DIGITAL MATCHING OF SPOT STEREO IMAGES BY FINITE ELEMENTS LEAST SQUARE TECHNIQUES

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[ABSTRACT] There ere no epipolar lines exist in SPOT stereo images and one-dimensional matching is unfeasible. An improved multipoint matching method is proposed, which does not require preliminary resampling along epipolar lines. The x and y parallaxes of grid points connected by bilinear elements are computed simultaneously from image data using the least square techniques. Constraints, such as continuity of the first derivatives of x and y parallaxes, are produced as fictitious observations. Based on the new method, a scheme of generating parallax grid is presented. Some preprocessing measures are also discussed. An experiment is conducted using a SPOT stereo pair of some place of china. Based on the analysis of experiment results the conclusions are also given.

1. INTRODUCTION

SPOT has been successfully launched in February 1986 and since that time stereo pairs are available on request. This presents a challenge to photogrammetrist: how to best utilize the data for map compilation in a rapid and efficient manner. There are two possible approaches: the first is to use the SPOT images in an analytical instruments with modified software to produce digital elevation models, orthophotos or line maps ([1],[2]). The second is to develop a new system which will handle the digital data directly([4]). Due to the data nature the digital image processing techniques seems to be most adequate for most users. And further more, the digital data have several important additional advantages : images can be enhanced,map compilation can take place from classified images, automated matching and feature extraction can take place, and very fast speed can be obtained([4]).
However, SPOT images are different from aerial photographs in many ways. SPOT images ae acquired using a linear CCD array in a pushbroom mode and it's stereo images are taken by sidelookings. Thus a pair of SPOT images does not have corresponding epipolar lines. The concept of epipolar lines are difficult to apply to SPOT images, as there is no single base line arround which to rotate an epipolar plane. In fact, there exist no straight epipolar lines and one dimensional matching is unfeasible if the digital elevation model doesn't exist prior to the processing.
In this paper an improved multipoint matching, namely "Finite Elements Matching by Least Square techniques (FEMALS)" , is presented. the method does not require preliminary resampling along epipolar lines. The x and y parallaxes of grid points

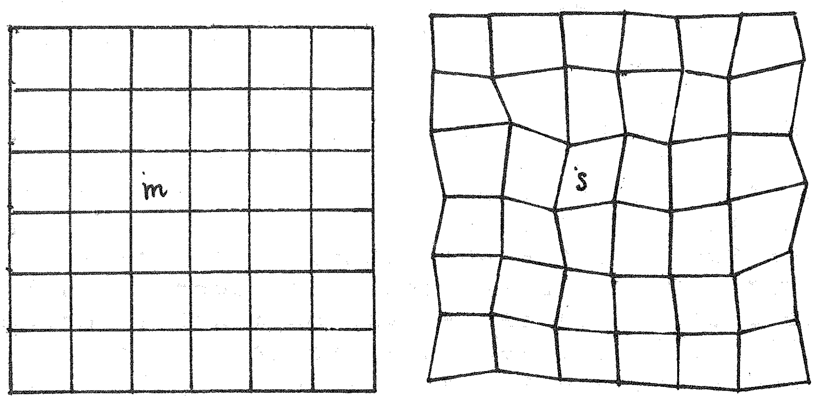
connected by bilinear elements are computed simultaneously from image data using the least square techniques.

2. PRIVIOUS WORK

In 1982, Forstner presented a paper called " On the Geometric Precision of Digital Correlation" [3] , in which a method for gray level matching of images based on the least square method was introduced. From then on this method is investigated and developed in many countries in the world , and very high accuracy is obtained. But in the areas of bad image texture or large radiometric diferences between the images, it is often impossible to obtain any result by use of least square matching A multipoint matching method was developed by Rosenholm [6] . Using this method, it is possible to bridge areas with low signal content, and to compute the x parallaxes of the grid point connected by bilinear finite elements[6].
Rosenholm has reported his experiment results, the accuracy of x parallax calculated with his method was higher than 11μm of root mean square deviation between manual measurements of check point and matchings([8]).

3. ALGORITHM FOR FINITE ELEMENTS MATCHING BY LEAST SQUARE TECHNIQUES

Due to the fact that there are no epipolar lines exist in SPOT stereo images, one-dimensional mamatching methods are discarded. Based on the multipoint matching method[6], an improved method, namely the "Finite Elements Matching by Least Square Techniques(FEMALS)" , is presented. The main idea of the FEMALS is similar to the multipoint matching method except that both x and y parallaxes of grid point are used as unknowns Without resampling along epipolar lines the improved method can compute x and y parallaxes of grid point simultaneously, which are connected with bilinear finite elements(figure 1).



(1)Left grid points (2)Right grid points

Figure 1

The radiometric transformation is formulated by

$$g_m(x_m, y_m) - n_m(x_m, y_m) = r_1 \cdot [g_s(x_s, y_s) - n_s(x_s, y_s)] + r_2 \qquad \text{-------} (1)$$

where m stands for mask, s stands for search, (x_m, y_m) and (x_s, y_s) are coordinates of arbitrary corresponding point m and s respectively, n stands for noise. g stands for gray level. If $p_x(i,j)$ and $p_y(i,j)$ represent the unknown x and y parallax of a grid point (i, j) respectively. As it is assumed that the parallaxes of grid points are connected with bilinear finite elements, the coordinates of the corresponding point of arbitrary non-grid image point (x_m, y_m) can be formulated by following expressions:

$$\begin{cases} x_s = x_m + \{p_x(i,j)\cdot(x_{i+1}-x_m)(y_{j+1}-y_m) + p_x(i+1,j)\cdot(x_m-x_i)(y_{j+1}-y_m) + \\ \quad + p_x(i+1,j+1)\cdot(x_m-x_i)\cdot(y_m-y_j) + p_x(i,j+1)\cdot(x_{i+1}-x_m)\cdot(y_m-y_j)\} \\ \quad /[(x_{i+1}-x_i)(y_{j+1}-y_j)] \\ y_s = y_m + \{p_y(i,j)\cdot(x_{i+1}-x_m)\cdot(y_{j+1}-y_m) + p_y(i+1,j)\cdot(x_m-x_i)\cdot(y_{j+1}-y_m) + \\ \quad + p_y(i+1,j+1)\cdot(x_m-x_i)\cdot(y_m-y_j) + p_y(i,j+1)\cdot(x_{i+1}-x_m)\cdot(y_m-y_j)\} \\ \quad /[(x_{i+1}-x_i)\cdot(y_{j+1}-y_j)] \end{cases} \quad \text{.........(2)}$$

We can now formulate the observation equation as

$$V(x_m,y_m) = g_s^o(x_s,y_s)\cdot\Delta r_1 + \Delta r_2 + \sum_{k=1}^{4}(r_1^o\cdot g_x\cdot c_k\cdot\Delta p_{xk} + r_1^o\cdot g_y\cdot c_k\cdot\Delta p_{yk}) - g_m(x_m,y_m) + r_1^o\cdot g_s^o(x_s,y_s) + r_2^o \quad \text{.............(3)}$$

Where

$$\begin{cases} c_1 = (x_{i+1}-x_m)\cdot(y_{j+1}-y_m)/[(x_{i+1}-x_i)\cdot(y_{j+1}-y_j)] \\ c_2 = (x_m-x_i)\cdot(y_{j+1}-y_m)/[(x_{i+1}-x_i)\cdot(y_{j+1}-y_j)] \\ c_3 = (x_m-x_i)\cdot(y_m-y_j)/[(x_{i+1}-x_i)(y_{j+1}-y_j)] \\ c_4 = (x_{i+1}-x_m)\cdot(y_m-y_j)/[(x_{i+1}-x_i)(y_{j+1}-y_j)] \end{cases} \quad \text{..........(4)}$$

Δr_1, Δr_2 and Δp_{xk}, Δp_{yk}, k=1,2,3,4 are the corrections to the unknown radiometric parameters and parallaxes. $g_s(x_s,y_s)$ is computed by bilinear interpolation.

and

$$\begin{cases} g_x = \partial g_s^o(x_s,y_s)/\partial x_s \\ g_y = \partial g_s^o(x_s,y_s)/\partial y_s \end{cases} \quad \text{..................(5)}$$

these are approximated with:

$$\begin{cases} r_1^o\cdot g_x \doteq [g_m(x_m+1,y_m) - g_m(x_m-1,y_m)]/2 \\ r_1^o\cdot g_y \doteq [g_m(x_m,y_m+1) - g_m(x_m,y_m-1)]/2 \end{cases} \quad \text{..........(6)}$$

Considering the continuity of the terrian, the continuity of first derivative of parallaxes is used as additional constraints.As a consequence,the connections between the points will be strengthened, especially when the areas of low signal content have to be stabilized. The corresponding observation equations for grid point (i,j) are expressed as:

$$\begin{cases} V_x(i,j) = 2\cdot\Delta p_x(i,j) - \Delta p_x(i-1,j) - \Delta p_x(i+1,j) - (p_x^o(i-1,j) + p_x^o(i+1,j) - 2\cdot p_x^o(i,j)) \\ V_y(i,j) = 2\cdot\Delta p_y(i,j) - \Delta p_y(i-1,j) - \Delta p_y(i+1,j) - [p_y^o(i-1,j) + p_y^o(i+1,j) - 2p_y^o(i,j)] \end{cases} \quad \text{.......(7)}$$

The equations are analogous in another direction.
For simplicity, all kind of fictitious observations are treated as uncorrelated and equal weigthed, and the weight is represented with WX . Moreover,the two fictitious observations for the two radiometric parameters are also formulated as:

$$\begin{cases} V_{r_1} = \Delta r_1 + r_1^o - 1 \\ V_{r_2} = \Delta r_2 + r_2^o \end{cases} \quad \text{...............(8)}$$

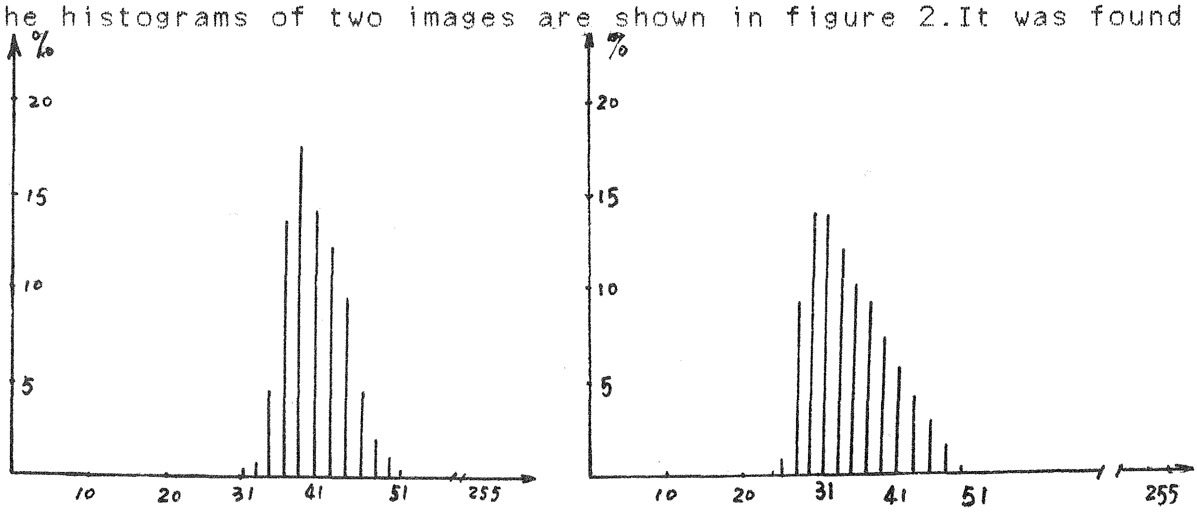
the weights of these two observations are represented as WR1 and WR2.
Solving this system by the least square method , a banded-bordered matrix will be obtained. It should be noticed that the structure of the normal equation system is not affected by the two kinds of additional observations.

4. TEST DESCRIPTION

4.1 Image Data

A pair of SPOT stereo image(PS) covering some place of south China was used for experiment. The left image, a vertical one,

taken at the end of Sept. 1986, the right image, 18°6 inclined, taken at the middle of Dec. 1986. Both image are 1A products
The stereo pair had a rather poor base/height ratio, i.e. 0.38. The histograms of two images are shown in figure 2.It was found



(a)Histogram of left image (b)Histogram of right image

Figure 2

that there are unregular horizontal and vertical noise lines in left image,this coincides with the description in [7].

4.2 Experimental Programs and Some Defaults

A basic experiment program MPLSMG and its modifications were developed and tested in FORTRAN 77 . Several auxiliary programs were also developed.Some characteristics of the programs are:

(1) The resampling of gray values is based on bilinear function.
(2) the convergence criteria are selected as: 0.08 pixels for x and y parallaxes,0.009 for multiplicative parameter and 1.0 for additive parameter of radiometric transformation.
(3) When the maximum number of iterations was reached (usually 20),the iteration procedure stop automatically.

Some Defaults:

If it is not special mentioned, the following methods and parameters are used as defaults.

(1) Two radiometric parameters are used, and the normal matrix is recomputed in each iteration.
(2) The grid space is 6 pixels, and 11*11 grid points are used as a matching block.
(3) The derivatives of gray values are computed from two neigbouring pixels on left image with the exception of the edge rows and columns, where only one neigbouring pixel is used.
(4) the approximate values of grid point parallax are computed by mapping method,which will be explained later.
(5) Right image is rectified to the vertical position by rotating 18°.6 which is read from SPOT CCT tape.

5. EXPERIMENT RESULTS AND DISCUSSIONS

5.1 Some comments on the accuracy and reliability

For estimation of accuracy and reliability of automatic parallax determination by using FEMALS , totally 108 regular grid points(grid space equal to 12 pixels)were manually measured on Planicomp 120.Due to the bad quality of left image,the accuracy

of parallax measured is not high, the defference of two
measurements of the same po difers among 0.1 to 2.0 pixels.

5.2 Weight Determination for Fictitious Observations

Weight of continuity constraints are crucial for the FEMALS. If it is too small the matching will not convergent and the results are totally wrong. If it is too big the accuracy and reliability will be affected. The weights 100,250 and 400 were tested. The results were tested. The results are shown in table 1. It can be observed that: With weight becaming larger, (1) the number of iterations and RMS of y parallax decrease slightly. (2) RMS and reliability of x parallax increase slightly. (3) rate of correlation coefficient which lower than two thresholds increase slightly.

Weight		W_x=100, WR1=0, WR2=130	W_x=250, WR1=0, WR2=130	W_x=400, WR1=0, WR2=130
Number of iteration per block		11.8	10.0	9.0
σ_0 (gray level)		2.2	2.3	2.4
rate of $\rho < 0.50$		20.0%	20.0%	23.1%
rate of $\rho < 0.60$		40.5%	42.4%	45.9%
RMS of P_x (μm)		14.5	14.9	15.4
RMS of P_y (μm)		7.0	6.3	6.1
reliability	rly x	80.6%	81.2%	79.0%
	rly y	85.2%	88.0%	88.6%
	rly xy	76.9%	77.5%	76.9%

Table 1

The weight for fictitious observations of two radiometric parameters were also tested, the results are shown in table 2. From table 2: (1) Comparing the first colunm with third one and second with fourth where WR2 is the same, WR1 seems have no effect on the matching and WR2 Influences the results considering the accuracy and reliability. (1) Comparing these two groups the case of WR2 equaling 130 is better than the other one.

Weight		W_x=250, WR1=0, WR2=130	W_x=250, WR1=0, WR2=0	W_x=250, WR1=130, WR2=130	W_x=250, WR1=130, WR2=0
Number of iteration per block		10.0	11.0	10.0	11.0
σ_0 (gray level)		2.3	2.0	2.3	2.0
Rate of $\rho < 0.50$		20.0%	23.8%	20.0%	23.8%
Rate of $\rho < 0.60$		42.4%	46.9%	42.4%	46.9%
RMS of P_x (μm)		14.9	15.1	14.9	15.1
RMS of P_y (μm)		6.3	7.3	6.3	7.3
Reliability	rly x	81.2%	79.6%	81.2%	79.6%
	rly y	88.0%	83.3%	88.0%	83.0%
	rly xy	77.5%	75.3%	77.5%	75.6%

Table 2

5.3 Selection of Radiometric Parameter

From equation (3) it can be observed that: all the corrections of coefficients except $\Delta r1$ do not change between the iterations. And if the multiplicative parameter is not considered in the FEMALS, all elements of design matrix will not change between iterations. This means that the matching can be speeded up many times. But what about the accuracy and reliability of the two alternatives? Table 3 gives the comparative results with linear and additive radiometric parameters.

It is obvious that use of additive parameter has almost the same accuracy and reliability as linear parameters, but the CPU time can be saved dramastically.

Weight		Wx=250, WR1=0, WR2=130	
Grid Space		GS=6	GS=3
Number of iteration per block		10.0	11.1
σ_0 (gray Level)		2.3	2.3
Rate of $\rho<0.50$		20.0%	22.6%
Rate of $\rho<0.60$		29.5%	30.8%
RMS of P_x (μm)		14.9	30.8
RMS of P_y (μm)		6.3	6.0
Reliability	rly x	81.2%	29.7%
	rly y	88.0%	78.1%
	rly xy	77.9%	25.8%

Table 4

Weight		Wx=250 WR1=0 WR2=130	
		Radiometric Parameters	
		a-Linear	Additive
Number of iteration per block		10.0	10.3
σ_0 (gray level)		2.3	2.6
Rate of $\rho<0.50$		20.0%	20.6%
Rate of $\rho<0.60$		42.5%	43.4%
RMS of P_x (μm)		14.9	15.1
RMS of P_y (μm)		6.3	6.2
Reliability	rly x	81.2%	79.6%
	rly y	88.0%	90.1%
	rly xy	77.5%	76.2%
CPU time per point (Second)		6.9	0.88

table 3

5.4 The Effects of Diferent Grid Spaces

In FEMALS each grid except the border ones uses the information provided by it surrounding $(GS-1)^2$ pixels (GS is the number of pixels between two grid points). So it seems that large GS will benefit the matching, but on the other hand because the grid points are connected with bilinear finite elements, the less GS will benefit the interpolation(in return that also benefits the matching). These two aspects are conflicting. Therefore it is necessary to test the effects of grid space on the matching.

Table 4 gives the test results, it is fairly clear that the results of GS equaling 3 pixels decreases greatly the accuracy and reliability. This is due to the fact that the information provided to each grid point with GS=3 pixels is too little to match. When using GS=9 pixels as grid space, the matching system cann't convergent at all, and the results are unacceptable. From table 5, GS=6 pixels seems to be suitable selection.

5.5 The Effects of Data Snooping

In FEMALS there great number of redundancy, this provides a possibility of using Data Snooping to exclude pixels with big gray level differnce[6].

Experiments show that with 3.0 and 4.0 as criterion respectively, Data Snooping benefits the y parallaxes slightly but has a contrary effects on the x parallax and parallax in radial direction.

5.6 The Effects of Image Preprocessing

5.6.1 The Effects on Rectification

Most SPOT stereo images are obtained by sidelookings. For the similarity, the inclined image has to be rectified. In this experiment we just rectified the image by rotating the image to the horizontal position, the rotating angle is read from SPOT CCT tape. The mathematic model used is(figure 3)

$$x' = f \cdot tg[w + tg^{-1}(\frac{x}{f})] \qquad \text{------------(9)}$$

where w is the sidelooking angle, f is the focal distance, x and x' is the coordinate of inclined and horizontal images respectively. The indirect method was adopted, gray level resampling is realized by linear interpolation.

Weight	Wx=250. WR1=0 WR=130	
Rectification	Yes	NO
Number of iteration per block	10.0	9.3
σ_0 (gray level)	2.3	3.0
Rate of $\rho<0.50$	20.0%	27.3%
Rate of $\rho<0.60$	42.4%	54.3%

Table 5

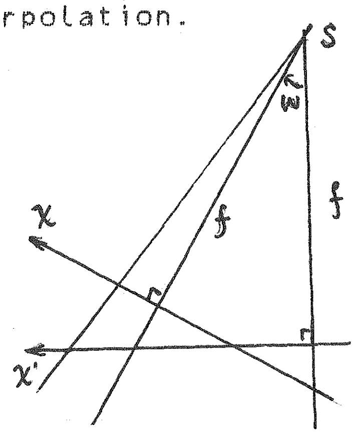


Figure 3

The results of test are shown in table 5 . It is clear from the table that the results of rectified image are much better than inclined one.

5.6.2 The Effects of Gray Level Preprocessing

Weight		Wx=250 WR1=0 WR2=130				
		Preprocessing Method				
		Original	Median	Average	Nor.-Median	Nor.-Average
Number of iteration per block		10.0	8.3	7.8	16.0	12.5
σ_0 (gray level)		2.3	1.95	1.91	17.2	9.37
Rate of $\rho<0.50$		20.0%	21.3%	21.3%	26.4%	25.6%
Rate of $\rho<0.60$		42.4%	43.4%	43.8%	44.8%	44.0%
RMS of P_x (μm)		14.9	15.5	15.4	17.3	16.8
RMS of P_y (μm)		6.3	7.2	7.0	12.5	11.3
Reliability	rly x	81.2%	78.1%	79.3%	76.2%	77.2%
	rly y	88.0%	83.3%	84.6%	69.4%	73.8%
	rly xy	77.5%	74.4%	74.7%	66.7%	69.8%

Table 6

The following prerocessings are investigated:

(1)Filtering the original images with 3*3 moving median filter

(2)Filter the original images by moving average filtering with a plate

1/10	1/10	1/10
1/10	2/10	1/10
1/10	1/10	1/10

(3) First enhanced the original images by histogram normalization(mean gray level equals to 110,standard error equals to 35) and then filter the enhanced images by method(1)

(4) Ehance the original images by the method as described in method(3),and then filter the enhanced images by method(2)

The results of the four experiments are showm in table 6. It is observed that:

(1) Median filtering and moving average filtering can speed up convergence,but decreace the precision and reliability slightly. This is due to the fact that original images have very narrow gray level extent, and mainly condenced in the field of low frequency.

(2) Although vidio effect can be greatly improved by histogram normalization, but the later two method have only negative effects on the matching. This is due the fact that image enhancements enlarge the noise in some extent.

6. SCHEME FOR AUTOMATIC GENERATING PARALLAX GRID AND FIRST RESULTS

6.1 Scheme for Automatic Generating Parallax Grid

One of the most important applications of matching is automatic generation of DEM. Based on the FEMALS, a scheme for generating parallax grid is proposed.

As shown in figure ,the parallaxes of grid points in a large area are automatic measureed by the FEMALS one block after another, and each matching block has two line or colums overlap with privious blocks.

Similar to Least Square Matching Method, The FEMALS also needs accurate approximate values, so prediction of approximate values is important for this scheme. The following two ways of prediction are adopted:

(1) Simple Extrapolation Pridiction

When the first block is matched, the approximate parallaxes of grid points were given by the parallaxes of a distinctive point that were given by manually method. Usually this distinctive point is the center point in this block. Then , moving this matching block with a overlap of 2 lines or 2 colunms, from left to right and from uper to down, and at the same time maitaining the continuity with privious matched grid points. When the number of iterations exceded the pre-given threshold, the iteration is forced stopped and matching of next block is started.

(2) Mapping Method

Another alternative is mapping method. First step, sveral distinctive point pairs were selected on the display unit manually, then using correlation mathod these pairs were computed with subpixel accuracy. Second step, using the following mapping functions to register two local images:

$$\begin{cases} x_R = a_0 + a_1 x_L + a_2 y_L + a_3 x_L^2 + a_4 x_L y_L + a_5 y_L^2 + a_6 x_L^3 + a_7 x_L^2 y_L + a_8 y_L^2 \cdot x_L + a_9 y_L^3 \\ y_R = b_0 + b_1 x_L + b_2 y_L + b_3 x_L^2 + b_4 x_L y_L + b_5 y_L^2 \end{cases} \quad (10)$$

In this experiment 15 point pairs were used to solve the coefficients of mapping function. Third step: Using mapping function,the parallaxes of grid points can be computed with the accuracy of 2 pixels,then matching the stereo pair with the way as first method except the computation of approximate parallaxes.

The results of experimets are shown in table 7. It can be seen that:with mapping method the average number of iterations obviously smaller than that of simple extra-polation pri-diction. In the respect of accuracy and reliability results of mapping method are fairly beter than another one. In practical applications,we can use auto-matic method to locate original corresponding point pairs for purpose of the realization of fully automatic measurement of parallaxes.Two ways of automatic method of locating corresponding point pairs are possible: one is the methods used in automatic registeration of remote sensed images[9];the other is recently developed namely "Feature based Corresponding Algorithm for Image Matching"[10].

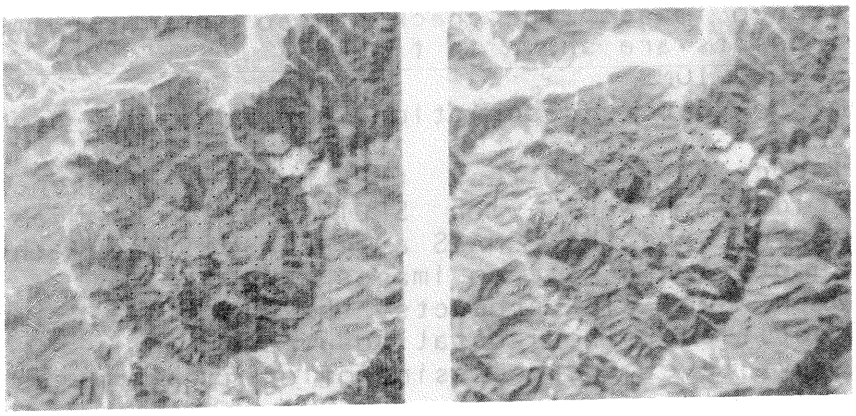


Figure 4 SPOT stereo pair

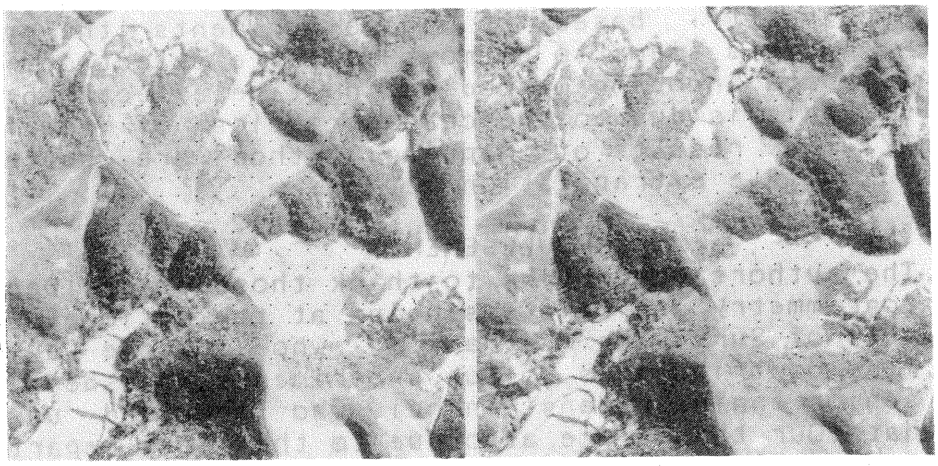


Figure 5 air photo stereo pair

The mapping method is also tested with aerial stereo images and

Weight		$W_x=250$ $W_{R1}=0$ $W_{R2}=130$	
Method		Mapping	prédiction
Number of iteration per block		10.0	15.3
σ_0 (gray level)		2.3	2.3
Rate of $\rho<0.50$		20.0%	23.6%
Rate of $\rho<0.60$		42.4%	44.4%
RMS of P_x (μm)		14.9	16.3
RMS of P_y (μm)		6.3	6.5
Reliability	rly x	81.2%	77.5%
	rly y	88.0%	87.0%
	rly xy	77.9%	73.8%

Table 7

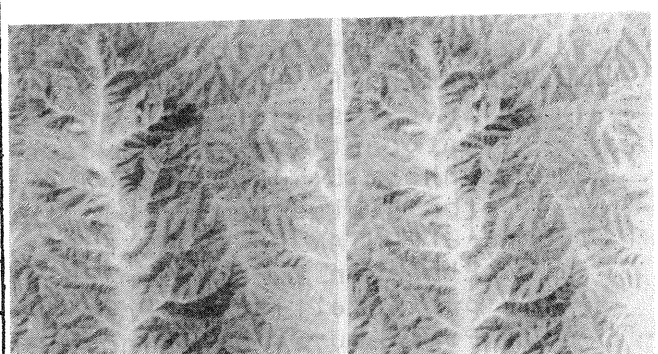


Figure 6 TM stereo images

TM stereo images. The check stereo images with corresponding grid points are shown in figure 4 . 5 . 6.

7. CONCLUSIONS

From the above description, the following conclusions may be drawed.

(1)The results show that the method of generating parallax grid by FEMALS with SPOT stereo imamges is feasible and correct.And the FEMALS also can be used with other kind of remote sening stereo images such as TM.

(2)With SPOT 1A products the inclined image should be rectified to horizontal position.

(3)Gray level preprocessing of original images do not improve the matching results.

(4)Considering the speed and accuracy, the additive radiometric parameter should be used instead of two-parameter.

(5) The diferent selection of grid space influence the FEMALS greatly, based on the experiments the grid space of 6 pixels seems to be most suitable selection.

(6) Data Snooping method has negtive effects on the the results. this is due to the charactristics of low frequent of SPOT.

(7) The results of mapping method are better than tha of simple extrapolation method.

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