Effects of Various Factors on the Accuracy of DEMs: An Intensive Experimental Investigation

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Abstract

A series of tests on the accuracy of DEMs is described. The effects of four factors on DEM accuracy have been tested, i.e., the accuracy, the density of source data, the characteristics of the terrain surface, and the modeling approaches. A large area covered by two 1:10,000-scale maps was selected for testing. The terrain types range from flat to hilly to mountainous. Various sources (photographs and contour maps) were used and various measurement methods were employed.

From test results, the following has been found: (1) source data measured manually with analytical plotters are the most reliable because automated measurement using image matching techniques could generate systematic errors; (2) the accuracy of DEMs decreases (or the RMSE becomes larger) with an increase in sampling interval, and the relationship is linear; (3) the inclusion of feature points and break lines improves the accuracy of DEMs significantly, especially when the terrain is rough; (4) generally speaking, the accuracy of DEMs decreases with an increase in relief; however, this is not always the case, and the best results may be obtained in hilly areas; and (5) direct modeling from originally measured data to form a triangular network will yield better results than indirect modeling using a random-to-grid interpolation to form a grid network. The difference could be significant if the terrain is rough.

From these conclusions, some advice on DEM production could be made as follows: (1) when using automated photogrammetric systems for data acquisition, editing by experienced operators should be considered; (2) in hilly areas, photogrammetric contouring can be the most efficient method for DEM data acquisition if analytical plotters are used; (3) feature points should always be measured and kept in order to reduce the data volume while retaining the fidelity of the DEM; and (4) when the terrain surface is rough, triangulation-based methods are recommended.

Introduction

Digital elevation models (DEMs) have received great attention since they came into use in the late 1950s (Miller and Laflamme, 1958). They have found wide applications in the fields of surveying, civil engineering, geology, mining engineering, landscape architecture, road design, flood control, agriculture, planning, military operations, aircraft and battlefield simulation, and so on. Recently, due to the popularity of geographical information systems (GIS), DEMs have also become an essential part of a national spatial data infrastructure (SDI) in the United States, Germany, the United Kingdom, China (Gong, 1997), and other countries, under the umbrella of a digital geospatial data framework (DGDF).

By becoming part of a national spatial data infrastructure, it means that DEMs will be produced to cover the whole country. For such a large DEM project, accuracy, efficiency, and economy are the three main factors to be considered (Li, 1992). Accuracy is perhaps the single most important factor to be considered because, if the accuracy of a DEM cannot meet the requirements, then the whole project needs to be repeated and thus the economy and efficiency will ultimately be affected.

Accuracy of DEMs is a traditional topic in the photogrammetric community because photogrammetrists are usually the DEMs producer. Numerous papers in this area have been published in journals and conference proceedings. Both theoretical analyses (Makorovic, 1972; Kubik and Botman, 1976; Frederiksen, 1981; Li, 1993) and experimental testing (Ackerman, 1979; Ley, 1986; Torlegard *et al.*, 1986; Balce, 1987; Carter, 1989; Li, 1992; Kumler, 1994; Li, 1994; Monckton, 1994) of DEM accuracy have been conducted by researchers. However, there are some limitations with these tests. The first limitation is that the size and the number of testing sites were normally very limited except in a few instances. The first intensive test was the ISPRS test reported by Torlegard *et al.* (1986), which employed six sites, and the data were measured using photogrammtric methods by many participating organizations. Using test data for three of the six areas, Li (1992) tested the relationship between the sampling interval and resultant DEM accuracy. Kumler (1994) reported an intensive test using existing contour maps as the source data. The second limitation is a lack of comparison between the accuracy of DEMs from various sources except for the comparative study by Li (1994). To have a better understanding of the nature of DEM accuracy, a very comprehensive test, using various modeling approaches, from various data, for different types of terrain surfaces, and covering two large test areas, was conducted and is reported on in this paper.

The first section of this report section outlines the design of this experimental test. This is followed by a description of the test area and test data sets. The test results are then presented and analyzed. Finely, after a discussion and analysis, some concluding remarks are made.

The Strategy Used in This Experimental Testing

The accuracy of a DEM is a result of many individual factors. However, the following may be regarded as the main factors (Li, 1990; Li, 1992):

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- the three attributes (accuracy, density, and distribution) of the source data,
- the characteristics of the terrain surface, and
- the method used for the construction of the DEM surface.

Accordingly, five plans (Li, 1992) for an experimental testing of DEM accuracy were established in each of which only one of the five factors is used as the independent variable and the other four were used as controlled variables. In this testing, the following plans were designed:

- The accuracy of the source data could be varied while all the other factors remained unchanged. This can be achieved by using different data acquisition techniques such as GPS, photogrammetry, and other methods. In this test, this plan was achieved by automated photogrammetric sampling, manual photogrammetric sampling, manual photogrammetric contouring, and cartographic scanning and digitization of contour maps.
- The density of the source data could be varied while all the other factors remain unchanged. This can be achieved by using a different sampling interval or data selection method. In this test, different sampling intervals such as 10 m and 25 m were used.
- The type of terrain could be varied while all the other factors remain unchanged. This could be achieved by using a terrain surface with various types of relief.
- Two types of modelling methods are used to construct two types of surfaces, i.e., direct modeling using a triangulated networks and indirect modeling using a random-to-grid interpolation to form a gridded network.

Test Data and Test Area

The test area is located in the Guangzhou province of south China. It covers an area of about 59 square kms on two complete topographic map sheets (number 28 and 29) at 1:10,000 scale. Terrain types varied from flat to hilly to mountainous. Isometric views of these two areas are shown in Figures 1a and 1b.

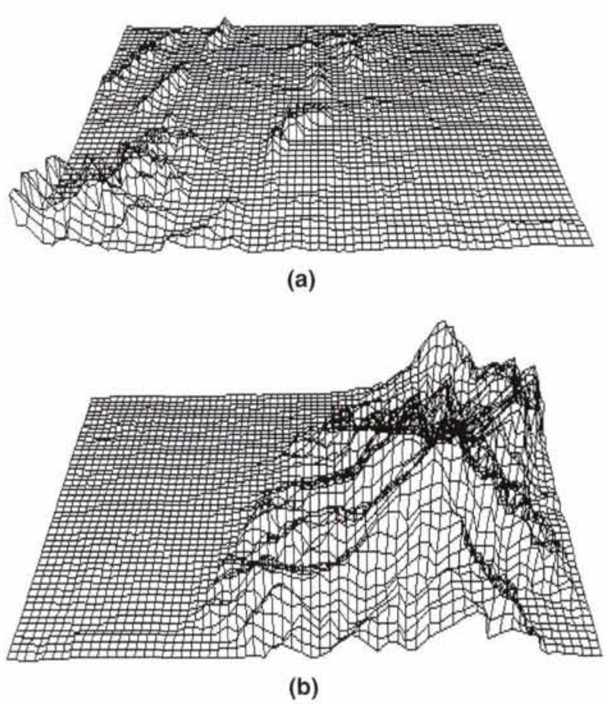

Figure 1. (a) Isometric view of the test area 1, Map Sheet 28. (b) Isometric view of the test area 2, Map Sheet 29.

Check points were measured with much higher accuracy than the sampled source data points. In flat and hilly areas, field surveying with precision leveling was performed. In mountainous areas, field surveying with total stations were used. The root-mean-square error (RMSE) of heights for check points was less than 10 mm, which is almost negligible in the assessment of DEM accuracy. Check points were evenly distributed over the whole test area.

One type of source data was measured from aerial photographs using photogrammetric techniques. The scale of the aerial photography used for photogrammetric measurement was 1:25,000, which was taken at a flying height of 3,800m with a 153-mm focal length. Both digital and analytical photogrammetric techniques were used. For their use in the digital photogrammetric system, these photographs were scanned with a resolution of 25 μm using a photogrammetric scanner (because it has been widely accepted that 25 μm is small enough for the transfer of geometric information from analog form to digital form).

For the digital photogrammetric data acquisition (by using two digital photogrammetric workstations (DPWs), two operational modes were employed, i.e., (1) fully automated digital photogrammetry which acquired the DEM source data by automated matching and (2) partially automated digital photogrammetry which acquired the DEM source data by a combination of automated image matching and interactive editing by operators. In this project, analytical photogrammetric plotters were also used for data acquisition although it was less efficient. Analytical plotters were used not only for sampling points in grid form but were also used to measure contours directly from stereo models, resulting in another type of distribution for the source data.

Contour data were also digitized from the contour maps. The contour intervals were 1 m for Map Sheet 28 and 5 m for Map Sheet 29.

Testing Results and Analysis

Variation of DEM Accuracy with Source Data and Terrain Type

The first test was on the accuracy of DEMs derived from various sources and from different types of terrain. The number of check points was 152 for the flat area, 83 for the hilly area, and 41 for the mountainous area.

The source data were measured by different methods, resulting in different accuracies. In this test, five types of source data were used:

(a) grid data measured by fully automated digital photogrammetry,
(b) grid data measured by fully automated digital photogrammetry plus feature points and with editing (i.e., the so-called partially automated digital photogrammetry in Table 1),
(c) grid data measured by analytical photogrammetry,
(d) contour data measured by analytical photogrammetry, and
(e) contour data digitized from contour maps.

The assessment of DEM accuracy was accomplished by comparing the height values of check points with the heights interpolated at the check points from the 10-m gridded DEM. This meant that, if the original data were not based on an interval of 10 m, a process of "random-to-grid" interpolation would take place. For the type (a) (i.e., fully automated photogrammetrically measured gridded) data, there was no "random-to-grid" interpolation because the data were already in grid form with an interval of 10 m. For type (b) (interactive photogrammetrically measured) data, a coarse grid with an interval of 25 m was first measured automatically by image matching; then, feature points were manually measured by an operator; and, at last, a 10-m grid DEM was interpolated through TIN-based modeling. For the type (c) data, every grid point was measured manually

Table 1. The Accuracy of DEMs Derived from Various Types of Source Data for Different Types of Terrain Surfaces

Type of Terrain Source Data	Flat Area		Hilly Area		Mountainous Area	
	No. of CP	RMSE	No. of CP	RMSE	No. of CP	RMSE
(a) Fully auto photog	152	2.88	83	2.60	41	4.73
(b) Partially auto photog	152	1.25	83	1.24	41	3.56
(c) Analytical photog	152	0.87	83	1.05	41	2.43
(d) Contour by analy. photo	152	1.18	83	1.16	41	3.77
(e) Contour from maps	152	1.20	83	1.12	41	3.99

by operators. For type (d) and (e) data, additional feature data were also utilized for TIN generation.

The results are shown in Table 1, which were obtained using 152, 83, and 41 check points for flat, hilly, and mountainous areas, respectively. A diagrammatic view is given in Figure 2.

It seems clear that the DEMs directly measured from the stereo models on an analytical plotter have the highest accuracy, the DEMs generated by the automated photogrammetric system have the poorest accuracy, and the accuracy of DEMs derived by other methods are almost the same. This could be due to the fact that automated matching is sometimes not very reliable. This test provides some hints about the effects of source data and terrain type on DEM accuracy.

The effect of "accuracy of source data" on DEM accuracy has been revealed by comparing the results along columns in Table 1. In this case, the data interval is identical but the accuracy of different types of data is different. The effect of terrain type on DEM accuracy is also revealed clearly by comparing the results along rows (i.e. for all three types of terrain, i.e., flat, hilly, and mountainous).

It is interesting to note that, for the DEMs, the hilly area has its highest accuracy when feature points are included, i.e., data types (b), (d), and (e).

Variation of DEM Accuracy with Sampling Interval

The effect of sampling interval on DEM accuracy is shown by comparing the results obtained from the first two types of data. In the case of partially automatically measured data, the interval of the automatically measured grid is 25m. Due to the inclusion of feature points and lines, the resulting DEMs attained a higher accuracy than those from the fully automated data.

The high accuracy of analytically measured data points promotes the idea of using these points as check points, providing a second test on the accuracy of other DEMs because the number of control points in this case could be huge (i.e. 600,000) and the results would be more reliable. The results are shown in Table 2 and a diagrammatic view is given in Figure 3.

The sampling interval is the single most important factor affecting DEM accuracy for a given area and sampling methodology. A test on this parameter was also carried out. In the case

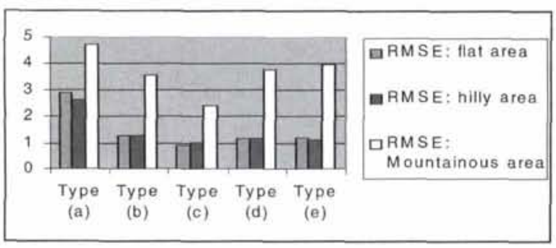

Figure 2. Accuracy of DEM derived from various types of source data.

Table 2. The Accuracy of DEMs from Various Sources vs Analytically Measured Data

	Flat Area	Hilly Area	Mountainous Area	Entire Area
Fully automatic digital photogrammetry	2.98	2.66	5.94	5.01
Interactive digital photogrammetry	1.39	1.52	2.79	2.71
Derivation from contouring by analytical plotter	1.41	1.26	2.58	2.35
Derivation from contours digitised from maps	1.40	1.26	2.52	2.43

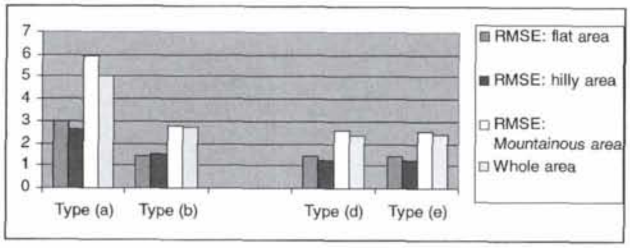

Figure 3. Accuracy of DEM from various sources vs analytically measured data.

of measured grid data, the sampling interval is characterized by its grid interval. On the other hand, in the case of contour data, the contour interval is a good indicator. In this study, both measured grid DEMs and DEMs derived from contours with varying (vertical) intervals were tested. The data measured using an analytical plotter were originally in a form of 10- by 10-m grids. By omitting some rows and/or columns, grids with coarser intervals (e.g., 20 by 30 m) can be easily derived. The results are shown in Tables 3 and 4. Table 3 shows clearly that with the

Table 3. Effect of Sampling Interval on DEM Accuracy

	Flat (28)	Hilly (28)	Flat (29)	Mount-29	Mount-29*
No. of C. Pt	77	82	73	8	33
10m × 10m	0.97	1.16	0.76	1.35	2.64
10m × 20m	0.99	1.16	0.76	1.35	2.82
20m × 20m	0.97	1.26	0.77	1.44	3.74
20m × 30m	0.99	1.23	0.77	1.65	4.89
30m × 30m	0.98	1.31	0.76	1.76	5.17
30m × 40m	1.01	1.40	0.82	1.69	6.02
40m × 40m	1.17	1.46	0.76	2.92	6.88
40m × 50m	1.11	1.63	0.74	2.47	8.30
50m × 50m	1.13	1.71	0.78	1.47@	8.40

*This area is bush land in which it is difficult to obtain high accuracy measurement;
@This number must be a mistake and should be ignored.

Table 4 Effect of Contour Interval on the Accuracy of DEMs

RMSE Area	Contour data with different contour intervals (CI)							
	CI = 1m	CI = 2m	CI = 3m	CI = 4m	CI = 5m	CI = 6m	CI = 7m	CI = 9m
Flat-28	0.74	0.85	1.05	2.22	2.23	3.10	4.03	4.9
Hilly-28	0.94	1.15	1.44	2.32	2.36	3.19	4.06	4.92

increase of sampling (grid) interval, the RMSE value of DEMs increases. The trend is illustrated in Figure 4. It appears that the increase is quite linear in the hilly areas. However, the change is very small when the terrain is very flat.

For the test of the variation of DEM accuracy with contour intervals, only the contour data from (map) Sheet 28 was used because the contour interval on this map is 1 m while the interval for Sheet 29 even for flat areas, is 5 m. Data sets with larger contour intervals (e.g., 2 m and 3 m) can then be easily derived from the 1-m contour interval. Table 4 shows clearly that, with the increase in contour interval, the RMSE value of the DEMs increases. The trend is illustrated in Figure 5. It appears that an increase in the RMSE is quite linearly proportional to the increase in the contour interval.

Variation of DEM Accuracy with Modeling Methods

The last test was carried out using two modeling methods, i.e., direct modeling to form a TIN and indirect modeling using a random-to-grid interpolation to form a gridded network. The results are shown in Table 5. It appears that the direct modeling method performs better. This is understandable because the indirect method causes a loss of accuracy in the random-to-grid interpolation process. One particular point to be noted is that, in the mountainous areas, the difference could be very large.

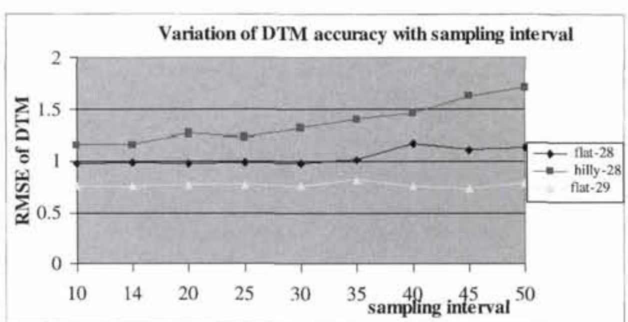

Figure 4. Effect of sampling interval on DEM accuracy.

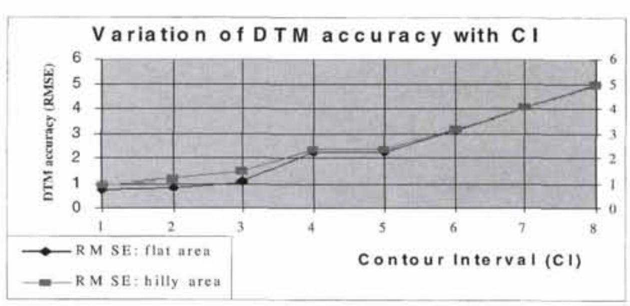

Figure 5. Variation of DEM accuracy with contour intervals.

Table 5 Effect of Modeling Methods on the Accuracy of DEMs

Accuracy Methods	Flat Area		Hilly Area		Mountainous Area	
	No. of CP	RMSE	No. of CP	RMSE	No. of CP	RMSE
Random to grid	152	1.52	83	1.18	41	3.77
Direct triangulation	152	1.20	83	1.12	41	2.94

Discussions

As a basic component of the national spatial data infrastructure, DEMs have received much attention from various authorities in China. A series of experimental investigations into the accuracy of DEMs was conducted for several months in Guangzhou, south China. Some of the test results have been reported in this paper.

Several factors which affect the accuracy of DEMs were investigated, i.e., the accuracy, the density of source data, the characteristics of the terrain surface, and the modeling approaches. The results were reported in the previous sections.

It is interesting to note that the accuracy of a DEM derived from contour lines digitized from existing maps is much lower than one-third of a contour interval, as given in map accuracy specifications and as reported by other researchers, e.g., Li (1994). On average, the accuracy of a DEM is about one-half a contour interval. This comes as a surprise. Some possible explanations are (1) the accuracy of contours on the original map did not meet the map accuracy specification, (2) the map distortion could be quite large, and (3) there might be a change of landscape because it is in the fringe area of a big city. To clarify this point, further experiments are expected.

The second point to be noted here is that the data acquired by the automated photogrammetric system were not very reliable. The accuracy of a DEM from such a data set was much poorer than that the data measured on an analytical plotter. Experience gained by the authors shows that it is very likely that an automated photogrammetric system will produce data with systematic errors. For example, if the water level in a reservoir is 100 m, every point along the reservoir shoreline should have a height of 100 m. However, the automated system may produce a height systematically higher than 100 m for all points. As a result, heavy editing by a skilled operator is necessary. In this test, no editing was performed because it was our intention to see how reliable the automated matching was.

Conclusions

The tests reported in this paper aimed to investigate the variation of DEM accuracy with sampling interval, source data, terrain type, and modeling type. In the case of source data, it was of particular interest to investigate how reliable automated photogrammetric systems would be without human editing in the generation of DEM data. From these test results, the following conclusions can be made:

- The accuracy of DEMs decreases (or the RMSE becomes larger) with an increase in sampling interval. The relationship is quite linear; and

- The inclusion of feature points and lines improves the accuracy of DEMs quite significantly, especially when the terrain is rough.

These conclusions are in accordance with those reached by other researchers (e.g., Li, 1992). However, the following conclusions provide deeper insights:

- Generally speaking, the accuracy of DEMs decreases with an increase in relief. However, this is not always the case. The best results may be obtained in hilly areas;
- Source data measured automatically by image matching is not as reliable as those measured manually with an analytical plotter. This is because automated matching may produce systematic errors but not due gross errors (generated by mismatching).
- Direct modeling from originally measured data to form a triangular network will yield better results than indirect modeling using a random-to-grid interpolation to form grid network. The difference could be significant if the terrain is rough.

From these conclusions, some advice on DEM production could be made as follows:

- When using automated photogrammetric system for data acquisition, editing by experienced operators should be considered;
- In hilly areas, photogrammetric contouring can be the most efficient method for DEM data acquisition if analytical plotters are used;
- Feature points should always be measured and retained in order to reduce data volume while retaining the fidelity of the DEM; and
- When terrain surface is rough, triangulation-based methods are recommended.

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