Journal of the Korean Society of Remote Sensing, Vol.16, No.2, 2000, pp.177~188

Quantitative Accuracy Assessment of a SPOT DEM along the Coast-Donghae City Area

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Abstract : Quantitative accuracy assessment of a SPOT DEM (Digital Elevation Model) generated by a fully automatic software is performed along the 90km long coast around Donghae city. The theoretical requirement on the layout of the GPS (Global Positioning System) check points is derived: the Nyquist sampling. Since in practice the Nyquist frequency of a terrain is difficult to determine, the relaxed requirements are introduced and 31 check points are collected accordingly. Accuracy of the SPOT DEM is calculated to be 8.9, 11.5 and 12.0m r.m.s. in latitudinal, longitudinal and elevation directions. The bias is distinguishable from zero only for elevation and is 2.2m. The simple comparison with the world's leading commercial softwares reveals the similar accuracy level.

Key Words : Digital Elevation Model, SPOT, Coastal Application, Accuracy Assessment

1. Introduction

An accurate DEM (Digital Elevation Model) along the coast is essential for disaster prediction, simulator generation and so forth. Quite a few DEM datasets are available such as DTED (Digital Terrain Elevation Data) and topographic maps. Use of these data sets, however, is limited by inaccurate representation of the coast, which arises mainly because they do not provide up-to-date topography. For example, the coastline in Gyung-gi Bay appears receded towards the land by about 5 km in 10" DTED Level II data[1]. Also a peninsular in Hwaseong-Gun is represented as an island. The 1:50,000 topography map updated in 1995 understandably do not show the breakwater and other coastal constructions near Incheon city. An alternative source of a DEM is a satellite image which offers regular and frequent imaging. The time taken for producing a DEM is another important issue: for example, one may need an up-to-date DEM over frequently inundated coastal areas before the typhoon season begins. Traditionally analytical plotters are used by human operators and this process requires several weeks to perform the stereo-match of one SPOT

1) As DTED is updated constantly the recession may not appear in the latest dataset. Nonetheless the time delay in DTED data is bound to exist.

Received 15 April 2000; Accepted 25 May 2000.

stereo-pair. By comparison an automated process can complete the same task within less than 30 minutes (Lee *et al.*, submitted). In view of the above limitations, for obtaining up-to-date DEMs along the coast automatic generation of DEMs from satellite images attracts significant interest.

For an operational use of a DEM generated automatically from satellite images its accuracy should be specified. By comparing the accuracy with the requirement of a particular application one may decide to what extent the SPOT DEM may be used. The most practicable method for accuracy assessment would be to compare with GPS (Global Positioning System) measurements. Though LIDAR (Light Detection And Ranging) records become more and more popular the cost is still too high. SPOT images are chosen to quantify the accuracy of the most widely used images. A classic paper on SPOT DEM quality assessment (QA) using GPS records is Al-Rousan *et al.* (1997). Applying the PCI EASI/PACE system to five SPOT stereo-pairs in Jordan they report the planimetric errors between 7 to 12 m and the elevation errors between 3 to 13 m. Further validation of a SPOT DEM would be still needed as their test sites are deserts: smooth topography and weak features in the desert would not be representative of a SPOT DEM over other terrains.

The second motivation of the QA is the accuracy assessment of the fully automatic software, Valadd-pro developed in Satellite Technology Research Center (SaTReC), KAIST (Lee *et al.*, 1999). Valadd-pro was shown to perform twice more accurately than commercial softwares in terms of both elevation (Lee *et al.*, 1999) and the representation of the coast (Kim and Park, submitted). The quality assessment, however, was made with reference to 10" DTED and a 1:50,000 topographic map. Rigorous assessment of the quality of Valadd-pro has yet to be made.

To implement the two motivations a SPOT DEM (hereafter Donghae DEM) is generated using Valadd-pro along the 90-km coast near Donghae city in the northeastern part of S. Korea. 53 GPS records are collected for building the absolute orientation and performing the quality assessment.

2. SPOT Images and DEM Generation

The path and row numbers of the SPOT panchromatic pair are 308 and 275 (Fig. 1). The left scene is taken on Oct. 20, 1997, at 13° tilt and the right scene is on Sept. 13, 1999 at 26° tilt. The 2-year difference in the acquisition time does not introduce severe difference between the two images since the northeastern coast does not experience active development. The Donghae city area is chosen because of the interest in simulation of ship approach. The focus is on the coastal strip about 10km wide. Various terrain types are available: steep hills, gentle hills, flat farmland, urban areas and harbors. Generally the area is rather steep: the elevation in the strip reaches about 500m.

A fully automatic software Valadd-pro is used to produce Donghae DEM and its details are as follows. The stereo-matching employs an area-based strategy incorporating the epipolar geometry of Kim (2000) and the region-growing method adapted from Otto and Chau (1989). Decision of match success or failure is based on the correlation of two images within a 5×5 pixel window (Lee *et al.*, submitted). To convert the match results to elevation absolute orientation is estimated using a camera model by Orun and

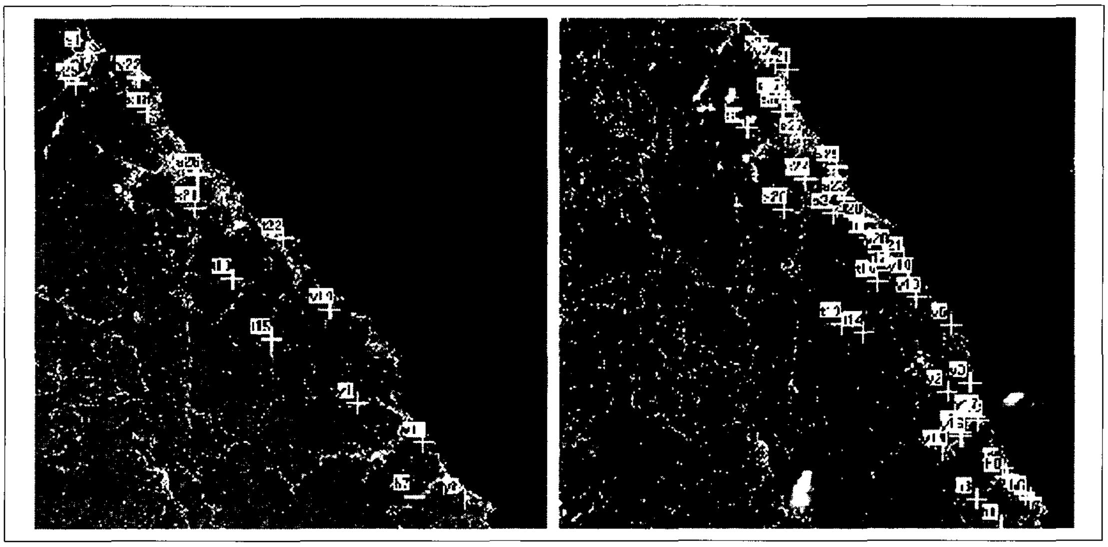

Fig. 1. SPOT panchromatic full scenes around Donghae city. 14 ground control points are plotted on the left image and 38 check points are on the right image.

Natarajan (1994) as it performs best in (Kim *et al.*, 2000). Stereo-matching is performed every 5 pixels since inaccuracy involved in the stereo-match and camera modelling is at maximum 2.5 pixels. In fact the match scheme at 1-pixel interval produces many blunders. Spurious elevation is removed using the t-test criterion of Felicisimo (1994). Gaussian interpolation shows the best performance on a 30 km × 40 km reference site (Kim *et al.*, 1999) and is chosen to transform the stereo-match results into a digital elevation model. To remove interpolation artifacts, intelligent interpolation schemes of Kim and Park (submitted) are applied.

3. Design of the Layout of Check Points

Previous works on DEM QA with GPS records do not address whether the check point layout provides the sampling sufficient enough to correctly represent errors in a DEM. In Al-Rousan *et al.* (1997) the check points are randomly distributed. Or frequently the comparison is made along one straight line (e.g., Desmet, 1997). If by chance the elevation of a DEM at all check points happens be error-free the consequent QA result cannot represent the true accuracy of the DEM. To overcome the sampling error, the minimum sampling frequency should be set to the Nyquist frequency, f_N, of a terrain. For example, if the elevation profile has a sine curve the minimum sampling frequency should be f_N of the sine curve (twice the frequency of the sine function).

f_N may be determined using the frequency spectrum of the terrain. However it is often the case that the frequency spectrum does not provide a clear cut-off. Thus alternatively one may utilise a decorrelation scale, the distance over which the autocorrelation becomes zero. Beyond the decorrelation scale the topographic features of two locations are regarded uncorrelated. In the case of a sine curve one may easily prove that

$$\textit{decorrelation scale} = \frac{\lambda}{2} = \frac{1}{2f_N},$$

where λ is the wavelength of the sine curve.

Noting that topography can be approximated by a linear combination of sine curves, the above equality holds for any topography. That is, the decorrelation scale of a terrain gives f_N of the terrain.

Difficulty arises because practically it is impractical to calculate the decorrelation scale of a SPOT DEM a priori. The reason is that the check point layout should be determined before GPS survey or generation of a SPOT DEM. Ideally GPS surveys should be taken two times: once to prepare control points and, having produced a DEM and calculated the decorrelation scale of the DEM, secondly to prepare check points. The only DEM available before the generation of a SPOT DEM would be DTED or a topographic map. The decorrelation scale from DTED or a topographic map would be greater than that from a SPOT DEM since a SPOT DEM is expected to contain spurious blunders. This implies that check points separated by the decorrelation scale of DTED are not sufficient to sample spurious errors in a SPOT DEM. The decorrelation scale from DTED would be that from a SPOT DEM when there is no spurious blunder, thus it may be used as a lower limit of the sampling interval. The decorrelation scale from DTED over the area of interest is 50 km and >70 km in across-coast and along-coast directions respectively (Fig. 2). Thus as long as there is one check point within a 50 km × 70 km box the minimum requirement is satisfied.

Having given up the ideal sampling at fN or the decorrelation scale of a SPOT DEM, instead, we aim at obtaining statistical significance of a mean error. This can be achieved if

$$\text{mean of error} \geq \text{standard error of the mean} = \frac{s.d.\ of\ error}{\sqrt{N}}$$

where N is the number of check points. Requirement on the mean error is set to 5 m, reflecting the magnitude of the sea/river level changes of interest. This requirement may be understood in such a way that if the mean error of a SPOT DEM is greater than 5m, the SPOT DEM is unacceptable. To make the important decision to reject the SPOT DEM, the mean error should be statistically significant. The s.d. error of the SPOT DEM generated by Valadd-pro is about 20m in

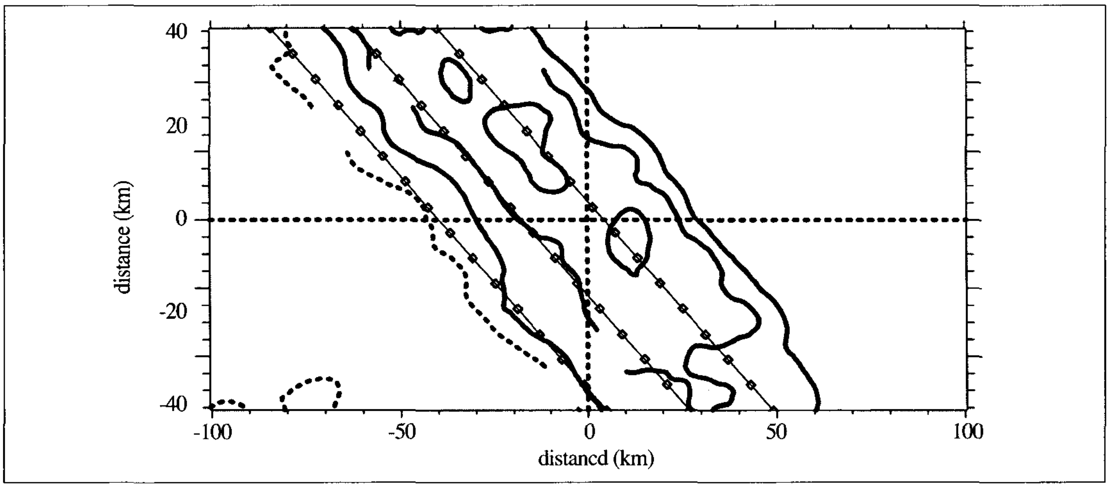

Fig. 2. Autocorrelation of the Donghae DEM area, computed using DTED. The numbers inside the panel is the correlation. The interval of correlation contours is 0.25. The dots mark the check point locations with an ideal layout.

Table 1. Distribution of check points with respect to elevation.

	Number of records
Check pt class I (h <25m)	17
Check pt class II (h = 25~65m)	14
Check pt class III (h >65m)	7

Seoul and BoRyung full scenes (Lee *et al.*, 1999). This leads to *N* of 16.

In summary, when the accuracy assessment is performed with 16 check points

- it is guaranteed that we can confidently discard a SPOT DEM if its mean error is > 5m
- the sampling of elevation by check points is insufficient thus the true error of a SPOT DEM may be greater than what the 16 check points produce.

Another issue of interest while designing the check point layout is whether the errors of a DEM are dependent of the signal, that is, greater elevation gives greater error. To examine this issue three elevation bands are chosen: < 25m, 25~65m and > 65m. Per each band 16 check points are planned. An ideal layout of check points is exemplified in Fig. 2, which meets the minimum requirement of 1 point within the 50km × 70km box, meets the requirement of N = 16 and enables the test of signal dependence. In reality it is difficult to facilitate many check points at high elevation since the region is near the sea level. Thus only 7 check points > 65m are collected (Table 1).

4. Preparation of Control & Check Points

We would like to describe the preparation of check/control points in detail since their accuracy determines the confidence level of the quality assessment. The check points and control points are prepared through GPS surveys. Three GPS receivers are used, one Trimble Pro XR and two Trimble 4000SSi. Each point is surveyed for 10-15 minutes at single carrier mode. With this configuration, the nominal accuracy is 1.2 m with Suwon as the reference station for differential GPS. Deviation from the Kalman filter model which is used for processing the GPS records (Parkinson and Spilker, 1996) is 0.32, 0.93 and 0.46 m respectively for latitude, longitude and elevation. One may treat the deviation as the random error in the GPS records.

The image coordinates of the GPS records are modified manually through fine tuning procedures, implemented in *KIMS3* software developed by SaTReC. The tuning procedure is based on the vector propagation camera model (Shin *et al.*, 1998). Since the cameral model is accurate to 1.5 pixels on SPOT images (Kim *et al.*, 2000), the image coordinates are modified when the corresponding error given by the model is greater than 1.5 pixels. Eight GPS records are discarded since their errors are too large to correct. After the fine tuning the accuracy of the GPS records is 0.9 and 1.0 pixels in row and column directions respectively. 72 GPS records are collected, out of which 20 are located in the mountain area and 52 along the coast. 75% of the 72 records have accuracy better than 1.5 pixels (Fig. 3).

Out of the 52 coastal points 14 are selected as

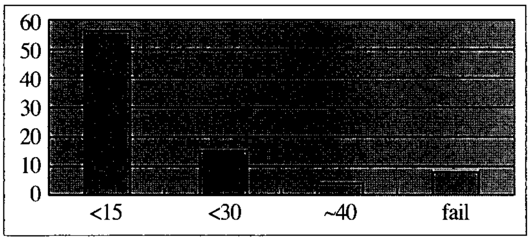

Fig. 3. The distribution (ordinate, in the number of records) of GPS records with respect to their accuracy (abscissa, in meter) assessed by the vector propagation model.

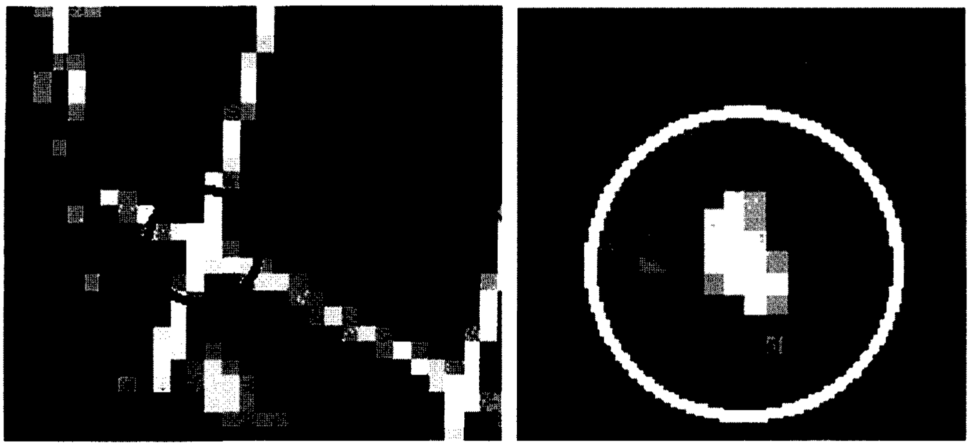

Fig. 4. Subjective classification of a GPS record based on their quality: class 'High' (left) and 'Low' (right).

ground control points (GCP) based on the following considerations:

- the 52 GPS records are classified into three quality groups and the GCPs should have High quality. The criteria used for the classification are (1) the magnitude of the errors given by the vector propagation camera model (Fig. 3), (2) whether the tuning is made purely for reduction of the camera model error or it has a physical basis and (3) after tuning how uncertain the location of the GPS records is in the image (*e.g.*, Fig. 4).
- GCPs should be dispersed evenly
- use a GPS record as a seed point of stereo-match. When the region-growing fails, allocate the record to control points since such a point cannot be used as a check point. In this way the number of a check point can be maximised.
- to obtain sufficient accuracy of the Orun and Natarajan's camera model about 14 GCPs are needed (Kim *et al.*, 2000).

The 14 GCPs are used also for the seed points during the stereo-match. No further tie points are created since the coverage of match points is not much affected by the number of seed points. Consequently 38 GPS records remain as check points and the number is 10 points less than required by the checkpoint layout design (Section 3).

5. Quantitative Assessment: Method

Input to the quality assessment program is the result of applying the stereo-match, the camera-model and the t-test editing. Each input point consists of five fields: column number, row number, latitude, longitude and elevation. Check points also have the same five fields. It is examined whether each input record falls within the boundary of a particular check point. The boundary is defined by the stereo-match interval – 5 pixels. Because the stereo-match interval is not a unit pixel the distance between a check point and a stereo-matched point may not be the multiple of the stereo-match interval (Fig. 5). To handle the varying distance bilinear interpolation is employed to obtain the latitude, longitude and elevation of stereo-matched points at the check point location (Fig. 6). For the bilinear interpolation to work, at least three quadrants around a

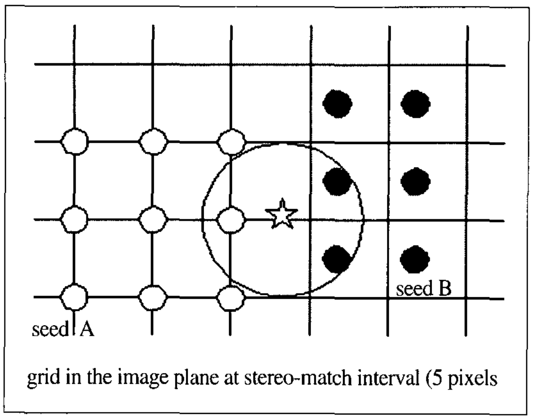

Fig. 5. Geometry of a check point (star) and stereo-matched points (smaller circles). The white dots have grown from the seed A and the black dots from the seed B. The larger circle is the search radius of the bilinear interpolation.

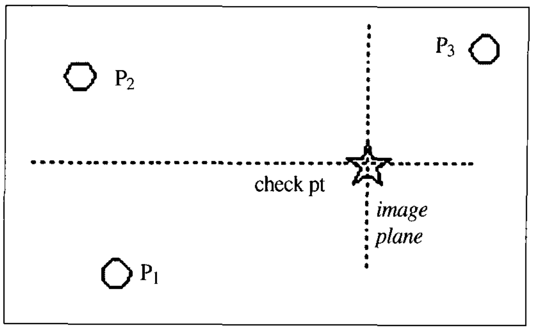

Fig. 6. Two-dimensional bilinear interpolation to obtain either latitude, longitude or elevation at the check point (star). The weighting is an inverse of distance, $\sqrt{(col_i - col_c)^2 + (row_i - row_c)^2}$, where col and row stand for column and row numbers, the subscript *c* for the check point and *i* is the index of a stereo-matched point (circle).

check point has to be occupied by the stereo-matched points[2]. For example, in Fig. 6 if only first and second quadrants are occupied by p2 and p3, the interpolated latitude cannot represent the latitude at the check point correctly. Excluding the cases where there are less than 2 occupied quadrants, 31 check points are left.

As an input to the quality assessment elevation before interpolation is used rather than after interpolation since the planimetric accuracy has to be assessed. The objects of the planimetric accuracy assessment are latitude and longitude parameters. During interpolation, however, the latitude and the longitude values of a stereo-match point are used thus are not present in the interpolated data. One may argue that the comparison of elevation before interpolation does not include any errors introduced during interpolation. However though interpolation alters elevation at a particular location, it does not alter the error over the entire DEM area since interpolation spreads errors in the input elevation[3]. Therefore sufficient sampling of check points would give the same elevation accuracy whether the interpolated elevation is used or not. In reality, of course, insufficient sampling would incur some discrepancy.

6. Quantitative assessment: results

Donghae DEM generated over the full scene area (60 km × 60 km) is shown in Plate 1 together with an enlargement of one coastal region. The topography shown by Donghae DEM agrees very well with a 1:50,000 topographic map.

The accuracy of Donghae DEM is surmarised in Table 2. In the planimetric components the mean errors are smaller than the corresponding standard errors (= standard deviation divided by the number of records), thus the errors are not

2) Two quadrants would be sufficient only if they are located in the diagonal direction.

3) Even during the exact interpolation such as Kriging smooth interpolation occurs if an interpolant is not at the output grid. Thus in general it is correct to say that interpolation smoothes input elevation.

Table 2. Planimetric and elevation accuracy when all 31 check points are used.

	Difference in meter (Donghae DEM check point)	
	mean	r.m.s.
In latitudinal direction	0.46	8.90
In longitudinal direction	0.48	11.46
In elevation	-2.17	12.04

distinguishable from zero. Therefore one may conclude that the mean planimetric error or the bias may as well be zero. The -2.17m bias in elevation is comparable with the standard error thus the elevation accuracy may improve by this amount if a physical basis of the bias is identified. The scatter diagrams in Fig. 7a-c show good comparison both in planimetric and elevation directions. The r.m.s. of the planimetric error is about 13m. As a rule of thumb, this would influence the elevation error by about 13 m × tan α where α is the terrain slope. Whether the influence will increase or decrease the elevation error depends on the geometry of terrain.

As the check points do not provide sufficient sampling (Section 3) it may happen that the ambience around a check point is more accurate than elevation at the check point, and vice versa. Thus for further quality check it would be worth examining the surroundings near a check point. Plate 2 shows the contours made from Donghae DEM around check points for three different terrain types. The contours show realistic topography with respect to the check point.

Now let us investigate if larger elevation gives larger error and vice versa, that is, signal

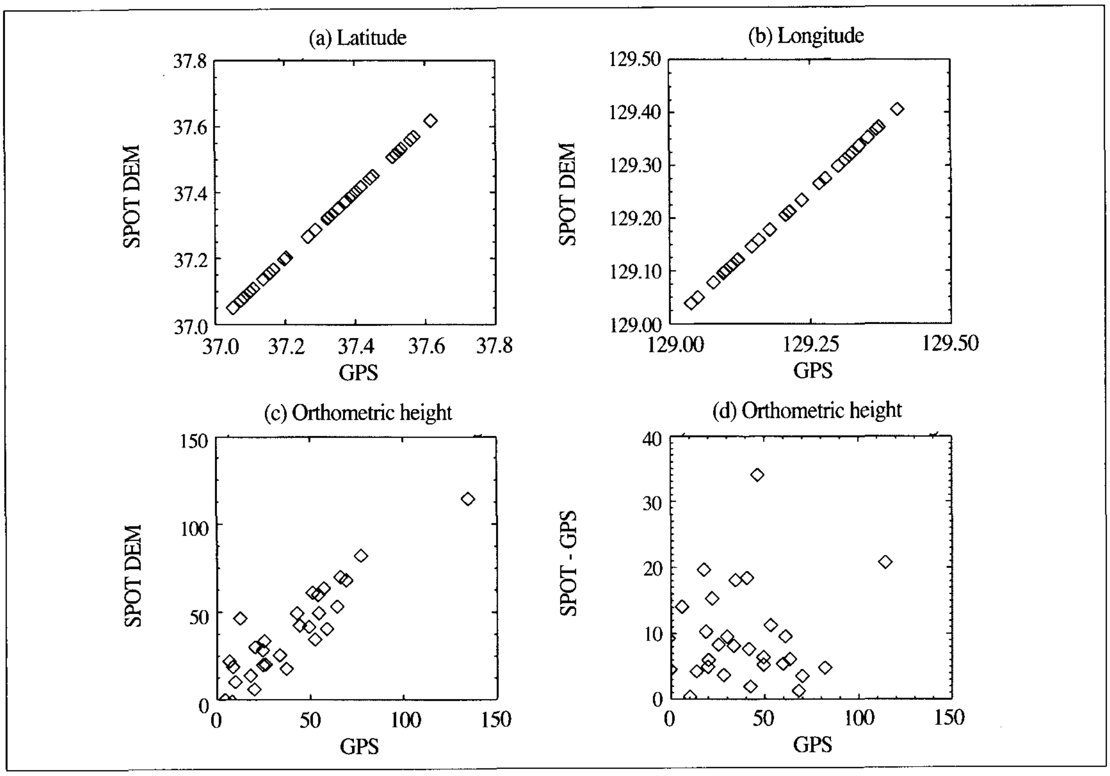

Fig. 7. Scatter diagram of latitude, longitude and orthometric height in meter between Donghae DEM and GPS check points (a-c). In (d) the elevation error is plotted against the check point elevation.

Table 3. Elevation accuracy for each elevation category.

	Difference in meter (Donghae DEM check point)	
	r.m.s.	Number of records
Check pt class I (h <25m)	13.15	12
Check pt class II (h = 25~65m)	10.82	14
Check pt class III (h >65m)	12.46	5

dependency. In Table 3, the mean and r.m.s. of the elevation error are calculated for the three elevation groups. The magnitude of errors is irrelevant of the signal magnitude. The irrelevance can be shown also in the scatter diagram in Fig. 7d. The lack of dependency would be reasonable. The explanations are, firstly, that the stereo-matching would perform independently of the magnitude of elevation as long as the elevation within a patch (5 ×5 window) does not vary much. Secondly the camera model accuracy is determined partly by the errors in GCPs, and the measurements and positioning of GCPs in the image plane are irrelevant of the magnitude of elevation. The lack of dependence implies that ~10m elevation error may arise in the land near the sea level and consequently the coastal land may be represented as the sea. Thus care should be taken when a SPOT DEM is used for coastal applications.

7. Discussions

Let us examine whether the Donghae DEM accuracy in Table 2 is reasonable. There are three major sources of the planimetric and elevation errors. They are check point (GPS measurements), camera modeling and stereo-matching. The check point error is about 1.5 pixels (Fig. 3) though this includes the errors in the vector propagation model. The camera model error is about 1 pixel (Kim *et al.*, 2000) though this includes potential errors in check points. The stereo-matching error is hard to estimate. The check point error would influence mainly the planimetric error. This is because the check point error comes primarily from positioning of a GPS record in a image plane, when the GPS measurement itself is assumed accurate enough. By comparison, the uncertainty in stereo-matching and camera modelling would cause both planimetric and elevation errors. In terms of the order of magnitude, the planimetric error is comparable with the check point error. So is the elevation error with the uncertainties in the check point and camera model. Thus it is concluded that the results in Table 2 as realistic.

Next let us consider the possibility of improving the accuracy of Donghae DEM. The fundamental limitation here is the resolution of SPOT images: 10 meter. It is not possible to prepare GCPs more accurate than 1 pixel since the manual positioning, in the image plane, of GPS records has inherent ambiguity of 1 pixel. The positioning ambiguity is also present in check point preparation, thus check points cannot be accurate better than 1 pixel. On the other hand if a physical cause of the mean bias in elevation is identified it may be removed from Donghae DEM. As in Krupnik (2000) use of only accurate check points may reduce uncertainties in the check points.

The accuracy of Donghae DEM in Table 2 is about 20% greater than the assessment by Al-Rousan *et al.* (1997) on the Jordanian desert using the PCI EASI/PACE: 8.2m, 8.9m and 10.0m in latitudinal, longitudinal and elevation directions. Recently Krupnik (2000) automatically generates SPOT DEMs over diverse terrain types using MatchT and Orthmax packages. He reports the elevation error of 6 to 22 m r.m.s. with reference to 1:40,000 topographic maps. Considering the

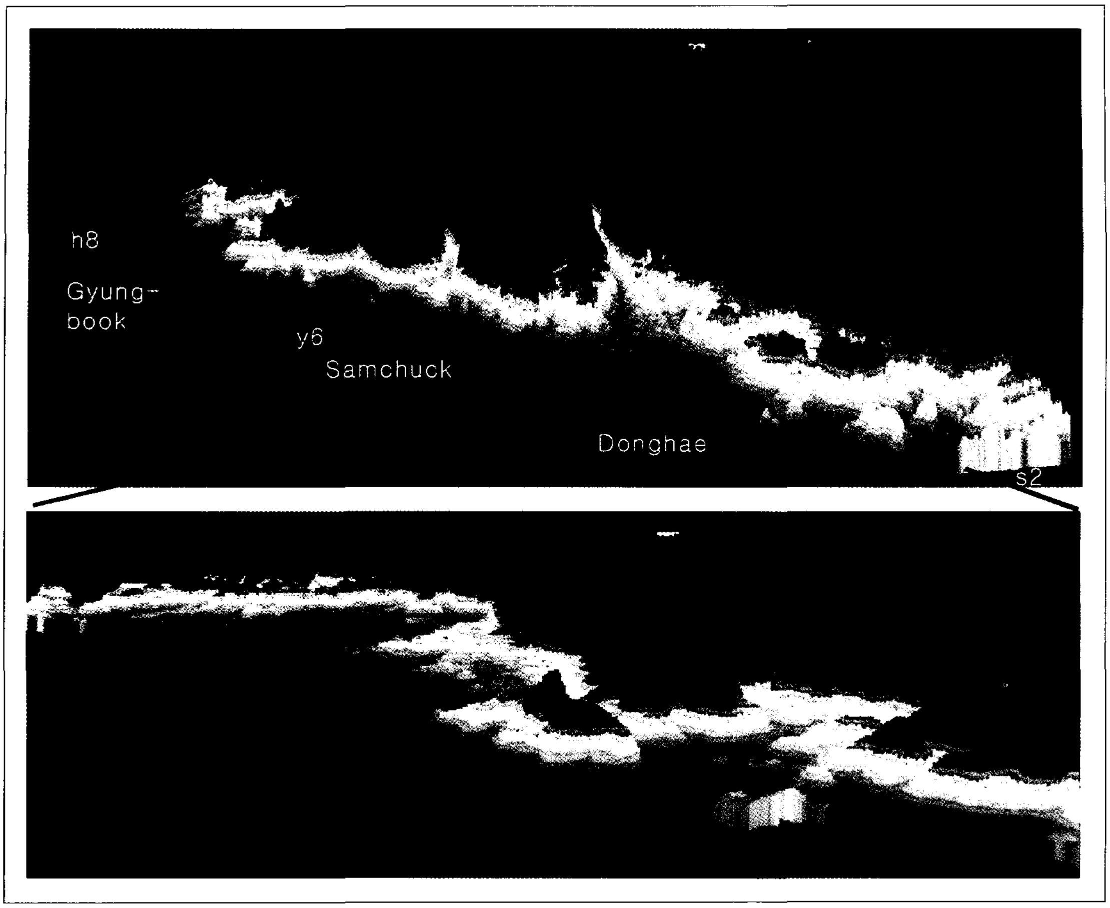

Plate 1. Donghae DEM: 60km × 60Km area(top) and an enlargement(bottom). The orthometric height is scaled between -30and 1,500m(top) and between -30 and 500m(bottom). The vertical scales are exaggerated by 20(top) and 30(bottom) times.

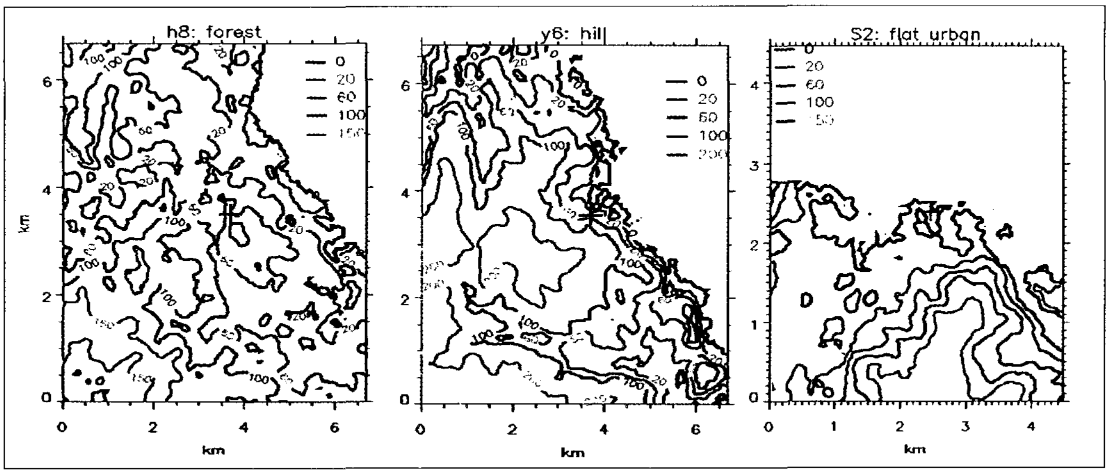

Plate 2. Comparison of orthometric height from the Donghae DEM with the check point elevation at three locations (marked by plus) indicated in Plate 1. Contours are in meters.

differences in the terrain type and preparation of GPS records it would be rather difficult to compare the accuracy of Donghae DEM with the previous results. To make a rigorous comparison it would be necessary to generate Donghae DEMs using their softwares and to perform accuracy assessment with the same check points as this study's. In fact, when the same test areas and the same GCPs are used Valadd-pro exhibits about two times better accuracy than the PCI with DTED and topographic maps as reference data (Lee *et al.*, 1999).

8. Conclusions

Quantitative accuracy assessment of a SPOT DEM (hereafter Donghae DEM) generated by Valadd-pro software is performed. The test sites are within a 90km long 10km wide strip along the coast around Donghae city and the topography includes steep hills, gentle hills, flat farmland, urban areas and harbors. The aim is to help a user to decide to what extent a SPOT DEM may be used for coastal applications with a view to replacing traditional DEMs which are out-of-date and slow to update. Also it is intended to provide rigourous accuracy specifications of Valadd-pro to continue the previous efforts by Lee *et al.* (1999) and Kim and Park (submitted). This comparison would also contribute to the literature on SPOT DEM accuracy.

The accuracy assessment is performed using check points from a GPS survey. The theoretical requirements on the check point layout is derived: only when the Nyquist sampling is applied the true magnitude of DEM error can be assessed. The Nyquist interval, however, is difficult to determine. One may use the alternative parameter, decorrelation scale, but it is impractical to calculate it a priori. As the relaxed requirements, it is aimed to detect large (> 5m) elevation errors with statistical confidence. For this, 16 check points are necessary. In addition, to inspect whether the elevation error is dependent of the magnitude of elevation, accuracy assessment is made on three elevation bands. Having discarded inadequate check points, 31 records are available.

Accuracy of Donghae DEM is calculated to be 8.9, 11.5 and 12.0 m r.m.s. in latitudinal, longitudinal and elevation directions (Table 2). These magnitudes are realistic considering the sizes of the major error sources: ~10m in the camera model and ~15m in the check points. The mean error or bias is distinguishable from zero only for elevation. The bias is −2.17m thus the elevation accuracy may improve by this amount if a physical basis of the bias is identified. As the elimination of the errors in the camera model and the check points is limited by the SPOT ground resolution it is difficult to expect significant improvement in DEM accuracy. Also it should be noted that the true accuracy of Donghae DEM may be greater as the Nyquist sampling is not performed. Last, the magnitude of elevation errors is not dependent of that of the elevation, thus care should be taken when a SPOT DEM is used for coastal applications.

The errors in another SPOT DEM over the Jordanian desert generated by the PCI EASI/PACE (Al-Rousan *et al.*, 1997) are comparable with those of Donghae DEM. The difference is about 20% but it is difficult to make direct comparison due to differences in terrain type and GPS records. To make a rigorous comparison it would be necessary to generate Donghae DEM using their softwares and to perform the accuracy assessment with the same check points as this study's.

Acknowledgements

This research was executed under the contract 'DEM generation along the coast' that KORDI commissioned SaTReCi Ltd. to perform. Researchers in SaTReC and SaTReCi are thanked for undertaking the GPS survey and E&G Ltd. for lending GPS receivers. Special thanks are given to T.H. Yoon, N.H. Lee and T.J. Kim for designing the GPS survey and post-processing. E&G Ltd. and Geosys Ltd. kindly processed the GPS data.

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