

DTM Generation Using SPOT Digital Data

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Abstract

This paper deals with the development of a procedure to use digital approach to generate DTM from SPOT stereopairs. Two phases are incorporated. In the first phase, bundle adjustment is used to determine the satellite orientation and the ground coordinates for check points. In the second phase, we transform image coordinates from original system to epipolar system according to the orientation parameters as determined. After epipolar resampling, the search for conjugate pixels is made along the same line number. After image coordinates of conjugate points are determined, the ground coordinates can be calculated. DTM can thus be generated by interpolation. Ground check points are used to evaluate the accuracy in both phases. The stereopair used in the study comprises two level 1A panchromatic digital images with about 30° convergent angle and covers about $60\text{km} \times 40\text{km}$ in an area near central Taiwan. The study area for DTM is limited to $3\text{km} \times 3\text{km}$.

1. Introduction

The SPOT/HRV system provides photogrammetrists and cartographers with the first systematic stereo satellite data in digital format. Because the viewing direction of each HRV can be varied through $\pm 27^\circ$ relative to the nadir and to the orbit plane, the base-height ratio could be larger than one. Together with its high spatial resolution, 10m for panchromatic mode, it makes the topographic mapping up to a scale of 1:50,000 possible [6]. Incorporating with SPOT stereopairs and some ground control points in adjustment, the orientation parameters of the sensors at different time will be determined. Further processing the results together with the image data, DTM can be generated. Worldwide research efforts have been concentrated on two different approaches to generate DTM using SPOT data. One of which is to use analytical plotters to process analogue film, for instance, BINGO SPOT-MODULE has been successfully implemented on ZEISS C-100 series [2]. Another approach is to use digital method.

This paper is to establish a scheme to generate DTM digitally. The study is divided into two stages. First, we develop a self-calibrated bundle adjustment program BASICC (Bundle Adjustment for Spot Imagery of CSRSR at Central University) to determine the orientation parameters for sensors. Four methods are used to determine the image coordinates for conjugate points. The second stage is to generate DTM. We transform image coordinates to epipolar system according to the orientation

parameters as determined. After epipolar resampling, the search for conjugate pixels is made along the same line number. Where we use normalized cross correlation in image matching. Once the conjugate image coordinates are determined, incorporating orientation parameters, ground coordinates can be calculated by space intersection. The DTM can thus be generated by interpolation. Grid check points are used to evaluate the accuracy for the DTM.

2. Mathematical Model

The model includes four parts : (1) BASICC, (2) epipolar image transformation, (3) image matching, and (4) DTM computation.

2-1. BASICC

For level 1A panchromatic image, a full scene is composed of 6,000*6,000 pixels. The image coordinates for each point are decided by line/sample number and CCD size. Which is 13 μ m*13 μ m. The sampling interval for two consecutive lines is 0.0015 seconds. The focal length is 1,082mm. For exterior orientation parameters, 6 elements per line, we have 36,000 elements. This large amount of parameters can not be used directly and therefore need to be simplified. Due to stable and fast moving for the satellite, the parameters can be modeled as functions of time. A lot of models have been used [2,5]. After some tests, we select the functions to the second order for orbit parameters and the third order for attitude parameters. Thus, 36,000 elements are reduced to 21. The collinearity equations are then modified as :

$$\begin{aligned} \Delta x_i + x_o &= -f \frac{m_{11t}(X_i - \bar{X}_t) + m_{12t}(Y_i - \bar{Y}_t) + m_{13t}(Z_i - \bar{Z}_t)}{m_{31t}(X_i - \bar{X}_t) + m_{32t}(Y_i - \bar{Y}_t) + m_{33t}(Z_i - \bar{Z}_t)} \\ \Delta y_i + y_i &= -f \frac{m_{21t}(X_i - \bar{X}_t) + m_{22t}(Y_i - \bar{Y}_t) + m_{23t}(Z_i - \bar{Z}_t)}{m_{31t}(X_i - \bar{X}_t) + m_{32t}(Y_i - \bar{Y}_t) + m_{33t}(Z_i - \bar{Z}_t)} \end{aligned} \quad (1)$$

where

f: focal length,

t: the time at sampling relative to a given instant,

$$\bar{X}_t = X_0 + X_1 t + X_2 t^2$$

$$\bar{Y}_t = Y_0 + Y_1 t + Y_2 t^2$$

$$\bar{Z}_t = Z_0 + Z_1 t + Z_2 t^2$$

$$\omega_t = \omega_0 + \omega_1 t + \omega_2 t^2 + \omega_3 t^3$$

$$\phi_t = \phi_0 + \phi_1 t + \phi_2 t^2 + \phi_3 t^3$$

$$K_t = K_0 + K_1 t + K_2 t^2 + K_3 t^3$$

$X_0, Y_0, Z_0, \omega_0, \phi_0, K_0$: orientation parameters at the given instant,

X_i, Y_i, Z_i : ground coordinates for point i,

m_{11t} to m_{13t} : elements of rotation matrix at time t, and

$\Delta x_i, \Delta y_i$: systematic compensations which correct for earth curvature and affinity.

The observation equations for collinearity condition can be obtained by linearizing eq.1. Combining which with pseudo observation equations for ground coordinates and orientation parameters gives a complete mathematical model of the photogrammetric problem, i.e;

$$\begin{bmatrix} V \\ \dot{V} \\ \ddot{V} \end{bmatrix} + \begin{bmatrix} B & \ddot{B} \\ -I & 0 \\ 0 & -I \end{bmatrix} \begin{bmatrix} \dot{\Delta} \\ \ddot{\Delta} \end{bmatrix} = \begin{bmatrix} \varepsilon \\ \dot{C} \\ \ddot{C} \end{bmatrix} \quad (2)$$

$$i, e; \quad \bar{V} + \bar{B}\bar{\Delta} = \bar{C}. \quad (3)$$

Hence, the least squares solution will be

$$\bar{\Delta} = (\bar{B}^T \bar{P} \bar{B})^{-1} \bar{B}^T \bar{P} \bar{C}. \quad (4)$$

2-2. Epipolar Image Transformation

If the original image is used to perform matching, two dimensional search is required. This will not only need too much computation time but also introduce matching ambiguities. In order to alleviate these problems in the process, we transform the image to epipolar system.

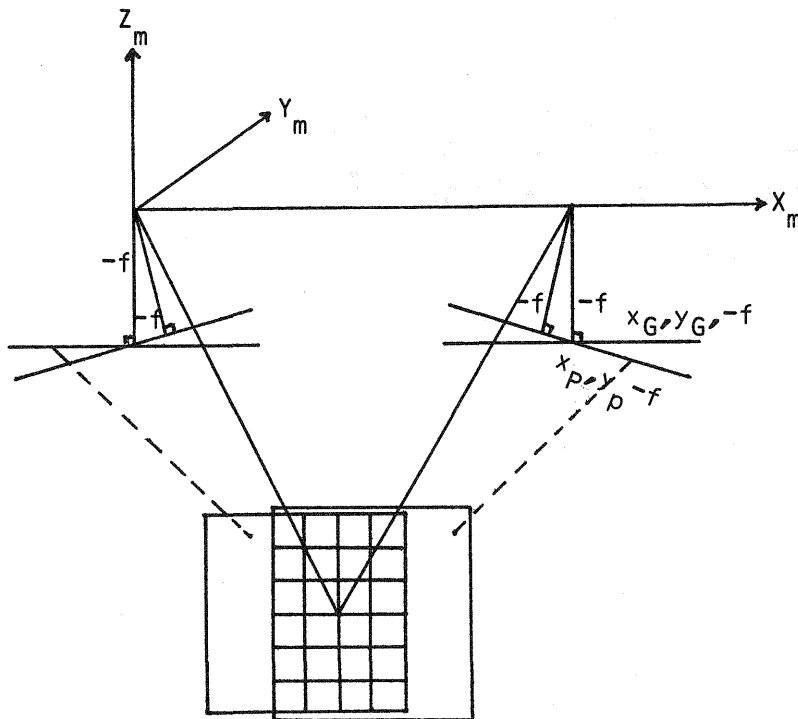


Figure 1. The relationship between image coordinate system and epipolar system

In the transformation, referring to fig.1, using eq.1 and let $\bar{X} = \bar{Y} = \bar{Z} = 0$, and $Z_i = -f$, we have

$$o = -f \frac{m_{11}U + m_{12}V - m_{13}f}{m_{31}U + m_{32}V - m_{33}f} \quad (5)$$

$$y_p = -f \frac{m_{21}U + m_{22}V - m_{23}f}{m_{31}U + m_{32}V - m_{33}f}$$

and

$$U = -f \frac{m_{21}y_p - m_{31}f}{m_{23}y_p - m_{33}f} + \Delta U \quad (6)$$

$$V = -f \frac{m_{22}y_p - m_{32}f}{m_{23}y_p - m_{33}f} + \Delta V$$

where

U, V : coordinates in epipolar system, and
 $\Delta U, \Delta V$: decided by orbital parameters.

Bilinear interpolation is used in image resampling.

2-3. Image Matching

Three image matching methods are studied : (1) normalized cross correlation (NCC), (2) least squares matching without considering geometric distortion (LS-1), and (3) least squares matching considering geometric distortion (LS-2). In bundle adjustment, all of three methods are used. Where 2-D operation is used in NCC. In DTM generation, we use 2-D window to perform 1-D search for epipolar images. For those points failed in matching, parallax are linearly interpolated by the parallax difference associated with the successfully matched neighbors.

2-3-1. NCC

The correlation coefficient is computed as

$$r = \frac{\Sigma \Sigma (T - \bar{T})(S - \bar{S})}{[\Sigma \Sigma (T - \bar{T})^2]^{\frac{1}{2}} \cdot [\Sigma \Sigma (S - \bar{S})^2]^{\frac{1}{2}}} \quad (7)$$

where

r : correlation coefficient,
 T, S : gray values for target window and search window, and
 \bar{T}, \bar{S} : average gray values for target window and search window,
then the sub-pixel interpolation for maximum correlation coefficient is

$$\Delta x = \frac{r(x+1) - r(x-1)}{4r(x) - 2r(x+1) - 2r(x-1)} \quad (8)$$

2-3-2. LS-1

The shifts for the best matching are

$$\Delta x = \frac{\Sigma\Sigma(I'_x \cdot \Delta I) \cdot \Sigma\Sigma(I'_y)^2 - \Sigma\Sigma(I'_y \cdot \Delta I) \cdot \Sigma\Sigma(I'_x \cdot I'_y)}{\Sigma\Sigma(I'_x)^2 \cdot \Sigma\Sigma(I'_y)^2 - (\Sigma\Sigma I'_x \cdot I'_y)^2} \quad (9)$$

$$\Delta y = \frac{\Sigma\Sigma(I'_y \cdot \Delta I) \cdot \Sigma\Sigma(I'_x)^2 - \Sigma\Sigma(I'_x \cdot \Delta I) \cdot \Sigma\Sigma(I'_y \cdot I'_x)}{\Sigma\Sigma(I'_x)^2 \cdot \Sigma\Sigma(I'_y)^2 - (\Sigma\Sigma I'_x \cdot I'_y)^2}$$

where

$I'_x = (S(x+1, y) - S(x-1, y)) / 2$,
 $I'_y = (S(x, y+1) - S(x, y-1)) / 2$, and $\Delta I = S(x, y) - T(x, y)$.
 We use bilinear interpolation in resampling.

2-3-3. LS-2

The condition equation for LS-2 is

$$T(x_i, y_i) = h_1 + h_2 \cdot S(x_i, y_i; A) \quad (10)$$

where

$$A = \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{bmatrix} \quad \text{is affine transformation matrix,}$$

h_1 : gray level shift, and
 h_2 : gray level scale.

2-4. DTM Computation

After the conjugate image points are determined, space intersection is used to calculate the ground coordinates. The DTM is computed by bilinear interpolation.

3. Case Study

The hardware/software facilities that were used in the study consist of a VAX 750 computer, a Deanza IP8400 image processor, an IDIMS image processing system, a CALCOMP 6000 digitizer, and another VAX 8650 computer. The stereopair covers Miao-Li area where is near central Taiwan. The convergent angle is 30.1° , and the base-height ratio equals to 0.57. The sampling dates are January 15 and 16 in 1987. Ground coordinates for control and check points were digitized from 1/5,000 scale photo base map. For BASICC, we compared the performance for four ways of image coordinate measurements: (1) reading the line/pixel number on IP8400 manually, and using (2)NCC, (3)LS-1, (4)LS-2. In DTM generation, we selected an area of 3km*3km with elevation ranging from 4m to 175m. The pair of epipolar image are shown in fig.2. We used 7*15 target window to do NCC along the epipolar line. We digitized the contour lines on a sheet of base map which was covered by the stereomodel and constructed a DTM as grid check points. The area was 2.5km*2.5km, with 50m spacing, so we have 2,500 check points.

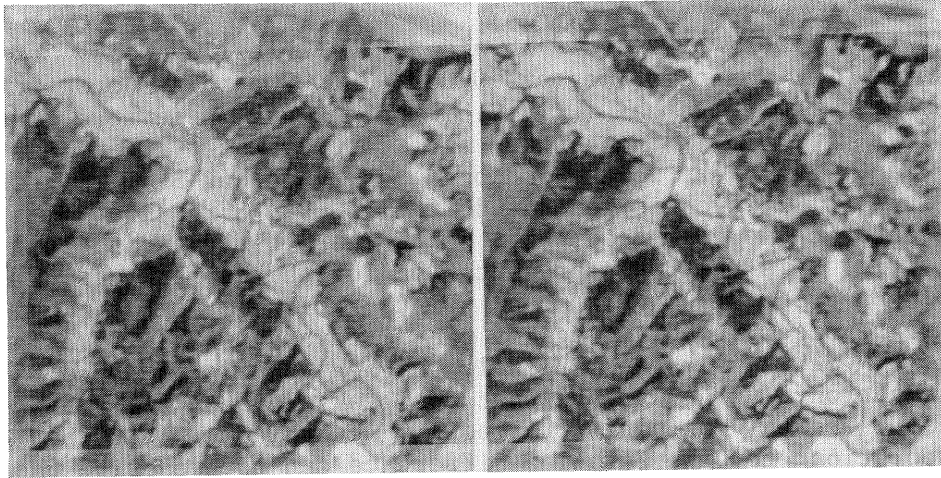


Figure 2. SPOT Stereopair

3-1. Results of BASICC

Detail analysis of these results is the subject of a separate paper in this issue, where [3] presents a more complete discussion of the numerical results and an analysis of its accuracy. We selected uniformly distributed 28 control points and 22 check points. Window size was 19*19. In NCC, if $r \geq 0.8$ we considered that the matching is successful. In LS-1 and LS-2, the results of NCC were used as initial values. The iteration was limited to 30. The CPU time for image matching and BASICC on a VAX 8650 is shown in table 1. The RMS for check points is shown in table 2.

NCC	LS-1	LS-2	BASICC
12	3.6	70	10

Table 1. CPU time (in second)

	IP8400	NCC	LS-1	LS-2
X	7.5	7.8	7.7	7.4
Y	4.0	4.6	4.6	3.9
Z	8.9	8.1	7.6	7.7

Table 2. RMS for check points (in meter)

3-2. Results for DTM generation

The target window size was 7*15 and the matching is an 1-D operation. Generated DTM comprises of 90,000 (300*300) points and each point represents 10m*10m area. Only 2,500 points were used to evaluate the accuracy. Fig. 3a is the contour map, Contour-Base, digitized from the base map. Fig. 3b is the contour map, Contour-SPOT, interpolated from the DTM which is generated from SPOT. Fig. 4a is the 3-D representation for DTM-Base. Fig. 4b is the 3-D representation for DTM-SPOT. Fig. 5 is the 3-D representation for the differences of DTM-SPOT and DTM-Base for 2,500 grid check points. Fig. 6 is the histogram of the differences. The average of the differences is +7.3m. This shows that DTM-SPOT is systematically higher than DTM-Base. Through investigation, we found out that the peak areas in fig. 5 were the places where matching failed. Accordingly, using linear interpolation for the parallax difference can not describe the terrain properly. The RMS for the differences was 13m.

The CPU time on a VAX 8650 computer for image transformation was 3.5 minutes, for NCC 1-D searching was 35 minutes, and 4.5 minutes for ground coordinate computation and DTM interpolation. Hence the whole process needed 43 minutes CPU time. That means it can perform about 2,100 points per minute (we have 90,000 points in total)

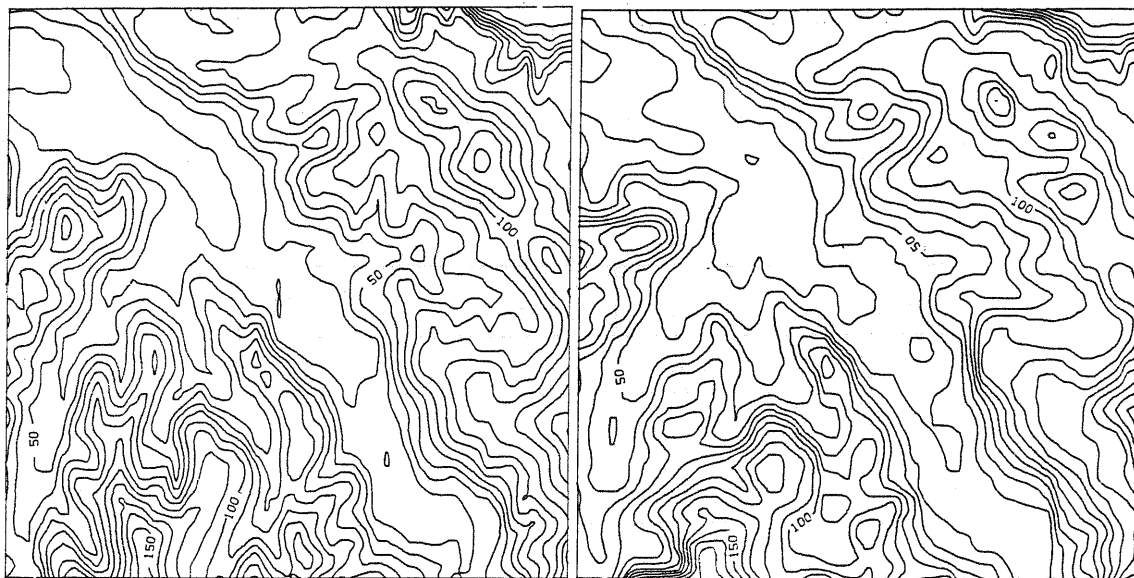


Figure 3a. Contour-Base

Figure 3b. Contour-SPOT

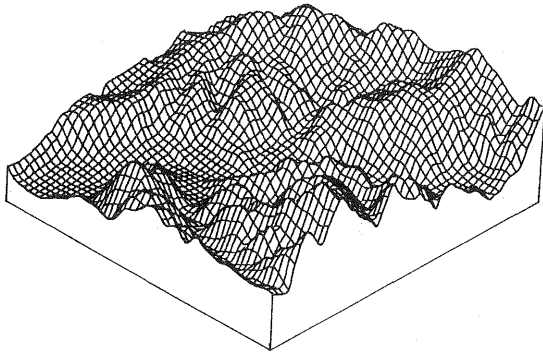


Figure 4a. 3-D representation
for DTM-Base

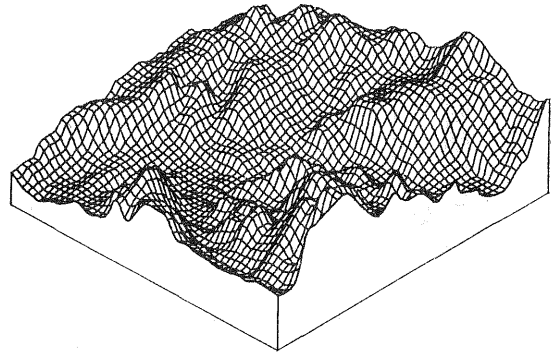


Figure 4b. 3-D representation
for DTM-SPOT

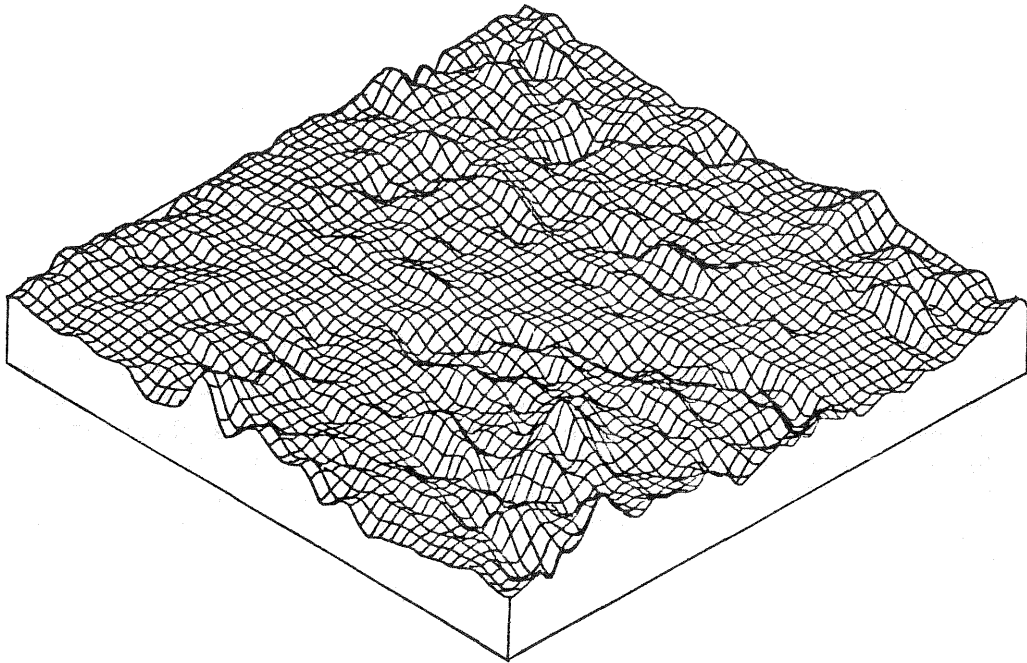


Figure 5. 3-D representation for the differences between
DTM-SPOT and DTM-Base

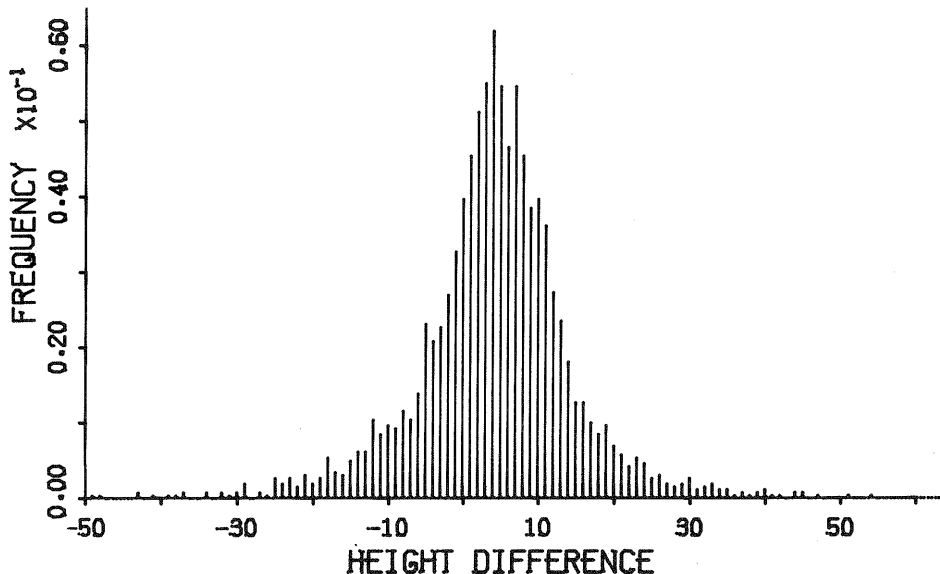


Figure 6. Histogram of the differences between DTM-SPOT and DTM-Base

3-3. Discussion

There are several reasons that make BASICC more accurate than DTM-SPOT, (7.7m vs. 13m in elevation).

- (1) The check points used in BASICC were well defined and can be easily recognized but grid check points were not, therefore incorrect matching introduces blunders in DTM generation.
- (2) In DTM generation, information loss was incorporated in the resampling.
- (3) DTM-Base delineates the true ground surface, but DTM-SPOT is a presentation of "visual surface". The differences between these two surfaces are much caused by the height of trees. The +7.3m systematic difference mentioned in 3-2. shows this phenomenon.
- (4) The error expression in BASICC is independent in three directions, while in DTM it is a combined presentation. That means in mountainous area, the planimetric error will influence elevation very much.
- (5) The DTM-Base is subjected to some errors in interpolation.

4. Conclusion

This study has established a scheme to use digital approach to generate DTM using SPOT data. Although the system has not yet been optimized, it has demonstrated that the accuracy level for BASICC can reach 7.4m, 3.9m, and 7.7m ($B/H=0.57$), and for DTM it can reach 13m. Although the study only refers to a small testing area, the results allow general conclusions as to the high potential of utilizing SPOT digital data to generate DTM.

Using different image processing techniques to improve matching quality, and to increase matching efficiency are still in progress.

Another ongoing project is to find a better way to interpolate the parallax difference properly and to evaluate DTM accuracy more reasonably. One thing needed to mention is that the sampling dates for the stereopair are in two consecutive days, hence the sun angle did not change much. Further research is required for the case when two images have large difference in radiometry due to different sun angles.

5. References

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