Intelligent interpolation methods for a full-scale SPOT-DEM

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Abstract: Intelligent schemes for an automatic generation of DEM (digital elevation model) are implemented. The need for these post-processing schemes is that interpolation alone produces severe blunders, however sophisticated it is. These blunders occur most seriously along the boundaries of a scene, over rivers, and along the coast. Even a state-of-the-art commercial software retains such blunders. The intelligent schemes implemented are (1) center-of-gravity and empty-center-index which quantify how evenly distributed interpolants are within an interpolation radius, (2) a segmentation scheme to discern whether or not an empty segment in stereo-match results should be interpolated, and (3) a segmentation scheme for removing noise-like features. With these methods, in the final DEM, identical coastline and river region to those in the original SPOT scenes are achieved. The DEM exhibits substantial improvements over the products of an existing commercial software.

Keyword: DEM interpolation, segmentation, SPOT, optimal interpolation, quality control.

1. Introduction

A digital elevation model (DEM) is one of the most widely used medium for terrain analysis and constructing geographical information system. DEMs from satellite photos 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 after sensor modelling, the consequent elevation values do not provide a complete spatial coverage. A 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 the optimal interpolation method. Renka (1988), Carlson and Foley (1991), Desmet (1997) and, for survey papers, Schumaker (1976) and Franke (1982) experiment using a test set with less than 100 scattered input. It was Kim *et al.* (1999) who study interpolation in a realistic size. 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 introduced to a significant degree; such artifacts occur inevitably along the coast; the elevation over rivers and lakes is interpolated to the elevation of surrounding land. These blunders are exemplified,

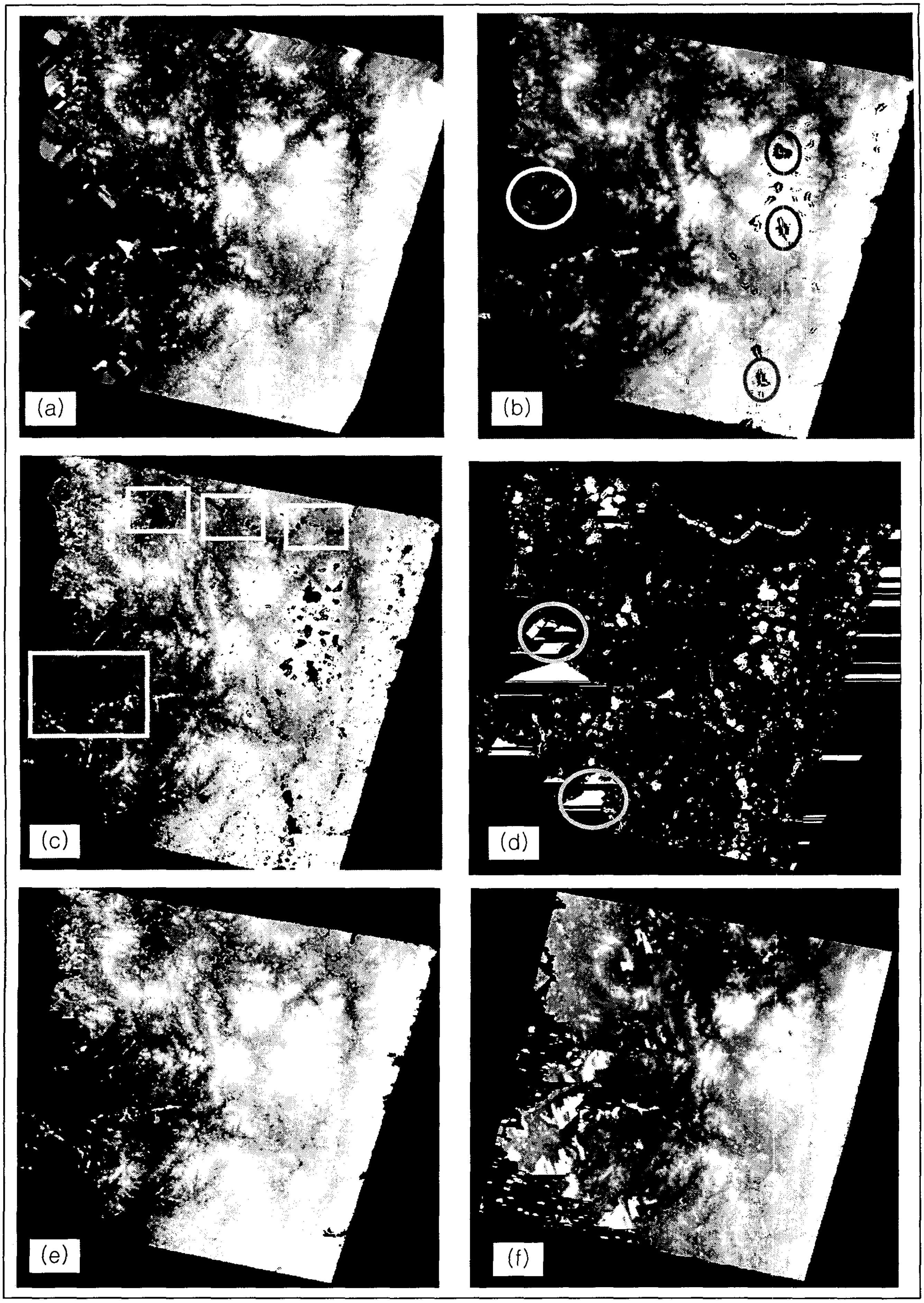
(a)
(b)
(c)
(d)
(e)
(f)

Fig. 1 (previous page). 60 km by 60 km SPOT DEMs in Seoul/KyungKi region: (a) generated by Gaussian interpolation without intelligent methods (b) after applying COG criterion (c) after applying ECI criterion (d) segments of empty areas (in white) after only one scan (e) final DEM after applying all intelligent schemes, and (f) PCI DEM.

and contrasted to correct elevation in Figs. 1a & 1e. With one-side of an image being the coast, the number of such blunders reach 23 % of the total matches for a DEM of Fig. 1a. Kim *et al.* introduce preliminary solutions: COG (center-of-gravity) and ECI (empty-center-index) thresholding. In this paper, the preliminary solutions are further investigated and additional schemes for enhancing interpolation performance are implemented. The series of the enhanced interpolation schemes are named 'intelligent interpolation'.

The importance of this work would stem from the fact that even a state-of-the-art commercial software suffers from the same blunders (Fig. 1f). Incorporation of the intelligent methods is expected to improve the performance of commercially available softwares.

Sections 2 describes data used. In sections 3 and 4, the intelligent interpolation methods and their performances are presented.

2. Data

A SPOT image-pair cover an area of 60 km by 60 km region. The details of the raw images are listed in Table 1. Stereo-matching is an area-based one using the epipolar correlation criterion (Lee *et al.*, 1999). 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.

Seoul/KyungKi	left	right
ID	304-275	304-275
Size (pixel)	6000x6000	6000x6000
Camera angle	-16'	2.2'
Time	1998 May 5	1997 Aug. 24

Table 1. Information of a SPOT image pair

3. Center-of-gravity & empty-center-index

3.1. Method

COG and ECI are used to remove unrealistic outstretch of elevation along the image boundary. Full mathematical definitions of COG and ECI are as follows (also refer to Fig. 2):

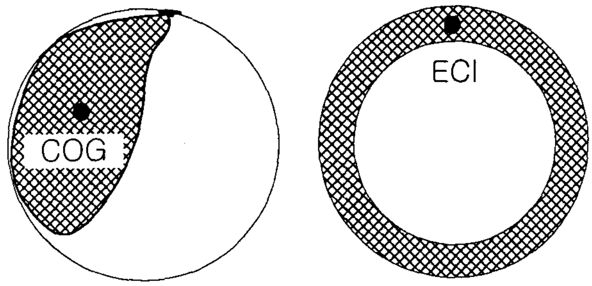

Fig. 2 Concepts of 'center-of-gravity' (COG, left) and 'empty-center-index' (ECI, right). ECI can be regarded as a 1D version of COG (1D being in the radial direction). The shaded area is where stereo-match succeeded, while the white area is not. The outer circle indicates an interpolation radius.

Center of Gravity

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

$$\overline{\Delta x} = \frac{\sum_{k=1}^{N} p(r_k)(x_k - x_o)}{\sum_{k=1}^{N} p(r_k)}, \text{same for } \overline{\Delta y}, \quad (1)$$

$$\mathrm{max\_dist} = \max\left(\sqrt{(\Delta x_k)^2 + (\Delta y_k)^2}\right)$$

where

$$p(r_k) = \frac{\cos(0) + \delta_{\mathrm{anti\_sigularity}}}{\cos\left(\frac{\pi}{2}\cdot\frac{\mathrm{dist}}{\mathrm{max\_dist}}\right) + \delta_{\mathrm{anti\_sigularity}}}.$$

x_o and x_k are coordinates of an output grid and an interpolants, respectively. $p(r_k)$ is to normalise the distribution of scattered input points. N is the number of scattered points. $\delta_{anti\_singularity}$ is to avoid singularity in $p(r_k)$. Evenly scattered points give 0 for COG.

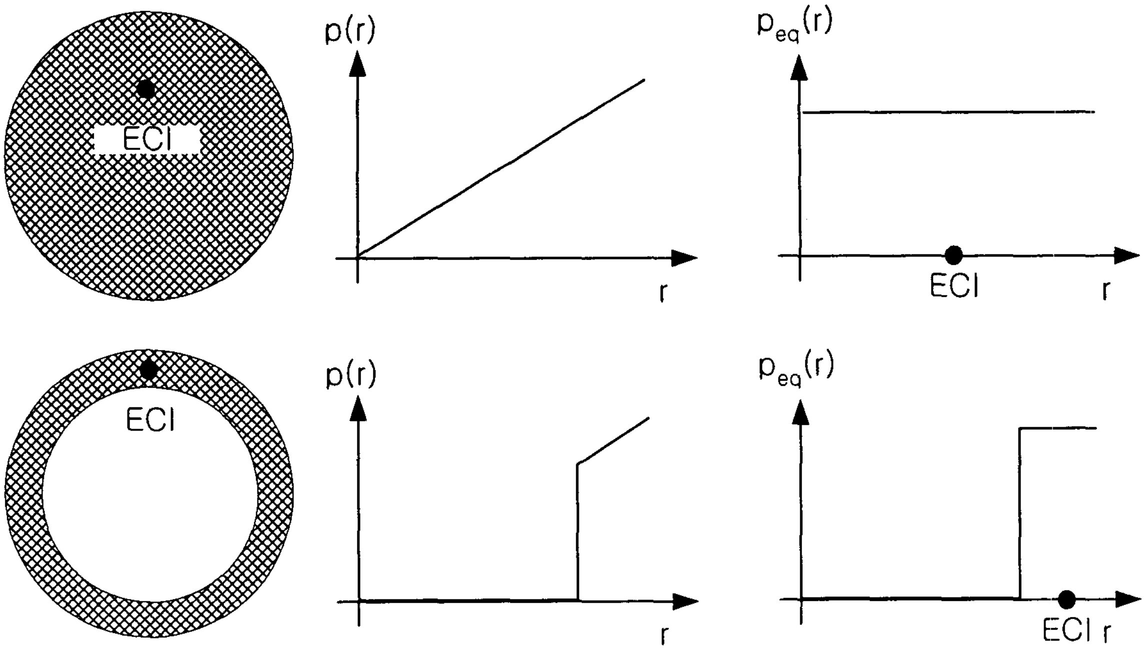

Fig. 3. Illustration of Empty-Center-Index. The outer circle in the first column indicates the radius of interpolation. Hatched regions are where interpolants exist. *r* is the distance from the output grid. *p(r)* is the point distribution function of interpolants. $p_{eq}(r)$ is *p(r)* after equalisation.

Empty-Center-Index

$$\mathrm{ECI} = \frac{\sum_{k=1}^{N} r_k p(r_k) w_{eq}(r_k)}{\sum_{k=1}^{N} p(r_k) w_{eq}(r_k)}$$

$$\text{normalised ECI} = \frac{\mathrm{ECI}}{\mathrm{max\_dist}}, \qquad (2)$$

where

$$r_k = \sqrt{(x_k - x_o)^2 + (y_k - y_o)^2} + \Delta r_{unit} \qquad (3)$$

$$w_{eq}(r_k) = \Delta s^{-1} = [8\pi r_k \Delta r]^{-1}, \text{where } s = 4\pi r_k^2$$

$p(r_k)$ = point distribution fct where $r_k \le r < r_{k+1}$. r_k is the distance from an output grid. w_{eq} equalises the distribution of *p(r)* (Fig. 3). To avoid singularity in w_{eq}, Δr_{unit} is added in Eq. 3. $\Delta r_{unit} = \sqrt{\Delta x_{unit}^2 + \Delta y_{unit}^2}$, with *unit* indicates unit distance. w_{eq} and *p(r)* satisfies $\sum w_{eq} p(r_k) = 1$.

The threshold values of COG and ECI are set to 0.4 and 0.8 respectively, through trial and error. Interpolated values with COG > threshold or ECI > threshold are rejected. Normalisation, expressed in Eqs. 1 and 2, does not work for reasons still unidentified. Thus for the time being COG and ECI are used without normalisation.

3.2 results

The result of applying COG and ECI is presented in Fig. 1. We perform simple interpolation and obtain a DEM of Fig. 1a with a significant amount of blunders

- after applying the COG criterion, the boundaries of DEM are free from blunders (Fig. 1b)
- in Fig. 1b there are thread-like features inside holes (marked by loops). These are because at the center of a hole, COG is 0 and an interpolated value is not rejected.
- application of the ECI criterion removes the thread-like features (Fig. 1c)

4. Segmentation schemes

A problem after applying COG and ECI application is that holes in a DEM, arising due to stereo-match failure, still remain (Fig. 1c). 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. 1c). 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 km^2 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. 1d). This scheme fails in preventing rivers from being filled, which is its limitation.

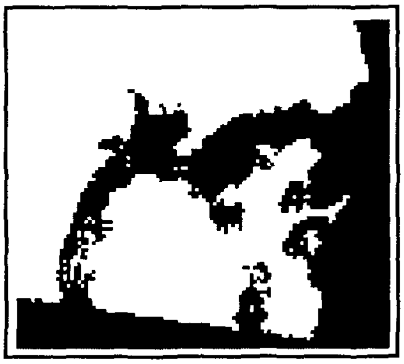

Fig. 4. Presence of small (<100 pixels, in white) islands off the coast. These noise-like features are segmented and removed.

The second scanning scheme is necessary to remove noise. The noise is a small land (of several pixels large) floating off the coast or off the lakeside (Fig. 4). 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 less than 3 minutes on SGI Octane platform. A DEM after the two segmentation is shown in Fig. 1e.

5. Conclusions

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

- COG parameter is used: if a COG within an interpolation radius is greater than 0.4, 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 km^2 are segmented and filled with interpolated values. This is necessary because COG and ECI criteria leave match-failure regions empty.
- Noise-like features (small islands off the coast) with less than 100 pixel size or 0.25 km^2 are segmented out.

The final DEM shows significant improvement over the DEM, generated by a commercial software, PCI.

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