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Extracting DEM from SPOT Stereo Images

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Abstract: In this paper, the theory and methods to extract DEM from SPOT stereo images are introduced in detail. How to remove the noise of DEM is also introduced. Using a pair of SPOT images of HongKong, a test result and the accuracy analysis are provided.
KEY WORDS: SPOT image, DEM, exterior orientation parameter, Matching.

1. Introduction

DEM has been widely used to generate digital products in different disciplines, such as to make contour maps, orthoimages, and perspective views. The research described in this paper mainly is to use SPOT images to extract DEM. In this paper, the exterior orientation parameters solution, image correlation matching, and removing noise of DEM are introduced in detail. We also use a pair of SPOT images of HongKong to do a test. The DEM and its accuracy analysis are provided.

2. Theory

2.1 Coordinates transformations

There are so many coordinates in the initial data. For example, the satellite position is in geocentric coordinates, the GCP is in local space rectangular coordinates, and the center position of SPOT image is in geographic coordinates. But we calculate exterior orientation parameters in tangent plane coordinates. Generally, we should transform all the data in other coordinates to the tangent plane coordinates before we calculate exterior orientation parameters. After extracting DEM, normally we should transfer the result to the local space rectangular coordinates. Several coordinate transformations are as figure 1.

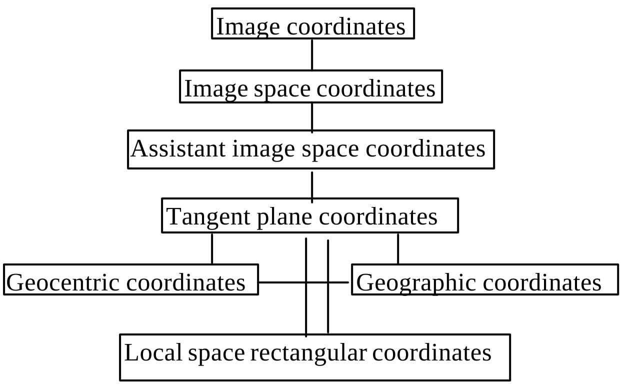


Figure 1, coordinates transformations

2.2 Exterior orientation parameters solution

In fact, there is 6 exterior orientation parameters in each line of a SPOT image. There are 6000 lines in a panchromatic SPOT image, so totally there are 36000 exterior orientation parameters in a SPOT image. There will be many difficulties to solve so many parameters in an image. In order to reduce the number of parameters, we adopted 6 linear functions to describe the relationships among these 36000 exterior orientation parameters. These 6 linear function are as following.

$$\begin{cases} j_i = j_0 + k_1 y \\ w_i = w_0 + k_2 y \\ k_i = k_0 + k_3 y \\ X_{S_i} = X_{S_0} + k_4 y \\ Y_{S_i} = Y_{S_0} + k_5 y \\ Z_{S_i} = Z_{S_0} + k_6 y \end{cases} \tag{1}$$

Where, "y" is row number, x_{si}, y_{si}, z_{si}, φ_i, κ_i, ω_i are exterior orientation parameters of row i.

We use co-linear equation to calculate the exterior orientation parameters. The co-linear equation is as below.

$$\begin{cases} x = -f \dfrac{a_1(X - X_s) + b_1(Y - Ys) + c_1(Z - Z_s)}{a_3(X - X_s) + b_3(Y - Ys) + c_3(Z - Z_s)} \\ 0 = -f \dfrac{a_2(X - X_s) + b_2(Y - Ys) + c_2(Z - Z_s)}{a_3(X - X_s) + b_3(Y - Ys) + c_3(Z - Z_s)} \end{cases} \tag{2}$$

Where, a_i, b_i, c_i are elements of the rotation matrix. f is focal length. Xs, Ys, Zs are coordinates of satellite in tangent plane coordinates. X, Y, Z are coordinates of GCP in tangent plane coordinates.

So the observation equations are:

$$\begin{cases} v_x - \dfrac{\partial x}{\partial X}V_X - \dfrac{\partial x}{\partial Y}V_Y - \dfrac{\partial x}{\partial Z}V_Z = (x) - x + \dfrac{\partial x}{\partial X_S}\Delta X_S + \dfrac{\partial x}{\partial Y_S}\Delta Y_S + \dfrac{\partial x}{\partial Z_S}\Delta Z_S + \dfrac{\partial x}{\partial j}\Delta j + \dfrac{\partial x}{\partial w}\Delta w + \dfrac{\partial x}{\partial k}\Delta k \\ v_y - \dfrac{\partial y}{\partial X}V_X - \dfrac{\partial y}{\partial Y}V_Y - \dfrac{\partial y}{\partial Z}V_Z = (y) - y + \dfrac{\partial y}{\partial X_S}\Delta X_S + \dfrac{\partial y}{\partial Y_S}\Delta Y_S + \dfrac{\partial y}{\partial Z_S}\Delta Z_S + \dfrac{\partial y}{\partial j}\Delta j + \dfrac{\partial y}{\partial w}\Delta w + \dfrac{\partial y}{\partial k}\Delta k \end{cases} \tag{3}$$

We use matrix to describe these equations.

$$AV = BX - L \tag{4}$$

Where,

$$X = \left[\Delta j, \Delta w, \Delta k, \Delta X_{s_0}, \Delta y_{s_0}, \Delta Z_{s_0}, k_1, k_2, k_3, k_4, k_5, k_6\right]$$

$$V_i = \left[v_x, v_y, V_X, V_Y, V_Z\right]^T$$

$$L_i = \begin{bmatrix} l_x & l_y \end{bmatrix}^T = \begin{bmatrix} x-(x) & y-(y) \end{bmatrix}^T$$

$$A_i = \begin{bmatrix} 1 & 0 & a_{14} & a_{15} & a_{16} \\ 0 & 1 & a_{24} & a_{25} & a_{26} \end{bmatrix}$$

$$B_i = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \end{bmatrix}$$

The least square solutions is given by

$$X = [B^T (AP^{-1}A^T)^{-1} B]^{-1} (AP^{-1}A^T)^{-1} L \qquad (5)$$

2.3 Maximum correlation matching

The procedure to do matching is as below.

(1) Given the pixel's position (X,Y,Z) and calculate its position in left image (i,j) and right image (i',j').

(2) Do correlation calculation

$$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \qquad (6)$$

(3) Change Z in a suitable region.

(4) Repeat (2) and (3) until all suitable Z are considered.

(5) Select the maximal correlation height (Z) as the pixel's height.

2.4 removing noise of DEM

The noise of DEM extracted by maximum correlation matching is random. We should detect all noise pixels before removing noise. Because the difference between the height of normal pixel and the height of noise pixel is very big, so we can set a threshold based on this height difference. Based on this threshold, we can detect all noise pixels on the edge of the noise. Then we can detect the pixel that is surrounded by noise pixels as noise pixel. So that we can detect all noise pixels. After that, we can replace the height of noise pixel with the average height of the noise's neighbors' heights to remove the noise.

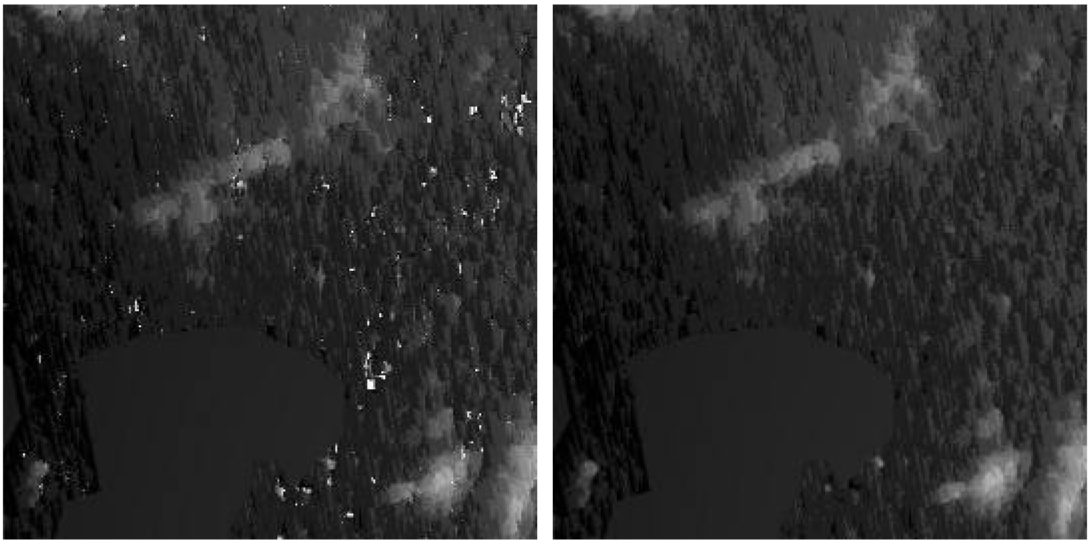
The procedure to remove the DEM's noise is as following.

(1) Set a threshold based on height difference.

(2) Detect the pixels on the edge of noise.

(3) Detect the pixels that surrounded by noise pixels as noise.

(4) Replace the noise with its neighbors.

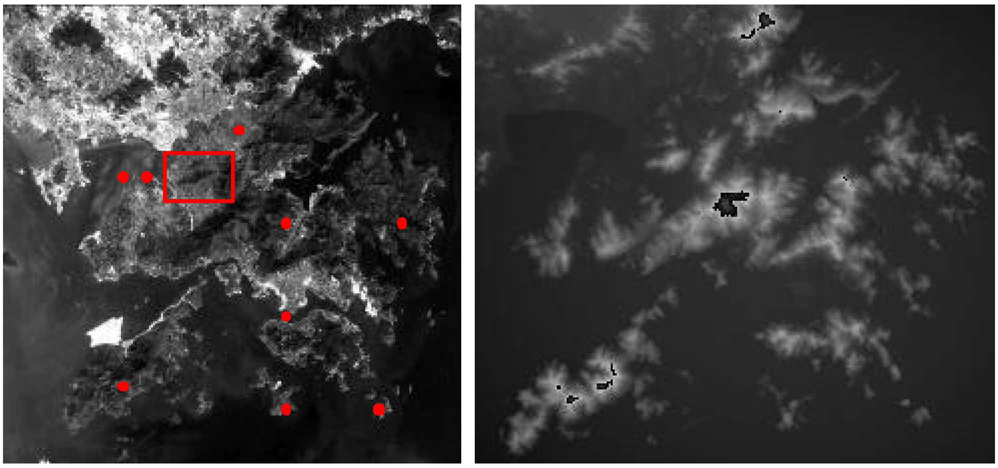


(a) (b)

Figure 2, (a): 400 by 400 DEM with noise. (b): 400 by 400 DEM after removing noise.

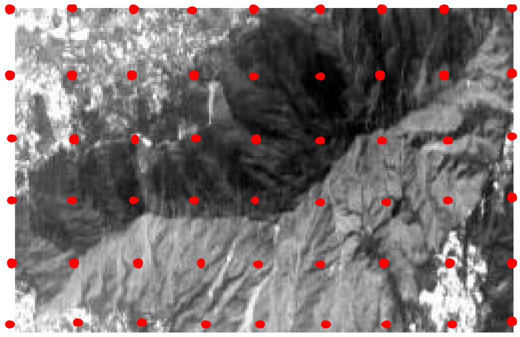
3. Experiment and accuracy analysis

We use a pair of SPOT images of Hong Kong which is received in January1996 to do the experiment. First, we generated a 2000 by 2000 DEM and then removed its noise. Second, we generated the 6000 by 6000 DEM and then removed its noise. In order to assess the accuracy of the DEM, we selected a mountain area to check the accuracy. We compare the height of the DEM with the height of Hong Kong map that is published in 1994, whose scale is 20000 under 1, whose contour interval is 20 meters. The 9 GCPs are also measured on this map. We selected 54 points to assess the DEM's accuracy.



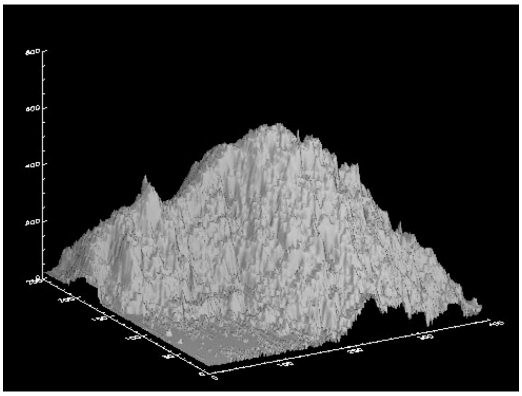
(a) (b)

Figure 3, (a), initial 6000 by 6000 SPOT image with 9 GCPs. (b) 6000 by 6000 DEM

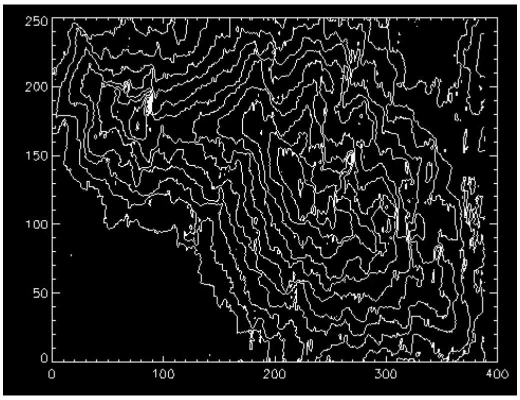


(a)

(b)



(c)



(d)

Figure 4, (a) the initial image with the check points. (b) DEM correspondent to (a), (c) 3-D DEM , (d) contour map

H(DEM)	H(Map)	deviation	H(DEM)	H(Map)	deviation	H(DEM)	H(Map)	deviation
27.5	10.0	17.5	26.1	10.0	16.1	173.8	170.0	3.8
24.4	30.0	-5.6	55.6	40.0	15.6	282.4	285.0	-2.6
66.6	57.0	9.6	89.6	60.0	29.6	320.2	315.0	5.2
77.0	65.0	12.0	134.1	130.0	4.1	362.0	340.0	22.0
46.0	45.0	1.0	397.2	400.0	-2.8	143.4	140.0	3.4
21.2	50.0	-28.8	549.9	540.0	9.9	40.5	45.0	-4.5
286.4	290.0	-3.6	359.9	300.0	59.9	129.3	110.0	19.3
217.4	230.0	-12.6	151.4	170.0	-18.6	126.8	120.0	6.8
23.7	20.0	3.7	43.6	40.0	3.6	30.0	20.0	10.0
26.8	10.0	16.8	89.9	90.0	-0.1	46.9	40.0	6.9
25.2	10.0	15.2	89.4	130.0	-40.6	138.1	150.0	-11.9
61.2	55.0	6.2	263.0	260.0	3.0	155.4	150.0	5.4
337.1	330.0	7.1	386.1	380.0	6.1	109.8	90.0	19.8
192.1	185.0	7.1	538.6	520.0	18.6	30.3	30.0	0.3
87.8	60.0	27.8	177.1	170.0	7.1	27.8	30.0	-2.2
105.3	90.0	15.3	25.5	10.0	15.5	24.4	10.0	14.4
23.0	10.0	13.0	70.0	40.0	30.0	336.0	330.0	6.0
33.9	10.0	23.9	265.4	210.0	55.4	247.4	230.0	17.4

Unit: meter

The height standard deviation is $SD = \sqrt{\frac{[\Delta\Delta]}{n}}$ =19.2 meters.

The absolute deviation is $AD = \frac{|\Delta|}{n}$ =14.2 meters.

4. Summary

The processing procedure of extracting DEM from SPOT imagery has been described. From the experiment result and the accuracy assessment, we can get a conclusion that we can extract DEM from the SPOT stereo images, and the height accuracy of DEM can be better than 20 meters.