to establish stereo models, using a total of 6 newly measured GPS ground control points (GCP), which fulfils the minimum requirement i.e. at least one each at block corners and one at the centre.

Since the 5 DAPs used were located in the same strip, only one block of adjustment was required for the process and subsequently 4 stereo models were formed. Stereo model images were generated through a pair-wise rectification process. During the aerial triangulation process the x and y coordinates give standard deviation of 1 to 1.5 m and z=0.4 m respectively. The accuracy achieved is satisfactory with RMS in x=1.2 m, y=1.0 m and z=0.1 m.

DEMs were extracted for various validation processes undertaken. The files were transferred to intermediate software of Global Mapper and 3DEM, for file re-formatting and merging before sent to ENVI software for application.

The merged DEM and mosaic produced was resized in ENVI into 1690 m by 3116 m DEM area is called the Sample Site DEM for reference. Profiles were generated from this DEM for reference. Fifty meters interval contours were also generated from this DEM also for reference.

- *Shuttle Radar Topographic Mission (SRTM) DEM*

The downloaded SRTM data was opened in ENVI as a topographic file which then the projection was converted from Geographic Lat/Long to UTM projection WGS 84 datum. Because of the conversion, the original pixels resolution size changed automatically from 3 arc second by 3 arc second to become 92 m x 92 m. Several techniques were used for the conversion, which found that contours and profiles generated using techniques of triangulation have patterns closer to the contours and profiles of DAP DEM, and were therefore used in this research.

This DEM (Figure 3 a) was later resized to the size of Research Site (Figure 3 b). At this stage the pixel resolution was maintained at its original resolution, which is 92 m when the contours were extracted. By maintaining the pixel resolution size the extracted contours (Figure 3 c) have the original smoothness, which are the correct contours to compare with the reference contours. These contours represent the Sample Area which is a smaller part of the Research Site area (Figure 3 e) and is the one that was used for contour comparison.

The Research Site DEM was again reduced to match the smaller Sample Area size (Figure 3 d) photographically derived DEM. The next procedures was to extract profiles from this DEM and then to compare these profiles with the profiles from the DAP DEM. To do so the SRTM profiles were extracted from the DEM having the same pixel size and dimensions, and having the same registration as the DAP DEM. The pixel size was changed to 2 m for this purpose.

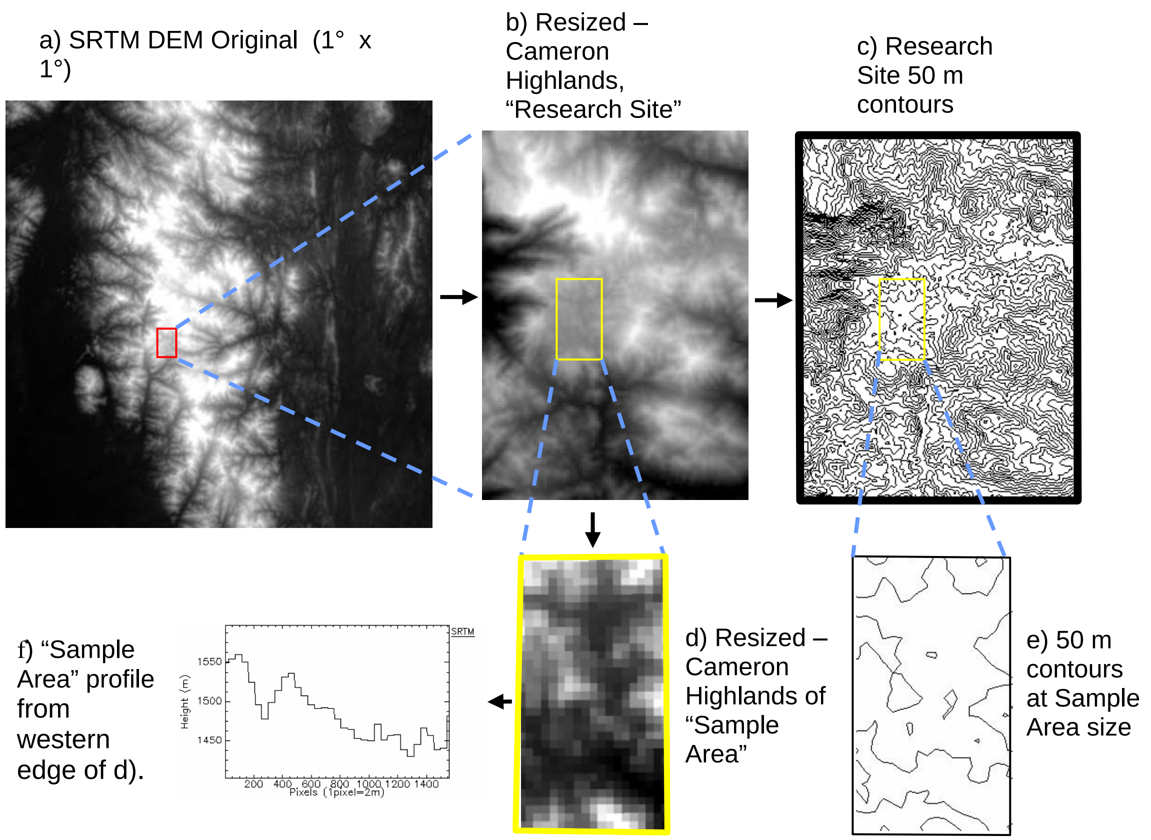


Figure 3: Sequence of procedures; SRTM DEM was resized to the research site and sample area and contour extraction.

ii) Co-registration of SRTM DEM with DAP DEM

Three relatively simple but new methods (not reported before) of co-registration were applied. The new techniques manually use graphic comparison of profiles and contours to aid for the co-registration of SRTM DEM with DAP DEM. In this research geo-referencing, re-sizing and re-sampling are part of procedures required before the horizontal assessment and the final co-registering process. In brief some of the important information and the co-registration procedures undertaken are as the following: The reference DEM is photogrammetrically extracted and is geo-referenced to UTM WGS 84. The assessment data of SRTM DEM is also geo-referenced to UTM WGS 84. Horizontal assessments were made by comparing profile and contours extracted from these geo-referenced DEMs. From the horizontal assessment, the final x and y displacement were determined. The final displacements were decided from those two results and then applied in the final co-registration process to co-register the images.

iii) Height assessment of SRTM DEM

After SRTM DEM was co-registered by correcting the displacement (1 pixel and the half=140 m to the west), height assessment was carried out as follows: 1) Comparison with profiles of DAP DEM, 2) Comparison with the whole pixels of DAP DEM of Sample Area and 3) Comparison with GPS GCPs. These methods involve computation and evaluating of height differences. The final height difference is measured in mean, standard deviation (SD), root mean square error (RMSE), minimum and maximum.

Comparing the true height elevation data and checking the resultant mean of the height differences is the best way to gauge the height accuracy of an assessment DEM. The closer to zero the more accurate is the mean of the height differences, so the better is the assessment data. Nevertheless mean can be affected by 'averaging out' problem, where a few extreme values can cancel out many good points which resulting less mean high difference. Therefore, standard deviation and RMSE were used to double check the resultant mean. The smaller the SD of the height differences the more precise is the assessment data. The problem with SD is when the data is masked the SD will definitely become smaller. RMSE is an indicator of the accuracy of the overall result but RMSE is dependent to mean and SD.

DEM data are normally subjected mainly to random errors together with other types with smaller errors. For SRTM DEM random errors can be caused by bad values, extreme values, data drop out, holes due to phase unwrapping problem, over lay and shadow areas. For DEM's extracted from DAP, random errors can be caused by clouds, cloud's shadows and shadows. To improve the data accuracy, the outliers need to be removed by removing the points/pixels with large height errors. It is widely assumed that only 90% of the data is useful while 10% of the data is assumed as containing most of the random errors and should be dropped. For each DEM, it is difficult to know which data is bad except data that contains extreme values. The method applied in this research to handle this problem, was to subtract SRTM DEM from DAP DEM. The assumption that has always been made is that pixels of the reference datasets (DAP DEM) have correct heights (i.e. after the 10% data was removed). From the height differences, pixels in both compared DEMs which are found to have large height difference value were dropped from the calculations.

Graphical presentation was employed with the aim to aid and complement the numerical height assessment. The height assessment was carried out by visually interpreting the graphic of height profiles and contour lines.

iv) Vertical (heights) correction of the co-registered SRTM DEM

The aim is to correct height of the following DEMs; the original, the co-registered (horizontally corrected) and the co-registered with the 90% of the data applied with mask DEM. It is important that the heights of the DEMs are properly corrected before being used in real work applications. For the correction, the first step is to form Linear Equation Models (LEMs) and the second step is to apply the models to the DEMs.

The Linear Regression Model that expressed as Response = a + b*Predictor was used in this research. The predictors are SRTM DEM and response is DAP DEM. 'a' and b' are two parameters to be determined by comparing the two set of DEMs heights (response and predictor). The least square method provides the formula to compute "a" and "b".

Having created the models, the best fit values (the corrected heights) of every pixels of the SRTM DEM can be computed by multiplying the original values that was used to create the models with computed 'b' and also added with 'a'.

Numerous models were derived from different types of comparisons i.e. comparison by pixels of profiles, pixels of an area and pixels/points. The technique of comparison is similar to the assessment of height difference by evaluating mean, SD and RMSE. Similarly, the derivations of LEMs were done in EXCEL and MINITAB software.

In the process of generating LEMs, an R-squared value is calculated simultaneously. The R-squared test was used to check the relationship between two datasets. If the resultant R-squared values of the compared datasets are high that means the relationship is good. The R-squared value was calculated in various tests of comparison using both assessment DEMs. One of the aims of checking relationship is also to prove the original data have height error and can be improved by registration and the 90% data is the ideal percent to remove random errors in SRTM DEM.

v) Applications

Two techniques were used to identify areas that prone to flash flooding. The first technique is to use multi-colours heights generated from the DEMs and the second technique is to apply models of different water levels on the DEMs.

On those images, areas that are supposed to be prone to flash flooding could be in the form of: a) underwater areas (polygons) that are completely separated from other larger underwater areas or b) underwater areas connected to other larger underwater areas by narrow channels.

In the first technique, by choosing a contour interval, example 50 m in this research and assigning different colours for each contour interval, the whole scene will be represented by multi-colours heights.

In the second technique, by changing the water levels i.e. applying different models, areas that are supposed to be underwater will be displayed in a new colour, example: white is used in this research, while the colours of the rest of the higher areas in the scene will remain unchanged. By changing the water levels i.e. by trial and errors, areas that are prone to flash flooding can be identified by looking at the pattern of the resultant shapes of the underwater areas.

Results

i) Co-registration and horizontal assessment

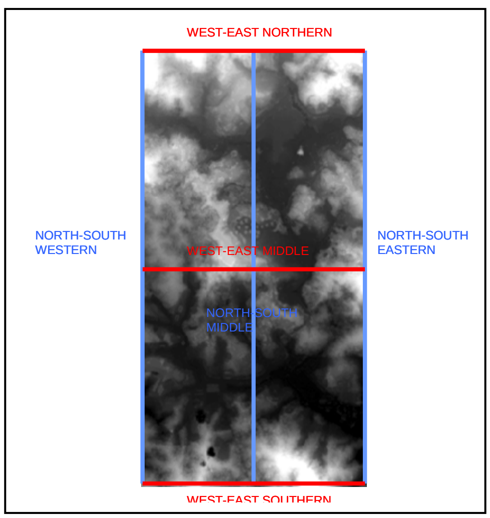


Figure 4: The location of the six transects (sample plots) superimposed on reference DEM of Sample Area.

Figure 4 shows the location of 6 transects superimposed on DAP DEM of the Sample Area. Only some examples of profile were used and displayed in this paper.

The resultant height profiles of the SRTM DEMs and the reference DAP DEM at each transect are plotted and displayed together in Figure 5 for transects in a North-South direction, while profiles in a West-East direction are shown in Figure 6.

From the North-South profiles, it can be seen that the SRTM DEM (Triangulation) matches better than SRTM DEM (RST) with the reference DEM profiles with no planimetric error in y (North-South) for SRTM data. Having considered SRTM DEM (Triangulation) as the best choice of the two SRTM DEMs, looking at West-East profiles, it can be seen quite clearly there is horizontal displacement of the SRTM DEM from the reference (DAP DEM) profiles. From all three windows, there is a displacement from East to West (x direction) with the offset about one and a half pixels (1 pixel = ~92 m).

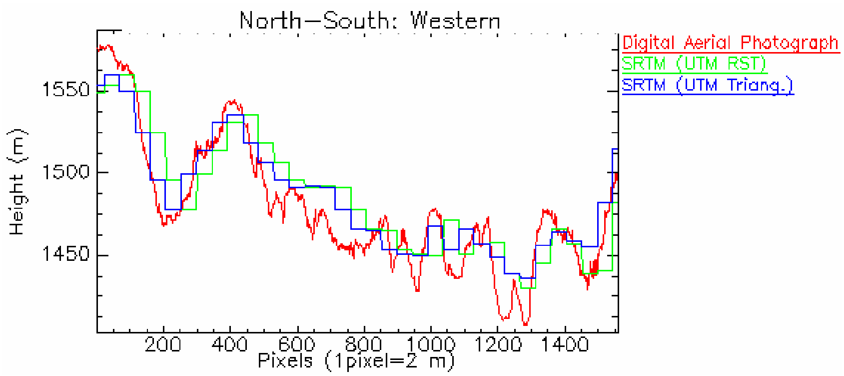


Figure 5: Comparison of profiles; SRTM DEM (UTM RST) in green, SRTM DEM (UTM Triangulation) in blue and DAP DEM in red of North-South Western transects.

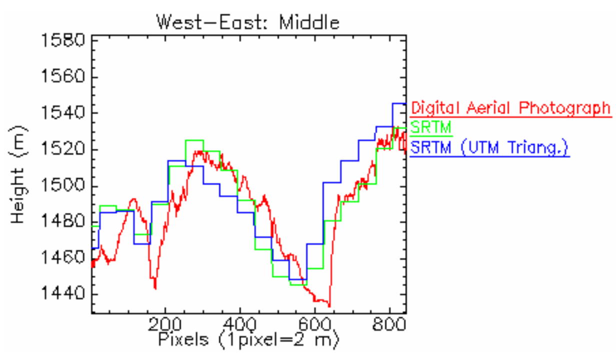


Figure 6: Comparison of profiles; SRTM DEM (UTM RST) in green, SRTM DEM (UTM Triangulation) in blue and DAP DEM in red of West-East, Middle transects.

Figure 7 shows the 50 m contours of SRTM DEM compared to the DAP DEM contours. It can be seen that the contours derived from SRTM DEM using Triangulation transformation have a uniform pattern of displacement but are closer to the reference contours compared to the DEM generated by the RST technique. By choosing the former it will be easier to correct the horizontal error. All displacements are to the West. The offset of the displacement is estimated to be equivalent to about one and a half pixels (140 m). There is also slight displacement in the y direction from South to North, which is small (less than half a pixel) and is not significant.

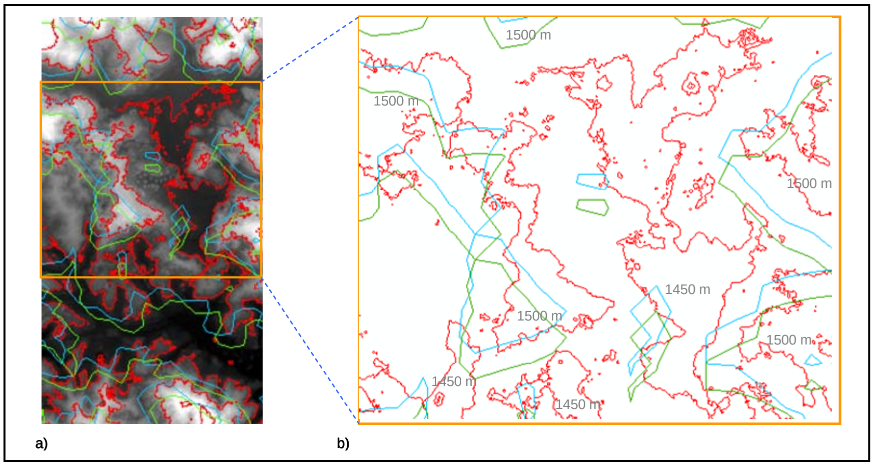


Figure 7: 50 m interval contours of SRTM DEM (UTM Triangulation) in blue and SRTM DEM (UTM RST) in green compared with DAP DEM in red, superimposed onto DAP DEM image: a) Bright areas in the DEM images represent area of higher relative elevation. b) Comparison of the contours in sub-area of the Sample Site.

ii) Height assessments

The results of the comparison of the Western transect are shown in Table 1. In column a) the minimum value, maximum value, mean, SD, and RMSE of height difference values between the original SRTM DEM and DAP DEM are -51 m, 57 m, 6.1 m, 21.1 m, and 21.9 m respectively. After co-registration all the above values have improved to -38 m, 44 m, 4.1 m, 13.1 m, 13.7 m respectively (see column b)). These results confirm that the co-registration process manages to reduce height differences between the two DEMs.

When 10% of the data are dropped the result improves further with a Mean, SD and RMSE became -14 m, 29 m, 4.0 m, 10.1 m and 10.9 (see column c)). The min and max values has dropped dramatically. By omitting 10% of the data, gross errors appear to have been reduced and the overall results show better resultant data. The resultant mean of 4.0 m is well surpassing the expected accuracy of 16 m.

Table 1: Height differences of pixels between SRTM DEM and DAP DEM of North-South Western transect.

SRTM / Height differences	a) Original, 100 % data	b) Co-registered (x+140m), 100 % data	c) Co-registered (x+140m), 90 % data
Minimum	-51	-38	-14
Maximum	57	44	29
Mean	6.1	4.1	4.0
Standard deviation	21.1	13.1	10.1
RMSE	21.9	13.7	10.9

The average of mean, SD and RMSE of the 90% data from the three transects are:
Average Mean = 4.0+7.6+3.9 = 5.2 m
Average SD = 10.1+8.2+9.2 = 9.2 m
Average RMSE = 10.9+11.2+10.0 = 10.7 m

All the resultant means are better than the expected 16 m height accuracy predicted for SRTM. The lowest mean height difference was achieved in the 90% data of the eastern edge transect with 3.9 m. Nevertheless, the best result was achieved by the 90% data of the Middle transect as the SD is the lowest i.e. 8.2 m.

The mean of western edge transect are consistent with those from the eastern edge transect. The reason may be due to the similarity of the land cover types and topography. The middle mean however is about 3.5 metres higher than the mean values of western edge and eastern edge transect. Nevertheless this 3.5 metres difference is small and negligible considering the targeted accuracy of SRTM is 16 metres. The middle's SD is lower than the other two transect which further indicates better height data. The better results of middle transect may be due to flatter topography and the surface is less forested. This transect is crossing through flatter areas with mixed coverage of towns, sparse plantation and forest areas, while the other two transects are crossing through mainly rugged topography covered by dense rainforest areas.

As a conclusion, the tests show comparisons by profiles provide a good technique for assessing the height accuracy of the SRTM DEM. All the resultant means satisfied the targeted accuracy. Land cover types and the topography of the area however may influence the height accuracy.

Height differences were computed by subtracting height elevations values of pixels in the Sample Area between the SRTM and the DAP DEM, the analysis includes; first test - Original SRTM DEM, second test - SRTM DEM (x+140m) and third test - SRTM DEM (x+140 m,90% data). The minimum value, maximum value, mean, standard deviation (SD), and root mean square error (RMSE) of the height difference values were computed and results are as listed in Table 2 below.

Table 2: Height differences between pixels of SRTM DEM and DAP DEM of Sample Area.

SRTM / Height differences	a) First test Original, 100% data	b) Second test Co-registered (x+140m), 100% data	c) Third test Co-registered (x+140m), 90% data
Minimum	-59	-49	-17
Maximum	73	82	27
Mean	6.1	6.1	6.1
Standard deviation	16.1	13.8	10.4
RMSE	17.2	15.1	12.0

The result of first test shown in column a); the minimum value, maximum value, mean, standard deviation (SD), and root mean square error (RMSE) of height difference values between the original SRTM DEM and DAP DEM are: -59 m, 73 m, 6.1 m, 16.1 m, and 17.2 m respectively.

After co-registration (second test) the above results become -49 m, 82 m, 6.2 m, 13.8 m, 15.1 m respectively (see column b)). While the mean remain the same, the SD and RMSE have improved. This again indicates that with co-registration, some large height differences can be removed, so it is an important step that should be applied before using the data.

In the third test, when 10% of the pixels were dropped the results were even better with min, max, mean, SD and RMSE become -17 m, 27 m, 6.1 m, 10.4 m and 12.0 m (see column c)). This confirms that the result will be better using 90% data thereby eliminating random errors as shown by huge reduction of the minimum and maximum values and also the SD. This test shows that comparison using a large numbers of pixels is suitable for SRTM data. The resultant mean, SD and RMSE of 6.1 m, 10.4 m and 12.0 m are not far from the average results obtained from the comparison by profiles which were 5.2 m, 9.2 m and 10.7 m respectively.

Together these results suggest that the technique of area comparison may be the most appropriate technique to be applied for whole of image analysis especially where different topography and land cover types exist.

The result and the statistics of height differences between the original SRTM DEM and GPS GCPs are shown in Table 3 below. In column b) the minimum value, maximum value, mean, standard deviation (SD), and root mean square error (RMSE) are 3.1 m, 62.5 m, 24.7 m, 18.0 m, and 30.6 m respectively. The resultant mean of height difference 24.7 m is much higher than the standard set by the data provider that the expected absolute height error should be less than 16 m for 90% data (Rodriguez *et al*., 2005).

Table 3: Height differences between SRTM DEM and GPS GCPs.

a) SRTM / Name of GPS GCP	b) Original, 100% data = 12 points	c) Co-registered (x+140m), 100% data = 12 points	d) Co-registered (x+140m), 90% data = 11 points
Minimum of height difference	3.1	0.9	0.9
Maximum of height difference	62.5	37.0	31.5
Mean of height difference	24.7	17.0	15.3
Std. dev. of height difference	18.0	12.1	11.0
RMSE of height difference	30.6	20.9	18.7

After planimetric correction (co-registration) all the above improved to 0.9 m, 37.0 m, 17.0 m, 12.1 m and 20.9 m respectively (see column c). This shows that the co-registration process has improved the results, so it is definitely an important step before comparisons can be carried out.

When the GPS GCP point with the largest height difference, which is situated in rugged area was dropped the result was better. As shown in column d), the Min, Max, Mean, SD and RMSE become 0.9 m, 31.5 m, 15.3 m, 11.0 m and 18.7 m respectively. The mean of the height differences is large but approaching the same value of 16 m, set by the data provider. One problem is the max height difference (31.5 m) is large this shows SRTM height is not reliable for rugged area because the resolution is too large so every single pixel is subject to height errors.

In summary this research shows the comparison of individual SRTM DEM pixels with GPS GCPs can not be used to establish good relationships.

Relationships between heights differences of two datasets were displayed in 2D scatter plots and the R-squared values were computed by comparing height elevations values of SRTM DEM with 1) the DAP DEM of the North-South Western transects and Sample Area; and 2) GPS GCPs. The SRTM DEM used are: the Original (not registered), horizontally corrected SRTM DEM (x+140 m) and SRTM DEM (x+140 m, 90% data). The linear Regression Models were also derived.

Figure 8 a) and b) show a plot of the relationship between DAP DEM and SRTM DEM of NS-Western transect: a) original pixels, b) with the displacement in x that corrected from West to East by 140 m. Comparing both figures; the co-registered SRTM DEM pixels shows better relationship with DAP DEM pixels with the points much closer to the regression line. The resulted R-squared value improved from 71.9% to 89.0%. This shows the original data have higher height differences than the co-registered; further confirming the finding by the method of comparing height differences. The scatter plot in Figure 8 c) shows that the relationships are stronger when 90% data was used. The derived R-squared value is larger (93.5%) and points are closer to the line.

The results of various percents comparison of sample area also show similar trend with the comparison of profiles.

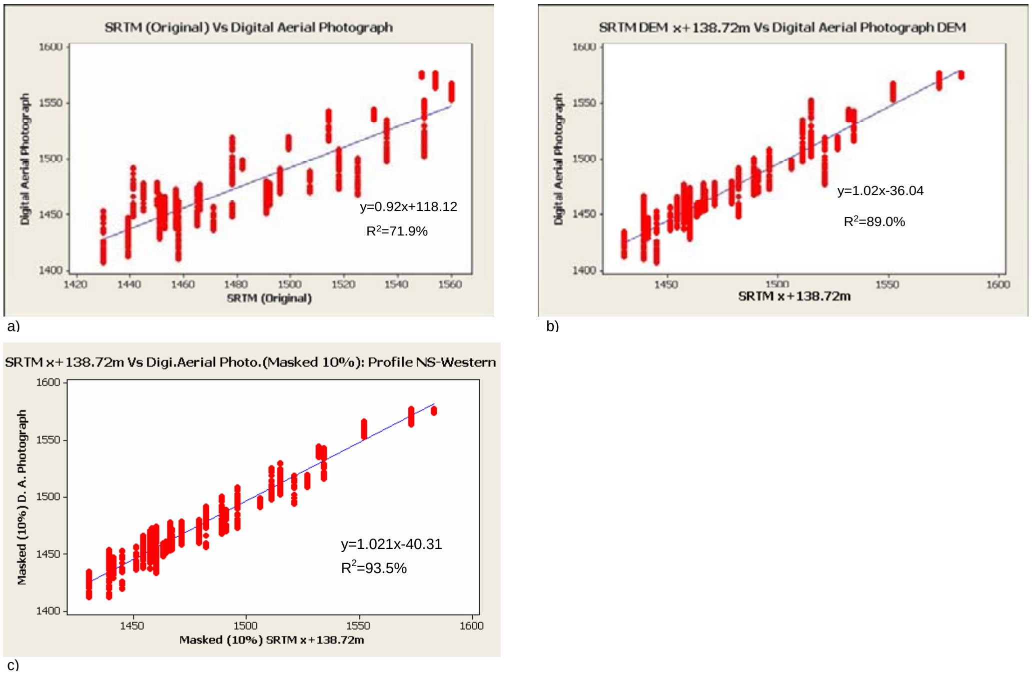


Figure 8: Relationship between and DAP DEM and SRTM DEM of NS-Western transect: a) Original b) x+140m and c) x+140m applied with 90% mask.

iii) Assessment of the vertically corrected SRTM DEMs

The resultants Linear Regression Models were applied to the co-registered SRTM DEMs to correct the heights. The models used were derived from comparison of profile (North-South Western transect), Sample Area and GPS GCPs. The 90% data of the corrected SRTM DEMs were used for the assessment by comparing with the DAP DEM of the North-South Middle transects and GPS GCPs.

Table 4: Height Differences of the North-South Middle transect between DAP DEM and the vertically corrected SRTM DEMs applied with models from comparison of a) pixels profiles of North-South Western transect) b) Sample Area c) GPS GCPs

Co-registered (y+140m) 90% data / Height differences	a) Profile NS-Western	b) Sample Area	c) Points (11 GPS GCPs)
Minimum	-15.0	-17.3	-30.6
Maximum	18.5	16.2	2.5
Mean	3.8	1.5	-11.9
Standard deviation	8.2	8.2	8.3
RMS	9.0	8.3	14.5

Results in Table 4 shows that the DEMs corrected using model derived from comparisons of transect, Sample Area and GPS GCPs give accurate result of mean and better data as indicated by smaller SDs. Mean is better than the expected accuracy of 16 m.

Results in Table 5 below shows that the corrected DEM using models derived from comparisons of transect and Sample Area give more accurate results compared to the comparison with profile as indicated by the smaller means and SDs of height differences. These are as expected because the height values of GPS GCPs are highly accurate and the points are located mostly on flat area, therefore the highs values on DAP DEM are also relatively accurate.

Table 5: Height Differences between GPS GCPs and the vertically corrected SRTM DEMs applied with models from comparison of a) pixels profiles of North-South Western transect) b) Sample Area c) GPS GCPs.

Co-registered (x+140m) 90% data / Name of GPS GCP	a) Profiles NS-Western	b) Sample Area	c) Points (6 GPS GCPs)
Minimum	-9.4	-11.4	-15.2
Maximum	28.1	26.0	21.9
Mean of height diff.	9.1	6.9	3.4
Std. dev. of height diff.	13.4	13.4	16.1
RMS of height diff.	16.2	15.1	16.5

iv) Comparison of profiles– generated from the original and the corrected DEMs

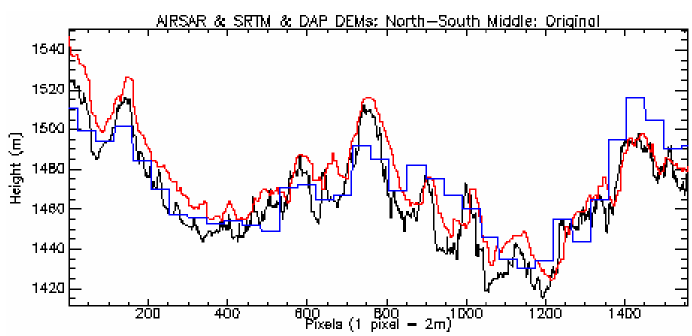


Figure 9: Comparison between profiles of the original of SRTM DEM (blue) with DAP DEM (black) and AIRSAR DEM (red) on North-South Middle transect.

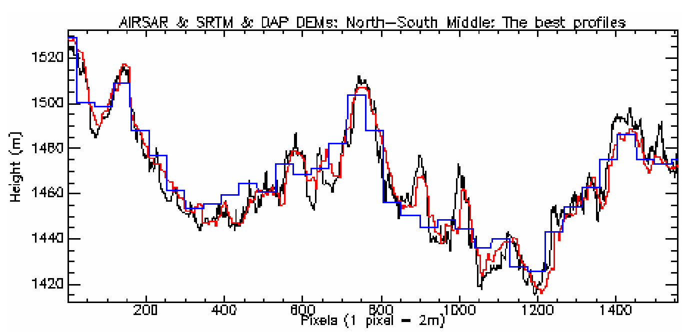


Figure 10: Comparison between the best profiles of vertically corrected / co-registered SRTM DEM (blue) with DAP DEM (black) and AIRSAR DEM (red) on North-South Middle transect. The SRTM DEM and AIRSAR DEM were corrected using models generated from comparison of Sample Area

Figure 9 shows the profile of the original SRTM DEM compared to the DAP DEM and AIRSAR DEM (original) on the North South Middle transect. Figure 10 shows the profiles of the corrected SRTM DEM and AIRSAR DEMs using models from comparison Sample Area. This is to show how much is the improvement has taken place when SRTM DEMs were co-registered and then the heights were corrected. The latter diagram shows the SRTM profiles are much closer to the DAP DEM and AIRSAR DEM (corrected).

v) Comparison of contours – generated from the original and the corrected DEMs

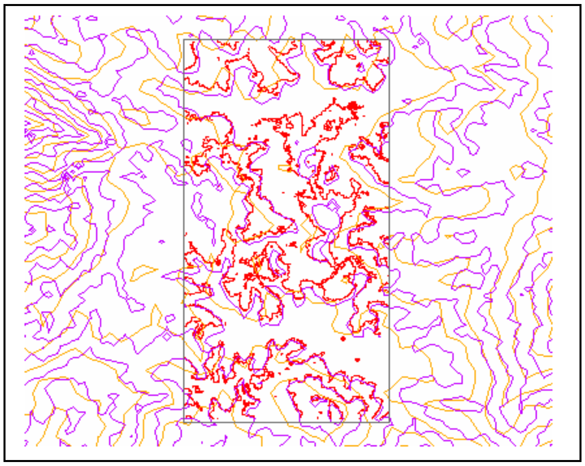


Figure 11: Comparison between 50 m contours of the original of SRTM DEM (orange) with DAP DEM (red) and AIRSAR DEM (purple) covering the Sample Area and the surrounding area.

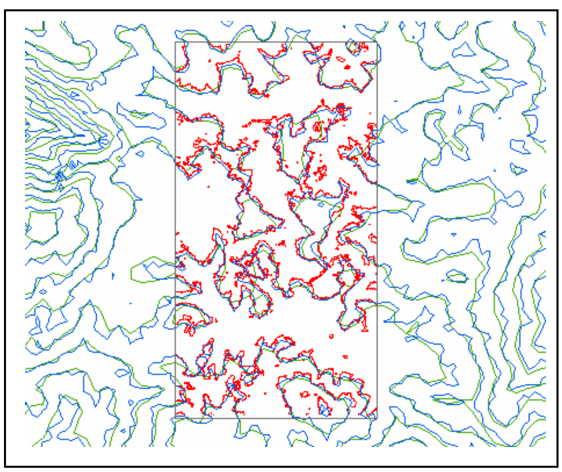


Figure 12: Comparison between 50 m contours of the best vertically corrected / co-registered SRTM DEM (green) with DAP DEM (red) and AIRSAR DEM (blue) covering the Sample Area and the surrounding area.

Figure 11 shows the contours of the original SRTM DEM were plotted together against the DAP DEM and original AIRSAR DEM. Figure 12 shows the best contours of the corrected SRTM DEM were plotted together against the DAP and the corrected AIRSAR contours. The diagram shows how the contours match each other not just inside the Sample Area but also the surrounding area which is much better when compared to their original comparison contours shown in Figure 11.

vi) Identifying flash floods prone

The result shown in Figure 13 below are the multi-colours heights generated from the corrected SRTM DEM of the Research Site. In the figure there are three areas (in black boxes) that have criteria suggesting that the areas are prone to flash floods. Each area consists of a wide area of a colour level that represents large valley. They are surrounded by a colour representing a higher level ground. They are connected with the lower level colour by narrow areas (see black arrows). In Box I and Box II, the mentioned colour level representing valley areas is the 1400 to 1449 meters range (sienna). In Box III the colour level is the 1450 to 1499 meters range (magenta).

From field observation and check on the topographical map, Box I is where the Tanah Rata town is situated. At arrow marked "a" there is an intake point where water is channelled through an man made underground tunnel to propel hydro electric turbines situated at the lower level area called Habu. Box II covers Tringkap Town, which is one the largest human settlement in Cameron Highlands. Box III is the location of a large man made lake. The narrow area shown by arrow "b" is the location a dam. The existence of towns which are normally built on flat areas surrounding by higher grounds is one indicator that the areas have the characteristic that match the areas that prone to flash flood. The existence of dams which usually built at narrow channel further confirms that the areas have similar characteristic of flash flood prone areas.

With the water level was modelled at 1450 m, examples of the detected areas that are possibly prone to flash floods on the corrected SRTM DEM of the Research Site are shown in Figure 14. Figure 14 a) is the corrected AIRSAR DEM of the Research Site and Figure14 b) is the 3D view. In the figures, the two identified flash flood prone areas can be seen as white colour areas inside Box I and Box II. These areas are the same areas identified by the first technique. The areas are surrounded by the higher level areas (yellow) and connected to larger under water areas by narrow areas (see red arrows). The narrow areas are channels where water is supposedly to be discharged out. If reservoir area (in Box III) is to be displayed, 1100 m is the water level to be defined.

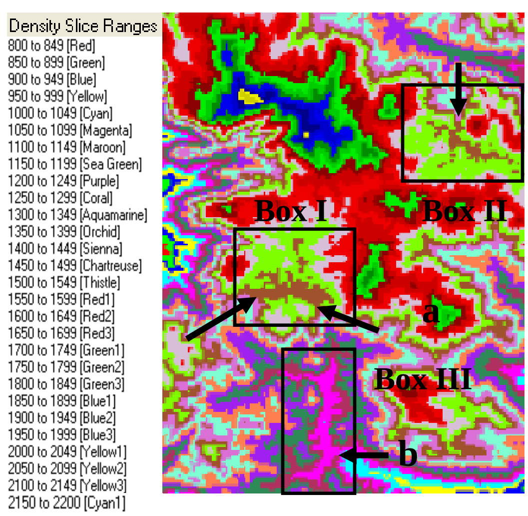
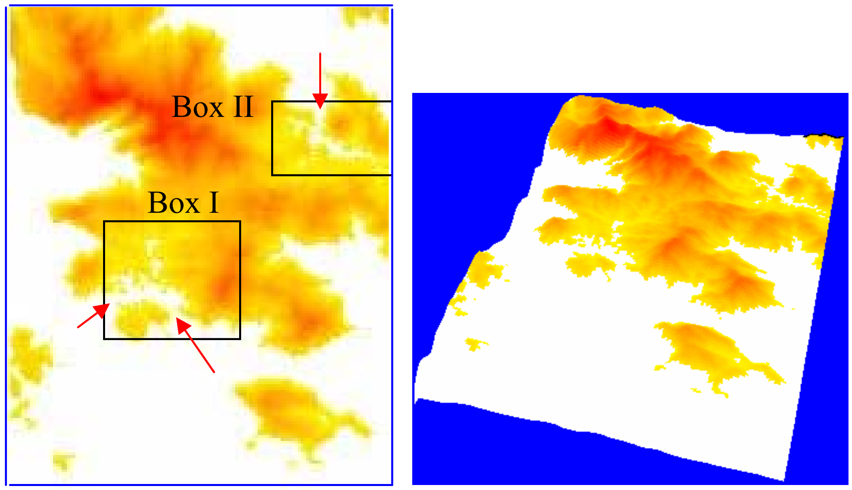


Figure13: The multi-colours heights generated from the SRTM DEM of the Research Site.



a) b)

Figure 14: Research Site: a) the corrected SRTM DEM modelled with 1450 m water level (white). The figure shown as b) is a perspective views.

Conclusion

This research has shown that comparison of profiles, contours of SRTM DEM with DAP DEM are effective techniques for determining horizontal misalignment. The comparisons of pixels profiles and Sample Area of SRTM DEM with DAP DEM and GPS GCPs were able to assess height accuracy.

The horizontal error of about one and a half pixels to the west was detected. The effect of the horizontal alignment of the DEM's was found to be critical. By correcting the horizontal errors (one and a half pixels to the east) the height error was reduced in the SRTM DEM. This was confirmed by height comparison with the DAP DEMs (profiles and Sample Area). In all comparisons, the resultant SDs of height differences decreased after co-registration. The improvements of SD achieved are as follow: from about 15.2 m to 10.1 m (middle transect), from 16.1 m to 13.8 m (Sample Area) and from 18.0 m to 12.1 m (points). This clearly illustrates the sensitivity of the height errors to horizontal geometry fidelity and data registration.

After co-registration and 10% masking, from comparison between SRTM DEM with DAP DEMs (profiles and Sample Area), the means of height differences were 5.2 m (profiles), 6.1 m (Sample Area). The SD of the height differences of the SRTM DEM also improved. The reductions from previous SD (co-registered) were as follow: from 10.1 m to 8.2 m (middle transect), from 13.8 m to 10.4 m (Sample Area) and from 12.1 m to 10.8 m (points). Both of the resultant SDs and means were suitable to check height accuracy: the resultant means indicate the targeted height accuracy of 16 m was achieved.

The techniques of applying LEMs to correct SRTM DEM have produced good results. The resultant mean height differences between the corrected SRTM DEM with DAP DEM on North-South Middle transect when compared with the uncorrected (co-registered) DEMs have improved from 7.6 m to the following: 3.8 m (applied with model derived from North South Western transect), 1.5 m (applied with model derived from Sample Area). The resultant means indicate models derived from comparison of transect and Sample Area were suitable to correct SRTM DEM. The results were much better than the targeted 16 m height accuracy. When the DEM were applied with model derived from comparison of points (masked 10%) the resultant mean has decreased to -11.9 m. This indicates models derived from comparison of points were not suitable to correct SRTM DEM.

The resultant mean height differences between the corrected SRTM DEM with GPS GCPs (100% data) when compared with the uncorrected (co-registered) DEMs have improved from 17.0 m to the following: 9.1 m (model derived from North South Western transect), 6.9 m (model derived from Sample Area). For the corrected SRTM DEM applied with model derived from comparison of GPS points (masked 50%) the resultant mean has improved from 18.2 m to 3.4 m. These results indicate on the ground surface in flat areas at the location of DEMs/GPS GCPs, all models can produce accurate heights. The targeted mean of 16 m height accuracy was achieved.

The graphical comparison of profiles and contours between the original and the corrected dataset of the SRTM DEM proved that the corrected DEMs are a lot better than the original DEMs, which confirms the numerical results. Therefore, the same techniques could be applied to other DEMs.

In DEM applications of the case study area, the corrected SRTM DEM was found useful for identifying flash floods prone areas. In identifying flash floods prone areas accurate DEM were proven important.

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