

INTELLIGENT INTERPOLATION METHODS FOR A FULL-SCALE SPOT-DEM IN COASTAL REGIONS

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ABSTRACT

Intelligent schemes for interpolating stereo-match results to generate a DEM (digital elevation model) are implemented, as a part of an automatic DEM production from a stereo-pair of satellite images. The need for these schemes is that interpolation itself is bound to introduce severe blunders, however sophisticated it may be. Due to these blunders, elevation becomes non-zero over the sea and rivers. Also topography is wrongly created outside stereo-scenes. Even well-known commercial softwares produce such blunders. To resolve these problems, intelligent schemes are implemented: firstly, center-of-gravity (COG) and empty-center-index (ECI) which quantify how evenly distributed interpolants are within an interpolation radius; secondly, hole-fill segmentation scheme to discern whether or not interpolation should take place in an empty segment of stereo-match results; and last, noise-remove segmentation scheme to remove noise-like features. The efficacy of these schemes is demonstrated on SPOT DEMs over two 60 km × 60 km areas in S. Korea. These methods remove all the blunders which amount to 15% of the stereo-matched points.

1 INTRODUCTION

A digital elevation model (DEM) is one of the most widely used data for terrain analysis and geographical information systems. DEMs from satellite images have gained increasing advantages over aerial DEMs thanks to regular scanning, unrestricted access to the global terrain, and high-resolution (up to 1-m) missions. In DEM generation, elevation values after sensor modeling do not provide complete spatial coverage. Complete coverage may be obtained by interpolating the scattered elevation values. In this way interpolation becomes a crucial element determining coverage and accuracy of a DEM.

One of essential issues in interpolation is to find an optimal interpolation method. Renka (1988), Carlson and Foley (1991), Desmet (1997) and, as a survey paper, Franke (1982) experiments using a test set with less than 100 scattered input. It was Kim et al. (1999) who study interpolation with a realistic size of input. Firstly, they use an area of 30 km by 40 km by creating scattered data through random sampling of a 1:25,000 ground survey map. 8 interpolation methods are applied to the scattered data, and Kriging method shows the best performance. Secondly, they use a SPOT DEM over a 10 km by 10 km region (1000 by 1000 pixels). Gaussian method shows superior performance to Kriging thanks to its capability to smooth out stereo-matching errors.

Kim *et al.* note further that simple application of Gaussian does not produce a satisfactory DEM. In detail, along the boundaries of a scene, artifacts are generated to a significant degree; such artifacts inevitably occur along the coast; the elevation over rivers and lakes is interpolated to the elevation of surrounding land. These blunders are exemplified in Fig. 1. In Fig. 1a one-side of an image is the coast, and the number of such blunders reaches 23 % of the total matches. Kim *et al.* introduce preliminary solutions: COG (center-of-gravity) and ECI (empty-center-index) thresholding.

In this paper, the preliminary solutions are refined and additional schemes for enhancing interpolation performance are implemented. The series of the enhanced interpolation schemes are named 'intelligent interpolation'. The need of intelligent interpolation also exists in state-of-the-art commercial softwares. In this study OrthoEngine v6.2 of PCI and ImageStation of Intergraph Co. are used. The PCI DEM is displayed in Fig. 1b, where again the elevation along the coast incorrectly reaches several hundred meters and unrealistic islands are present. To our conjecture interpolation, together with a 'pyramid' approach for stereo-matching, would be the cause of the problems in the PCI DEM. This paper presents development of intelligent interpolation methods with a view to resolve the limitations in the currently available DEMs. Section 2 describes data used. In sections 3 and 4, the intelligent interpolation methods and their performances are presented.

2 DATA

Each pair of SPOT stereo-images cover an area of $60 \text{ km} \times 60 \text{ km}$. Stereo-matching is an area-based one using the epipolar correlation criterion (Kim, 2000). About 20 GPS measurements are used as ground control points. To save computing time, stereo-matching is performed at every 5 pixel, thus the output resolution is 50 m. The stereo-match results are transformed into elevation using a camera model by Orun and Natarajan (1994). Gaussian interpolator of Kim et al. (1999) produces a DEM shown in Fig. 1a.

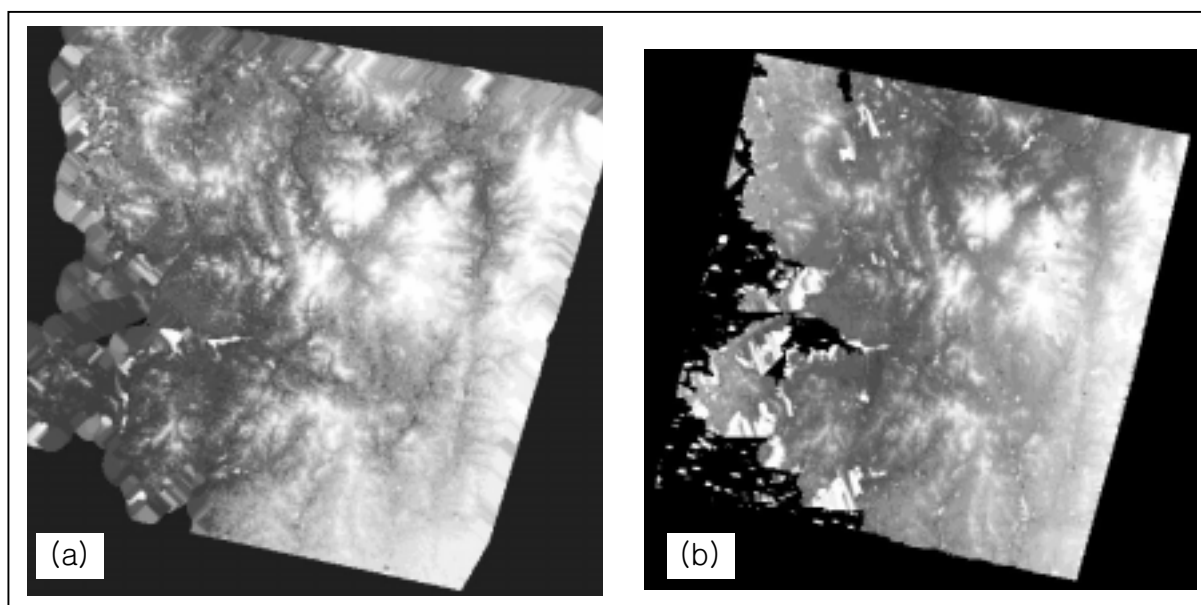


Fig. 1 Limitations of conventional interpolation methods (a) generated by Gaussian interpolator without intelligent methods and (b) PCI DEM over a $60 \text{ km} \times 60 \text{ km}$ area in Seoul/KyungKi region, S. Korea. The coast is on the left.

3 CENTER-OF-GRAVITY (COG) AND EMPTY-CENTER-INDEX (ECI)

COG and ECI are used to remove unrealistic outstretch of elevation along an image boundary. Interpolated values whose COG or ECI fail to meet threshold values are removed.

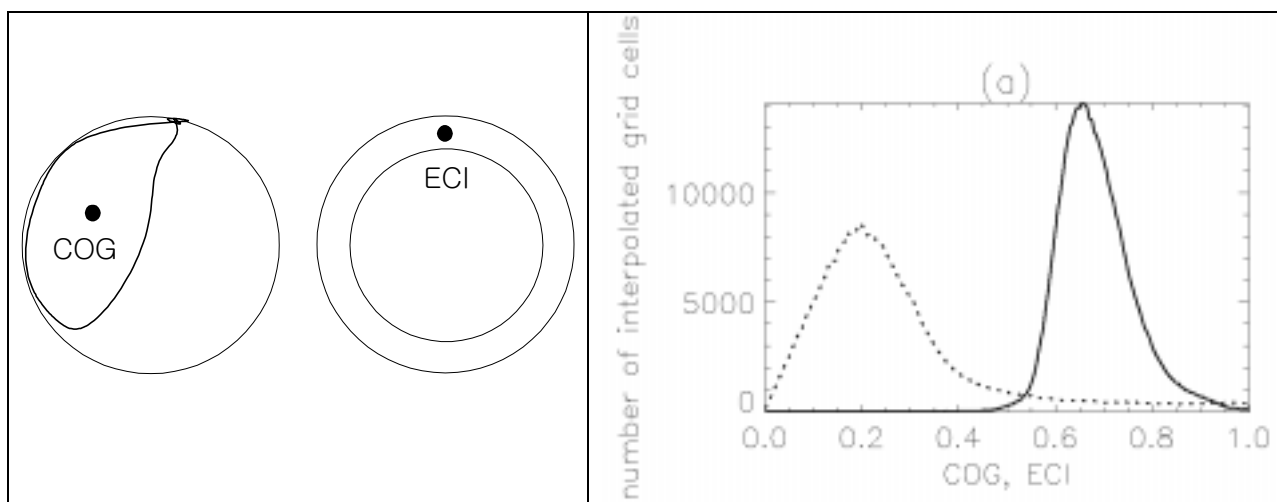


Fig. 2 Illustration of 'center-of-gravity' (COG, left) and 'empty-center-index' (ECI, right). ECI may be regarded as a 1D version of COG (1D being in the radial direction). The shaded area is where stereo-match succeeded, while the white area is not. The outer circle indicates an interpolation radius.

Fig. 3 Distribution of COG (dotted) and ECI (solid) computed over a $35 \text{ km} \times 30 \text{ km}$ area. The total number of COG (and ECI) samples is 471,000.

3.1 COG

COG aims at removing interpolated values if the interpolants are unevenly distributed. COG is defined as

$$COG = \frac{\sqrt{(\overline{\Delta x})^2 + (\overline{\Delta y})^2}}{max_dist}$$

where $\overline{\Delta x}$ and $\overline{\Delta y}$ are the mean of the distance between a scattered input and interpolated point. max_dist is the maximum of the distance. Evenly scattered input gives 0 for COG and unevenly distributed input gives high COG. To determine the threshold of COG, COG is computed over a 35 km × 30 km area. This computation produces about 471,000 samples and their distribution is shown in

Fig. 3. The mean COG is 0.28 with peak at 0.20. The mean is not zero because the distribution of scattered input is not uniform with respect to the distance from the interpolated point. Equalisation of the distribution was tried but then the performance of COG was not good. The COG threshold is determined empirically by applying various values to the DEM in Fig. 1. COG threshold of 0.6 gives the best result in terms of removing the artifacts along the coast. The result is in Fig. 4a, which shows significant improvement over the DEM by the simple interpolation in Fig. 1a.

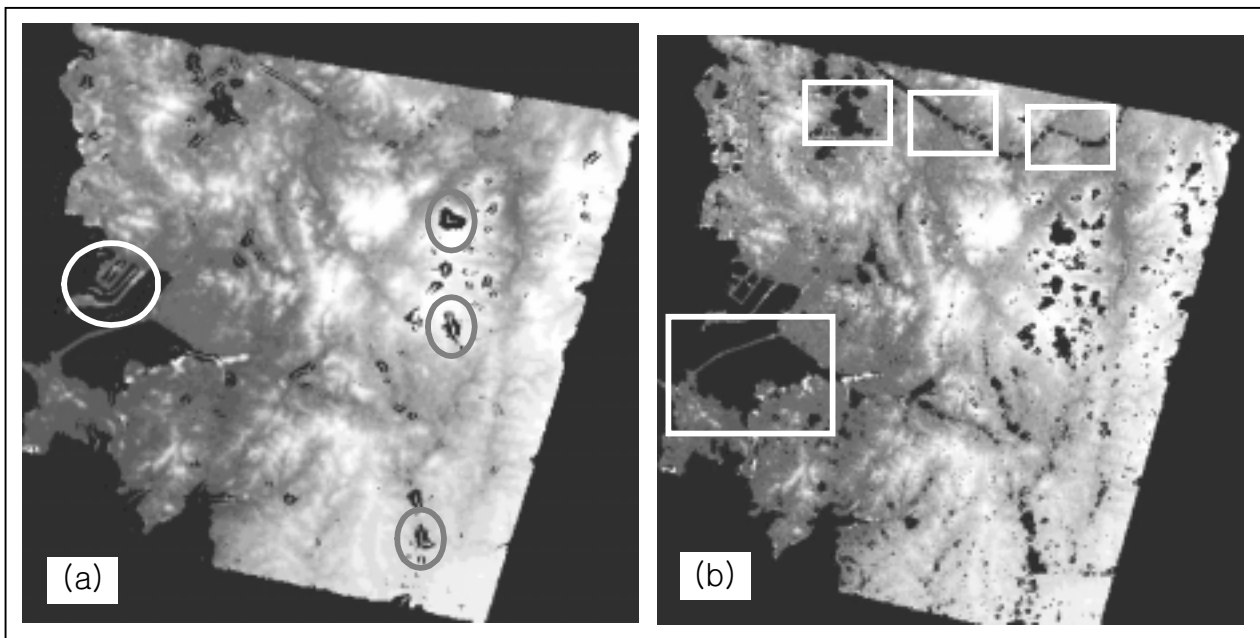


Fig. 4 Results of applying (a) COG and (b) ECI to the DEM by simple interpolation in Fig. 1a.

3.2 ECI

The DEM obtained after applying COG criterion is still incomplete. There are thread-like features inside holes (marked by loops in Fig. 4a). These occur because at the center of a hole COG is 0 and an interpolated value is not rejected. The normalised ECI defined below would be able to remove such thread-like features:

$$ECI = \frac{\sum_{k=1}^N r_k p(r_k) w_{eq}(r_k)}{\sum_{k=1}^N p(r_k) w_{eq}(r_k)} \quad \text{and} \quad \text{normalised ECI} = \frac{ECI}{max_dist}$$

where r_k is the distance from an output grid. $p(r)$ is the distribution function of scattered input when the search area is full. w_{eq} equalises the distribution of $p(r)$ thus is an inverse to $p(r)$. Therefore $\sum w_{eq} p(r_k) = 1$. Consideration is given so that w_{eq} may not reach singularity.

The threshold of ECI is determined empirically as described for COG threshold in § 3.1. The mean ECI is 0.69 (

Fig. 3). Ideally ECI should be 0.5 while anti-singularity measure adds a bias of $1/max_dist$. max_dist of 5 pixels results in a bias of 0.2 thus such size for max_dist is realistic. The ECI threshold is determined by applying various values to the DEM in Fig. 1a. ECI of 0.8 gives the best result in terms of removing the threadlike features while still minimising any undesirable removal (Fig. 4b).

4 SEGMENTATION SCHEMES

A problem after applying COG and ECI criterion is that holes in a DEM, arising due to stereo-match failure, still remain (Fig. 4b). It is needed to fill the holes. However, a hole-filling scheme should not fill a lake or rivers (for example, marked by a rectangle in Fig. 4b). Lakes are identifiable by their large size whereas match-failure regions tend to have smaller size. To select a hole surrounded by land, a closed and empty region is segmented. Then segments with areas < 6000 pixels or 15 km² are regarded match-failure and consequently filled. Empty pixels are grouped in 8-connectivity sense. The grouping is performed by scanning four times (each scan starting from each corner of an image). Four scans are needed since one scan makes one segment into several fragments (marked by loops in Fig. 5a). The hole segmentation scheme fails in preserving rivers (which is a w-shaped feature at the top in Fig. 5a) as an empty area. This still remains to be refined.

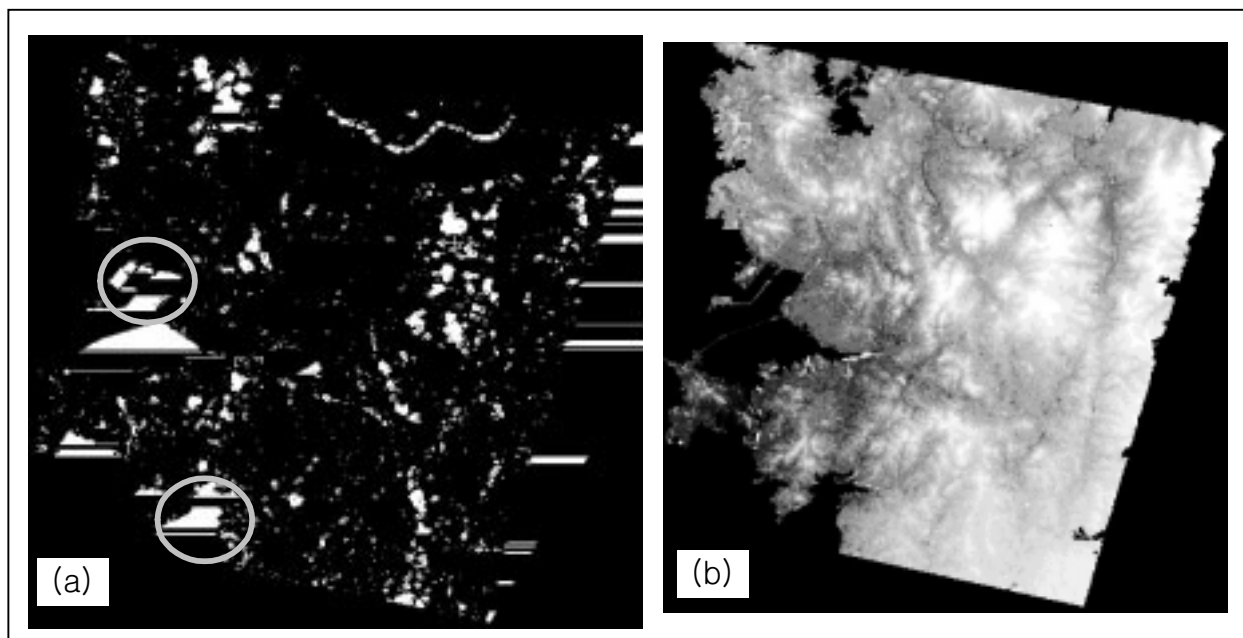


Fig. 5 Results of (a) applying hole-fill segmentation scheme and (b) final DEM. In (a) scan is performed only once thus the segments are fragmented.

The second segmentation scheme is necessary to remove noise. The noise is a small land (of several pixels large) floating off the coast or off the lakeside. The noise occurs due to imperfect performance of ECI thresholding. To remove the noise, land is segmented and segments with sizes < 100 pixels are eliminated. 4-connectivity segmentation is employed and 4 scans as in the hole-filling segmentation are applied. The hole-filling and the noise-remove segmentation are completed in less than 3 minutes on SGI Octane platform. A DEM after the two segmentation is shown in Fig. 5b. The series of intelligent interpolation schemes eliminate 15% of elevation interpolated by simple Gaussian method.

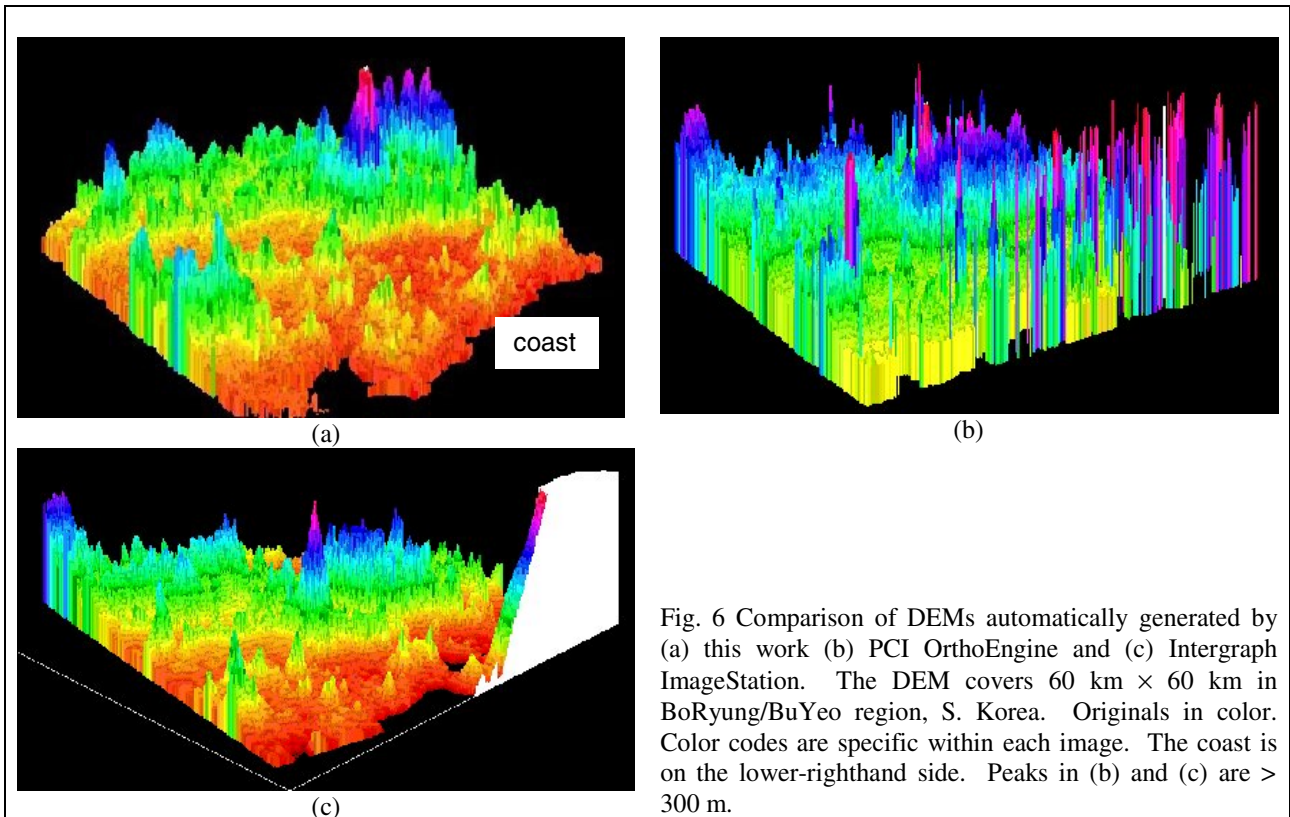
The final DEMs are compared in a different region in Fig. 6. The DEM from this research produces a correct and detailed coastline in this region as well. By comparison the coastline of PCI DEM is deteriorated by erroneous elevation (spikes) and artificial islands. Intergraph DEM is better than PCI DEM, however the coastline is not as detailed as this study's DEM. In addition Intergraph DEM adds substantial error along the coast (large and high island-like feature). The relationship between color codes and elevation is different among the three cases.

5 CONCLUSIONS

Intelligent interpolation schemes are implemented to improve the quality of a SPOT DEM. To eliminate blunders of simple interpolation methods such as those in Franke (1982) or Kim et al. (1999),

- COG parameter is used: if a COG within an interpolation radius is greater than 0.6, the interpolated value is ignored. This eliminates blunders along image boundaries.
- ECI parameter is used: if ECI within an interpolation radius is greater than 0.8, the interpolated value is ignored. This eliminates thread-like features in the result of COG thresholding.
- Holes in the DEM with sizes less than 6000 pixels or 15 km² are segmented and filled with interpolated values. This is necessary because some match-failure regions should be filled but COG and ECI criteria leave them empty.

- Noise-like features (small islands off the coast) with less than 100 pixel size or 0.25 km² are segmented out. The final DEM shows significant improvement over the DEM generated by commercial softwares, PCI and Intergraph.



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