On the generation of parallax grid by using off-line digital correlation

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Abstract

This paper presents some experiments on digital correlation which have been performed on a digital image processing device SCANDIG 3, FILMWRITE 2 with a control computerNOVA 3. In order to increase the reliability and accuracy of digital correlation, some strategies were adopted. At first the pixels of the pair of photographs were rearranged according to their respective epipolar lines, thus following a pair of so-called epipolar line images. Digital correlation was carried out with two-dimensional window on these epipolar line images. The correlation criterrion was based upon the computed correlation coefficient and multi-level correlation method was adopted. Two kinds of programs have been developed for detecting the blunders which are caused by low contrast imagry or other remaining gross errors in the results of correlation.

Two test areas of different terrain types have been selected for the experiment. These results are demonstrated on the epipolar line images superimposed with parallax profile lines resulting from the correlation. The correlation accuracy of parallax grids has been found to be 25 μm for montainous area and 40 μm for moderate undulation area by the measurments of more than 1000 points for each area.

1. Introduction

As a part of a research work in photogrammetric automation several experiments in off-line digital correlation have been performed. The equipment used was mainly SCANDIG 3 - a drum image digitizer. FILM-write 2 - a digital image output device and their control computer - NOVA 3. The two stereo pairs of photos used in these experiments are shown in table 1.

Table 1

stereo pair	I	II
camera	RC-8	RC-10
focal length	114.2 mm	152.0 mm
scale	1:16000	1:10400
type of terrain	mountain area	moderate undulation area

The main procedures are the following:

1) Digitization of Imagery: Two stereo pairs of aerial photographs are digitized on SCANDIG with a scanning interveral of 50 μm. The digitized data amounts to 21.2 Mbytes for each photo in frame size of 23 cm x 23 cm and is stored on magnetic tapes.

2) Interier orientation of the digitized imagery is carried out by determining six parameters of an offine transformation between the photo coordinate system (x, y) and the scanning coordinate system (I, J):

$$x = m_0 + m_1 I + m_2 J$$
$$y = n_0 + n_1 I + n_2 J$$

3) Resampling of the digitized imagery along epipolar lines is based

on the elements of interier orientation (six parameters) and of the relative orientation, the later being taken from the results of an aerial trangulation. The method of resampling used in this experiment is characterized by rearranging the pixels along epipolar lines directly on the digitized imagery (fig. 1 a) to form a so-called epipolar line image (fig. 1 b). With the suggested method only two instead of the usually four needed pixeles are involved for resampling each pixel.

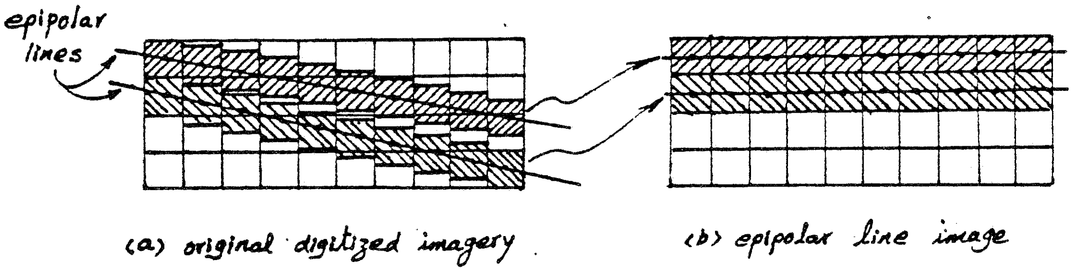

Fig. 1

Resampling of the digitized imagery

4) Digital correlation along the epipolar lines is a main step in our automatic mapping system for determining a series of parallaxes of conjugate points to form a ragular parallax grid on the left photograph. The spacing of the parallax grid is equal to 0.4 mm both in the x and in the y direction.

5) It has been shown that the detection of gross errors from correlation results is of vital importance for improving the quality of correlation and measures have been taken to remedy it.

In the following sections of this paper, only digital correlation, dedection of gross errers as well as their related problems will be discussed.

2. Analysis of Digital Correlation

In this section some aspects of digital correlation related with the size of the window area (on the left photograph) and of searching area (on the right photograph) on the results of digital correlation will be analyzed. It is a basis for rational design of a digital image correlation system.

2.1 The Influence of the Size of the Window Area and of the Searching Area on the Results of Digital Correlation

As the left and right photos are taken from the different stations, the two gray-value sequences are not identical for radiometric and for geometrical deformations. The most significant effects on digital correlation are caused by the different camera orientation and the terrain relief. The commonly applied approachs to reduce these influences to an acceptable level are based on an iteration procedure, i.e. at first, digital correlation is carried out without any transformation of the imagery and then subsequent transformation parameters are calculated from the first (or any preceding) approximate results of correlation. The success of iteration, however, depends to a large extent on the approximations used for geometric transformation. Here in this experiment emphasis has been laid on the analysis of the relationship between the window size and the accuracy and reliablity of the correlation results and reasonable strategies in correlation have been adopted for reducing the influence of terrain slope.

According to the theory of signal detection we know that correlation is equivalent to a matching filter which is used to detet a previously given "useful signal" (signal $x_1(t)$) from the input signal (signal $x_2(t)$) based on the criterion of the maximum signal-noise ratio and to indicate the posistion at which the "useful signal" appears. Therefore the highest peak of the correlation function always tends to coincide with the component of "useful signal" having the highest power in the searching area.

Suppose, for simplicity, only two rectangular gray value distributions exist in the corresponding epipolar lines as shown in fig. 2 (a), (b). The width of square waves is equal to T, but the signal power at point b is stronger than that at point a, i.e. the signal amplitude B is higher than A (B > A). Due to terrain slope there exists a differential parallax $\Delta p = a_1 b_1 - a_2 b_2 = t_1 - t_2$. Under these circumstances, different correlation results will be obtained depending upon different sizes of the target window and the searching area.

(1) If the predicted position of correlation has been achieved accurately, smaller target window ($x_1(t)$: $|t| < t_1$) and searching area ($x_2(t)$: $|t| < t_2$) can be adopted. In this case the cross-correlation of the signals $x_1(t)$ and $x_2(t)$ is equivalent to a auto-correlation function. It is a triangular wave with amplitude A^2T and width $\pm T$ (fig. 2 (c)). The peak value of correlation function is located at $\tau = 0$ and therefore correct position of the conjugate point is found.

(2) In the case of either poor prediction or even without prediction, the searching area of signal $x_2(t)$ should be enlarged say $-(t_2+t_1) < t < t_2+t_1$ and the size of target window remains to be unchanged $(x_1(t) : |t| < t_1)$. In this case the correponding cross - correlation function R(τ) consists of two triangular waves (fig. 2 (d)) with different peak values respectively A^2T and ABT. The highest peak appears at $\tau = t_2$ which leads to a wrong conclusion. It means that the right image point b_2 has been matched uncorrectly as the conjugate point of a_1 , resulting in a blunder in the digital correlation.

(3) The situation is same as in case 2 except that the target window is also enlarged $(x_1(t) : |t| > t_1)$. Thus multiple (four)

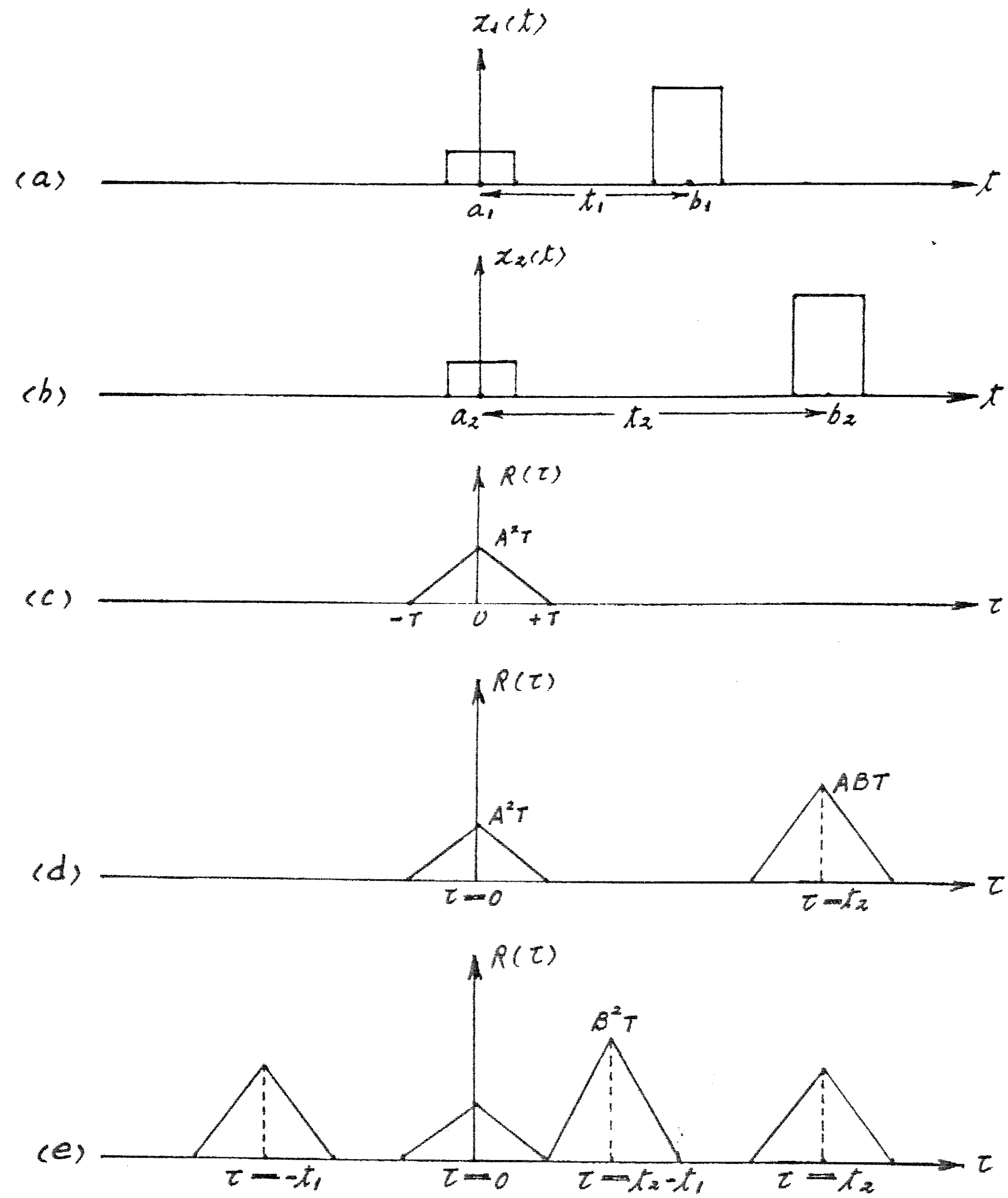

Fig. 2

peaks appear in the correlation function at $\tau = 0$, $\tau=-t_1$, $\tau=+t_2$ and $\tau=t_2-t_1$ with the highest peak at $\tau=t_2-t_1$. It means that the conjugate point b_2 of point b_1 has been found instead of the conjugate point a_2 of the central point a_1 in the target window.

Fig. 3 shows the interseced model points A_1, A_2 and A_3 respectively in accordance with those different correlation results.

Both points A_2 and A_3 are wrong. The former one is a blunder which makes point a_1 matching with point b_2 and the later one is an error caused by the large target window size, the maximum value of this kind of error dp max being related to the size of the target window length Δx and terrain slope θ_x :

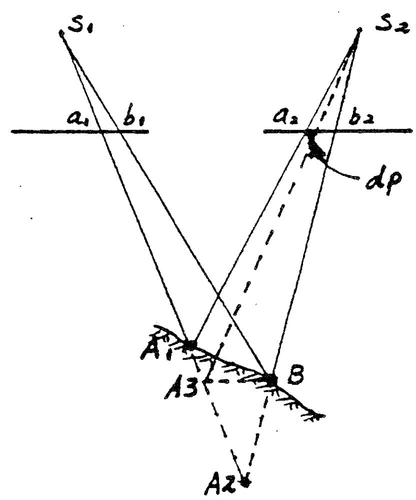

Fig. 3

$$
\begin{aligned}
\text{dpmax} &= \frac{f}{H}\,dh \\
&= \frac{f}{H}\cdot\frac{1}{2}\Delta X\cdot\tan\theta_x \\
&= \frac{1}{2}\Delta x\tan\theta_x
\end{aligned}
$$

2.2 The Function of Multi-Level Correlation —— "From Coarse To Fine":

The technique of multi-level correlation - "from coarse to fine" is really a kind of low pass filtering procedure. The simplest operators of low pass filter are formed by means of averaging the adjacent pixels, such as [1 1] , the effect of which corresponds to a convolution of the original signal (such as $x_1(t)$ or $x_2(t)$ in fig. 2) with a rectangular wave having a width of 2Δ (Δ is the sampling interval). The convoluted signals $x_1'(t)$, $x_2'(t)$ are demonstrated in fig. 4 (a), (b). This procedure of filtering can be done step by step to form a hierachical structure of multi-levels of signals. The necessary mumber of hierachical levels depends on the accuracy of predicting position.

It is obvious that the components of higher spatial frequencies in image data in higher level of signals are mere poor than that in the lower level. The operation of digital correlation is

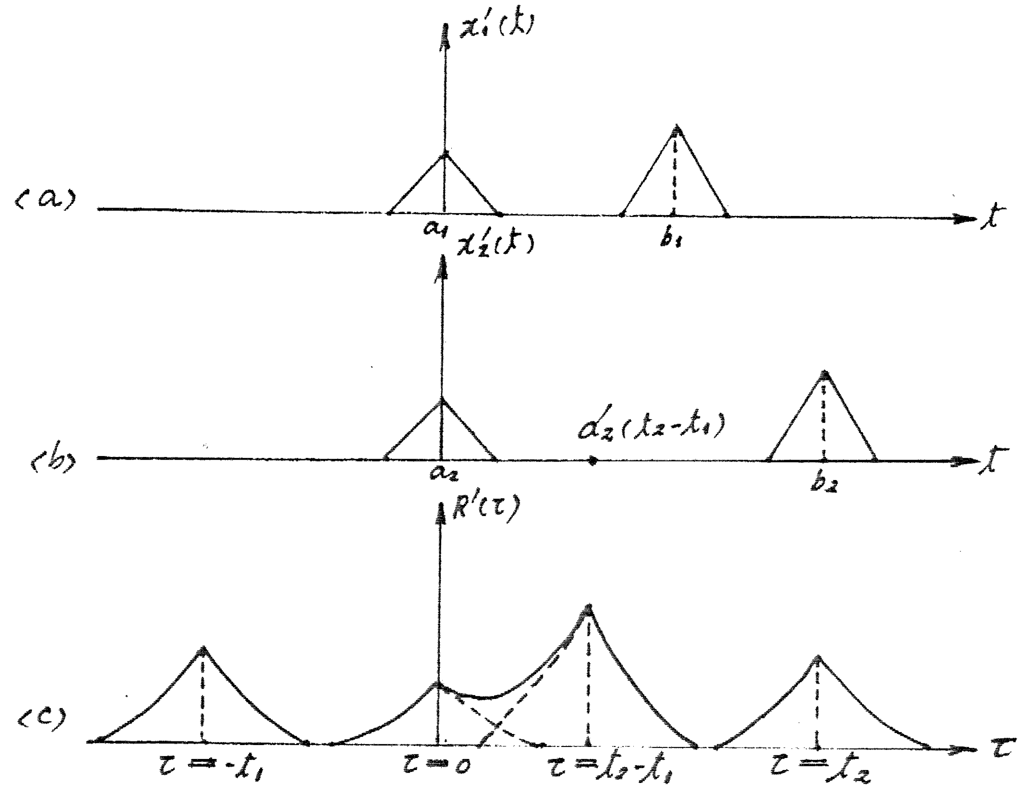

Fig. 4

always carried out from higher level of signal to lower level. Such as the convoluted signals $x_1'(t)$ and $x_2'(t)$ are correlated with wider target window area and the searching area, and it's correlation results are just same as before, i.e. the highest peak of correlation function function $R'(\tau)$ (fig. 4 (c)) remains still at point $\tau = t_2 - t_1$ (or say at point a_2' —— fig. 4 (b)). But now this approximate position a_2' is used as centre of a new searching area for further finer digital correlation with signals $x_1(t)$ and $x_2(t)$. In this process of sequential matching - "from coarse to fine", the components of higher spatial frequencies in image data are gradually increased. It is highly possible to improve the correlation results step by step, and to achieve a relatively high reliabilty. With this approach it can also be anticipated to reduce the matching computation load. However, it has to be pointed out that the blunders or gross errors might not be able to be eliminated entirely from the final correlation results in this strategy of "from coarse to fine". Therefore further detection of blunders from correlation results is still necessary.

2.3 The Relationship between Confidence Level of Estimated Value of Correlation Coefficient and Sample Size of Target Window

Correlation coefficient:

$$\rho_{xy} = \frac{\sigma_{xy}}{\sqrt{\sigma_{xx}\,\sigma_{yy}}}$$

is a statistic quantity applied to assess the similarity between two stochastic signals x and y. It is used here to find conjugate image on two (or more) photographs, only samples from stochastic signals x and y can be used to determine the correlation coeffeicient, so what we have obtained is it estimated value:

$$r_{xy} = \hat{\rho}_{xy} = \frac{\hat{\sigma}_{xy}}{\sqrt{\hat{\sigma}_{xx}\,\hat{\sigma}_{yy}}}$$

It is obvious that reliability of the estimated value r_{xy} depends on the sample size N (i.e. number of points in target window). In order to examine the reliability of r_{xy} we form a stochastic variable

$$w = \frac{1}{2} \ln \left[\frac{1+r_{xy}}{1-r_{xy}}\right]$$

which is approximatelly normal distributed with the expectation and variance:

$$\mu_w = \frac{1}{2}\ln\left[\frac{1+\rho_{xy}}{1-\rho_{xy}}\right]$$

$$\sigma_w^2 = \frac{1}{N-3}$$

Thus the standardized stochastic variable:

$$\frac{w-\mu_w}{\sigma_w} = \sqrt{N-3}\cdot(w-\mu_w) = \frac{\sqrt{N-3}}{2}\ln\left[\frac{1+r_{xy}}{1-r_{xy}} \Big/ \frac{1+\rho_{xy}}{1-\rho_{xy}}\right]$$

It's confidence interval of 95% amounts to,

$$-1.96 < \sqrt{N-3}\,(w-\mu_w) < 1.96$$

or :

$$-\frac{y-1}{y+1} < r_{xy} < \frac{y-1}{y+1}$$

$$y = \frac{1+\rho_{xy}}{1-\rho_{xy}}\cdot e^{3.92/\sqrt{N-3}}$$

The estimated correlation coefficient r_{xy}, sample size N and ρ_{xy} are listed in table 2 with the confidence level of 95%. From table 2 it is obviously seen that if ρ_{xy} is a constant, the

Table 2 The Threshold value of r_{xy}

r_{xy} \ N / ρ_{xy}	11	21	31	41	51	61
0.1	0.66	0.51	0.44	0.40	0.37	0.34
0.2	0.71	0.58	0.52	0.48	0.45	0.43
0.3	0.76	0.65	0.59	0.56	0.53	0.51
0.4	0.81	0.71	0.66	0.63	0.61	0.59
0.5	0.85	0.77	0.73	0.70	0.68	0.67

threshold value of correlation coefficient r_{xy} which is chosen to evaluate the reliability of correlation result is related with the number of points used in target window. In other words, when the threshold value of r_{xy} has been fixed, it's confidence level C depends on the number of points N. For $\rho_{xy} = 0.3$, threshold of correlation $r_{xy} = 0.5$, the relationship between confidence level C and the number of points N is shown in fig. 5

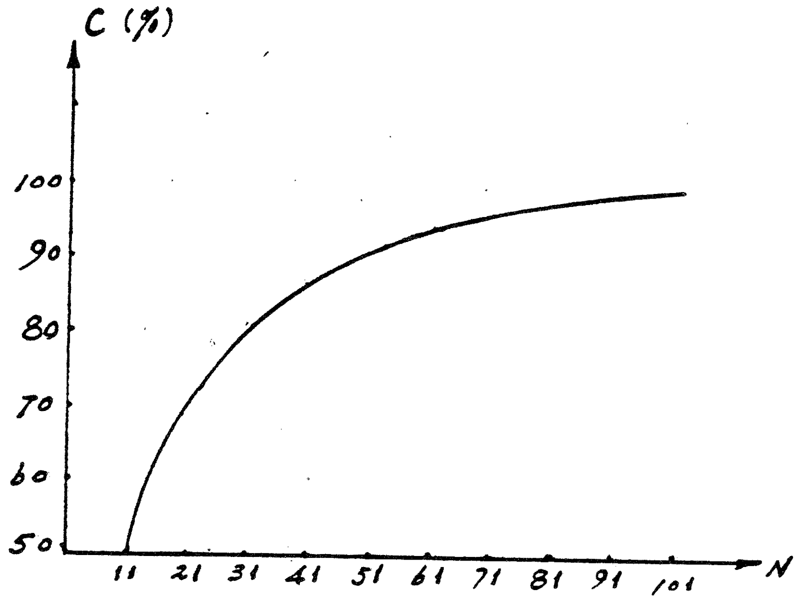

Fig. 5

3. Strategies in Digital Correlation

The accuray and reliability of digital correlation results are primarily influenced not only by mathematical algorithm used for implementation of image matching process, but also by the adopted strategies (such as the process of executing image correlation, prediction of matching point, the shape and size of the target window and of the searching area and the use of multi-level correlation technique etc.). Based on the analysis of digital correlation mentioned above some strategies have been suggested and applied for successful implementation of the digital correlation experiments.

Another point to be noted is that unavoidable gross errors always exist in the correlation results. It is more practical that the generated parallax grid as a result of digital correlation should roughly represent the terrain model in general and the local gross errors remaining in the correlation results may be treated afterward in an another process of blunder detection.

Based upon the above mentioned fundamental requirements to digital correlation, some measures have been taken in the process as follows:

1) The matching procedure of a stereo pair of epipolar line images is divided into two parts that is: the digital correlation for the first several epipolar lines and the correlation for all the remaining epipolar lines. Since there is usually little reference information to predict the matching points at the very beginning, it is more difficult to correlate for first several epipolar lines than the remaining ones.

2) Operations for the first several epipolar lines:

1. Several consequential epipolar lines from which the correlation process will be started should be carefully selected. The requirement for this area is that the image texture overthere is relatively favourable for correlation.

2. The searching range is determined by maximum x - parallax ΔP_{max}. The number of multi-levels N can be estimated from the following inequality:

$$\frac{\Delta P_{max}}{0.05 \times 2^{N-1}} \leq 7$$

It shows that the number of searching areas is limited to a maximum value of 7 points.

3. Digital correlation for each grid point is carried out independently without any prediction made during this stage.

4. After completion of correlating several epipolar lines blunders or gross errors should be detected based on some reliability criterion to be discussed later.

3) Processing all the remaining epipolar lines:

A new matching point $N_{i,j}$ can be predicted by the average parallax of three adjacent points $N_{i-1,j-1}$, $N_{i-1,j}$ and $N_{i-1,j+1}$:

$$x_{i,j} = \frac{1}{3}(x_{i-1,j-1} + x_{i-1,j} + x_{i-1,j+1})$$

The searching range is determined by the maximum parallax between two adjacent grid points. Usually multi-level correlation is also used here if the size of searching area exceeds 7 pixels.

4) Selection of the target window :

From the analysis mentioned above, in mountainous area the length of target window strongly depends on the terrain slope. The relationship between terrain slope θ_x and the maximum length of target window is listed in table 3 with maximum matching error caused by θ_x not exceeding 1.5 pixels.

Table 3

Terrain Slope θ_x	5°	10°	15°	20°	25°	30°	35°	40°
Maximum Length (pixels) of Target Window	35	17	11	8	6	5	4	3

It is seen that the larger the terrain slope, the shorter should be the target window. In other words, the target window should be limited to a shortest possible length capable of supporting a sufficient correlation accuracy level. But from the point of reliability, the larger the target window size, the more confident the correlation results. In order to give a consideration to both accuracy and reliability critériens, several adjacent epipolar lines have been used instead of only one single epipolar line during the correlation proeedure. Thus a two dimensional target window has been formed although the correlation is still carried on in one dimension. It has been found in the correlation experiments that the results of correlation carried out with two- dimensional target window are much reliable as compared with the one-dimensional one.

4 Detection and Correction of Blunders in the Correlation Results

Because unavoidable blunders always exist in correlation results it is indispensable and of great importance to determine whether any point is reliable, in order to detect the mismatching points and finaly to corret them. In a sense the proeess for detection of correlation blunders is more important than the correlation itself.

Blunder of detection can be carried out either during the process of correlation or after correlation of all epipolar lines has been completed. The later case is more essential, because in this case a integral consideration of both the information of the imagery gray value (such as gradient-vales. variances of target and searching windows and correlation coefficients etc) and all parallax informations generated from correlation can be made. The process of blunder detection has been divided into the following several steps:

1) Determination of reliable groups of the matched points: Since it is sometimes difficult to decide the reliability of single matching point, the socalled "reliable group of matched points" is adopted here which is a group of neighbouring matched points satisfying the following criteria:

- Value of the correlation coefficient of each matched point within the group should be larger than a certain threshold.
- Sum of the correlation coefficients of these matched points should be larger than a certain threshold.

• Parallax difference between adjacent two points should be smaller than a certain threshold.

• Sum of squares of these parallax differences should be smaller than a certain threshold. The threshold of correlation coefficient is determined by the size of target window and the parallax difference threshold is related with the terrain slope.

2) Detection and correction of blunders caused by low contrast:

In the low contrast area (such as water surface. meadow. farmland and shadow in mountainous area etc) it is more difficult to find conjugate points with digital correlation because of the **very poor** signal-noise ratio. The correlation blunders in this area usually make the equal parallax curves on the epipolar imagery appearing as either high spikes or deep holes instead of small distarbances. A special program has been developed for eliminating this kind of blunders. It's main points are as following:

a. Based on the variance of gray values of target window to determine the low contrast image area;

b. In accordance with the criterions of correlation coefficient, variance of gray values and the reliable group of points to locate the boundary line surrounding the low contrast area.

c. By the use of the parallaxes of the reliable points located on the boundary to obtain the parallaxes of the points within the low contrast area through linear interpolation.

3) Detection and correction of blunders by the method of parallax smoothing:

The method of parallax smoothing is normally used for detecting the correlation blunders. It means that by comparing the parallax of a point with the average of parallaxes of its neighbouring two, four or eight points the matching quality of this point can be assessed. If this difference exceeds a predetermined tolerance the parallax of this point will be replaced by the average value of the neighbouring points. In order to prevent the discarding of correctly matching points by this method of parallax smoothing, some operations have been programed:

a) A straight line is fitted on the neighbouring four points k-2, k-1, k+1, k+2 of the point k (fig. 6) in either x-direction or y-direction. Then the standard deviation σ_k and the residual error V_k of the central point k are obtained.

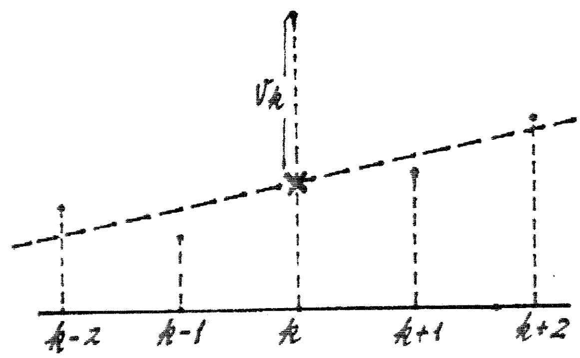

Fig. 6

b) After calculating the standard deviations σ_k and residual errors V_k of all points in the whole correlation area, the detection of blunders and correction of them will begin for those points where the standard deviations σ_k are the smallest in the whole area.

c) The tolerance of the residual errer V is not a predetermined constant, and depends on the corresponding standard deviation σ_k . Generally $3\sigma_k$ can be served as the telerance of residual error V.

d) The solution has to be obtained by iterative steps.

5. Correlation Results and It's Accuracy Evaluation

A special approach has been adopted in our experiments to effectively evaluate the accuracy of digital correlation. Mere a pair of "epipolar line images" suprimposed with the stereoscopic profile lines automatically produced from digital correlation is used for assessing the correlation accuracy. For simplicity the image will be referred to as "profile image". On profile image there is no y - parallax in theory. Because of the regular arrangement of parallax grid, the profile lines are equally spaced straight lines perpendicular to the epipolar on the left image, while these profile lines are broken lines on the right image effected by the undulation of terrain surface. Under a stereoscope the pair of profile images can be observed as a stereo terrain model with a series of profile lines lying on the terrain surface. On a stereocomparater, the differential parallaxes between the profile lines and the corresponding terrain model surface can be measured under stereoscopic vision to find any error on the surface constituted by the parallax grid. Hence the accuracy of digital correlation can be assessed easily.

The advantage of this method lies in that:

- This method is quite simple and straightforward. There is no necessity of any previous measurements.
- With this method it is very convenient to check any point whether it has been correctly matched or not.
- A very large amount of measurement can be easily acquaired and therefore the assessed accuracy might represent the level of correlation quality.
- An accuracy of digital correlation can be evaluated without the effects of film deformation and errors due to the elements of orientation.

Fig. 7 shows the result of digital correlation in the form of a stereo pair of " profile images ". The profile lines are generated directly from corrolation without the use of the above mentioned method of blunder elimination. It is shown obviously that quite a number of points have been mis-matched, especially on the low contrast areas (water surface of a reservoir. farmland etc) and at mountain slopes.

After the implementation of the method of blunder detection (at first

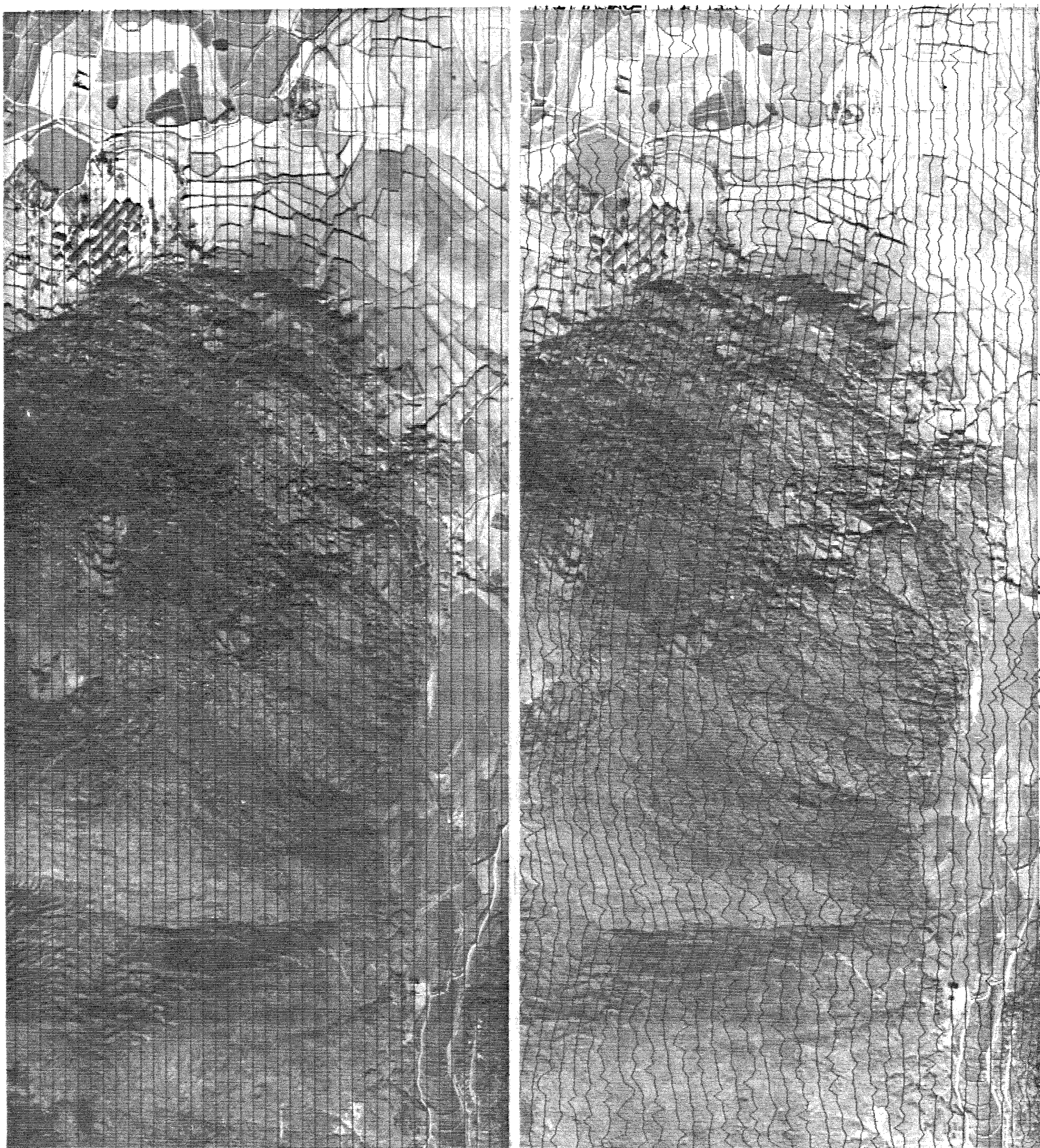

Fig. 7

the blunders on low contrast areas are eliminated and then on the remaining others) the result is again shown in fig. 8.In this test area x - parallaxes of altogether 24600 points have been determined. By comparing the results of fig. 7 and fig. 8, the number of thus corrected points amounts to 5463 - about a quater of the total grid points. The distribution of the magnitude of the correlation errors corrected is shown in fig. 9. Errors greater than 2 pixels is equal to 69.1%.

In order to assess the accuracy of parallax grid which is generated by digital correlation and in which the gross errors have be removed, we have measured x - parallaxes of altogether 1079 points on a stereocomparator. The distribution and accumulated distribution of their residual errer are shown in fig. 10. The root mean square errer of digital correlation is found to be 24.8 μm (equivalent to one half of the sampling interval and spot size of 50 μm). Error greater than three times of RMS amounts to 2.5% and the maximum residual errer is 167 μm.

Besides this mountainous test area, another correlation experiment of a moderate undulation area has been also performed with the same program. It's profile image appears in fig. 11. The accuracy of correlation results in this test area is found to be 40 μmby comparing with the measurement of 1050 points on a stereocomparator. The reduction of correlation accuracy in the moderate undulation area are mainly due to the existance of too many artificial earthworks (like the ridges of terraced fields).

From these experiments the follwing conclusions can be made:

(1) By the use of epipolar line geometry, the task of correlation of stereo image can be reduced to a one - dimensional case. However, a two dimensionc target window should still be adopted in the correlation process, in order to obtain a better digital correlation result.

(2) After completing digital correlation, the operation of detection

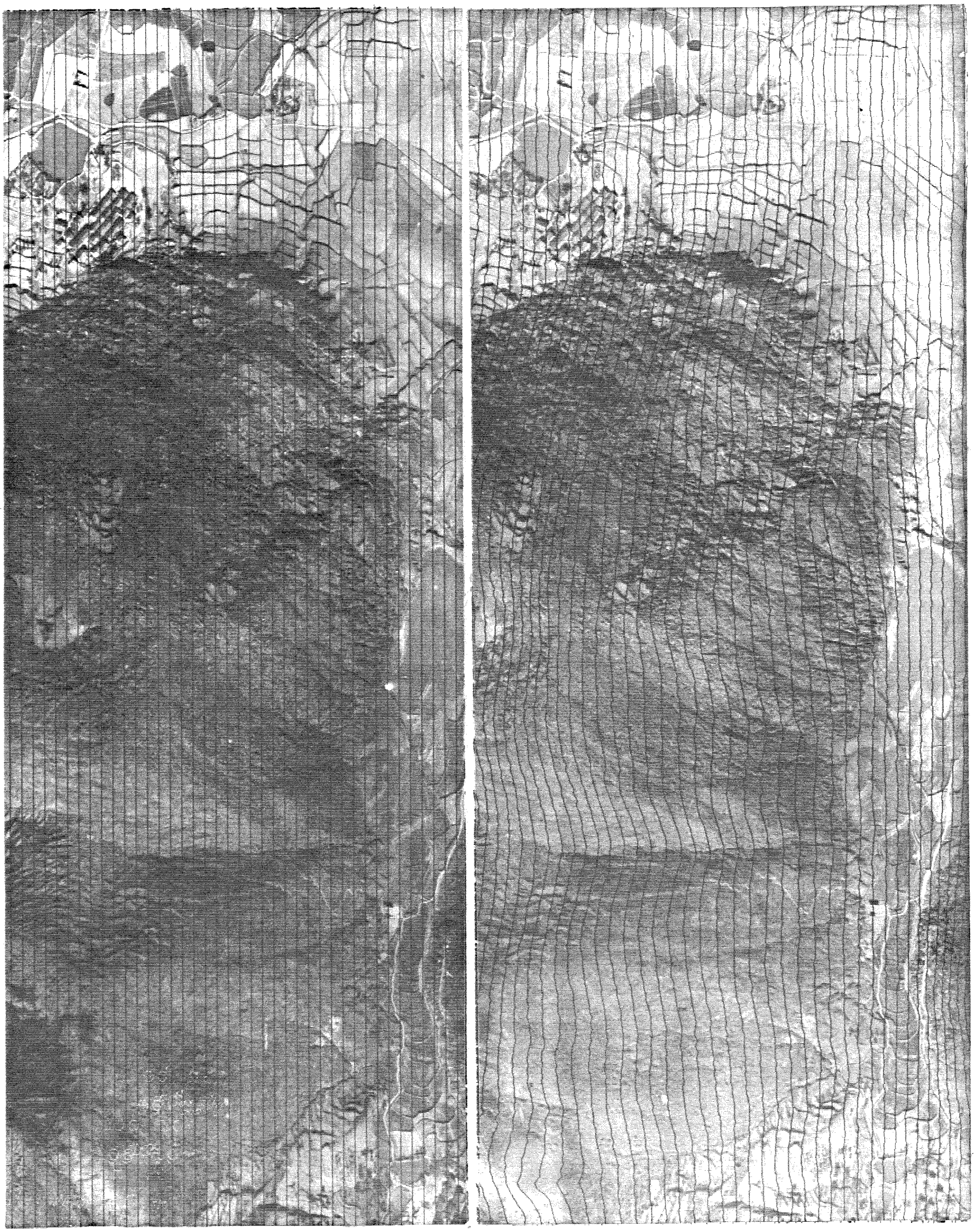

Fig. 8

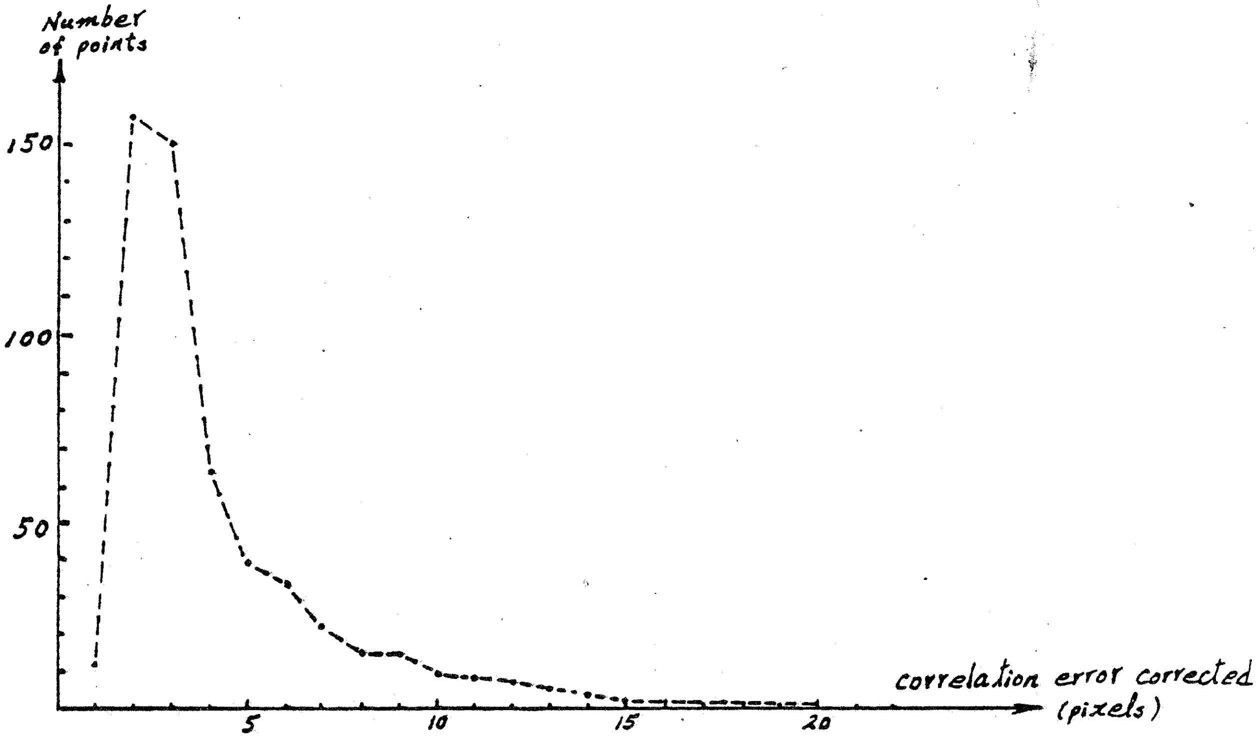
Number of points
150
100
50
5
10
15
20
correlation error corrected (pixels)

Fig. 9

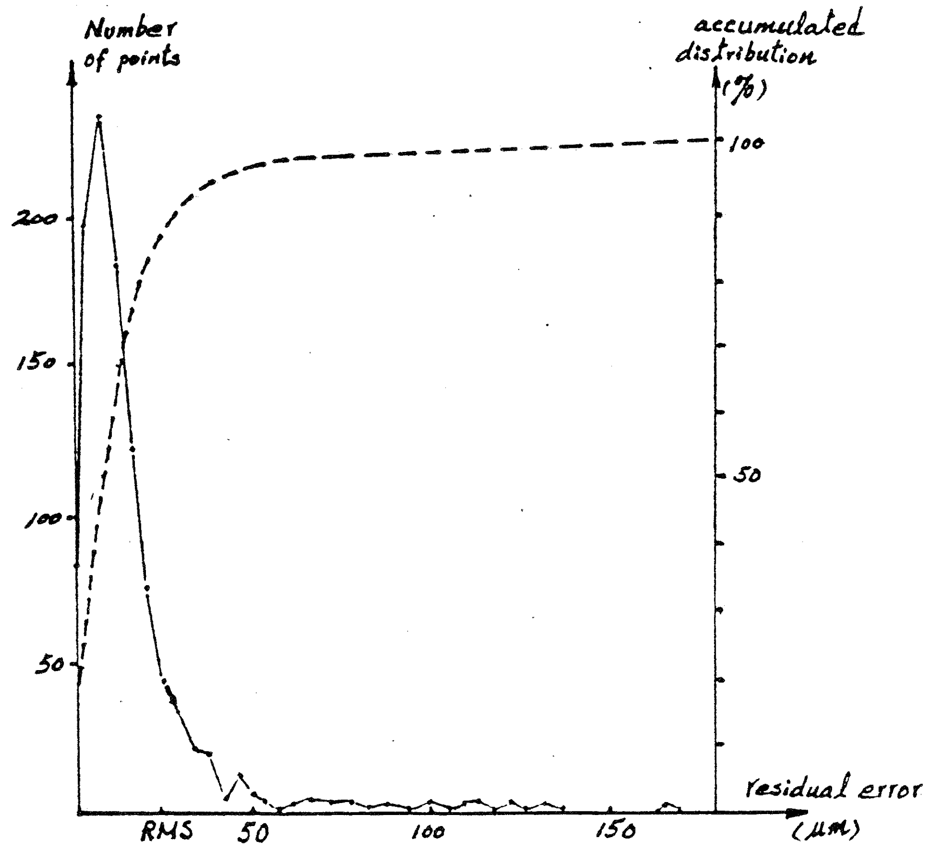
Number of points
accumulated distribution (%)
200
150
100
50
100
50
residual error
RMS
50
100
150
(µm)

Fig. 10

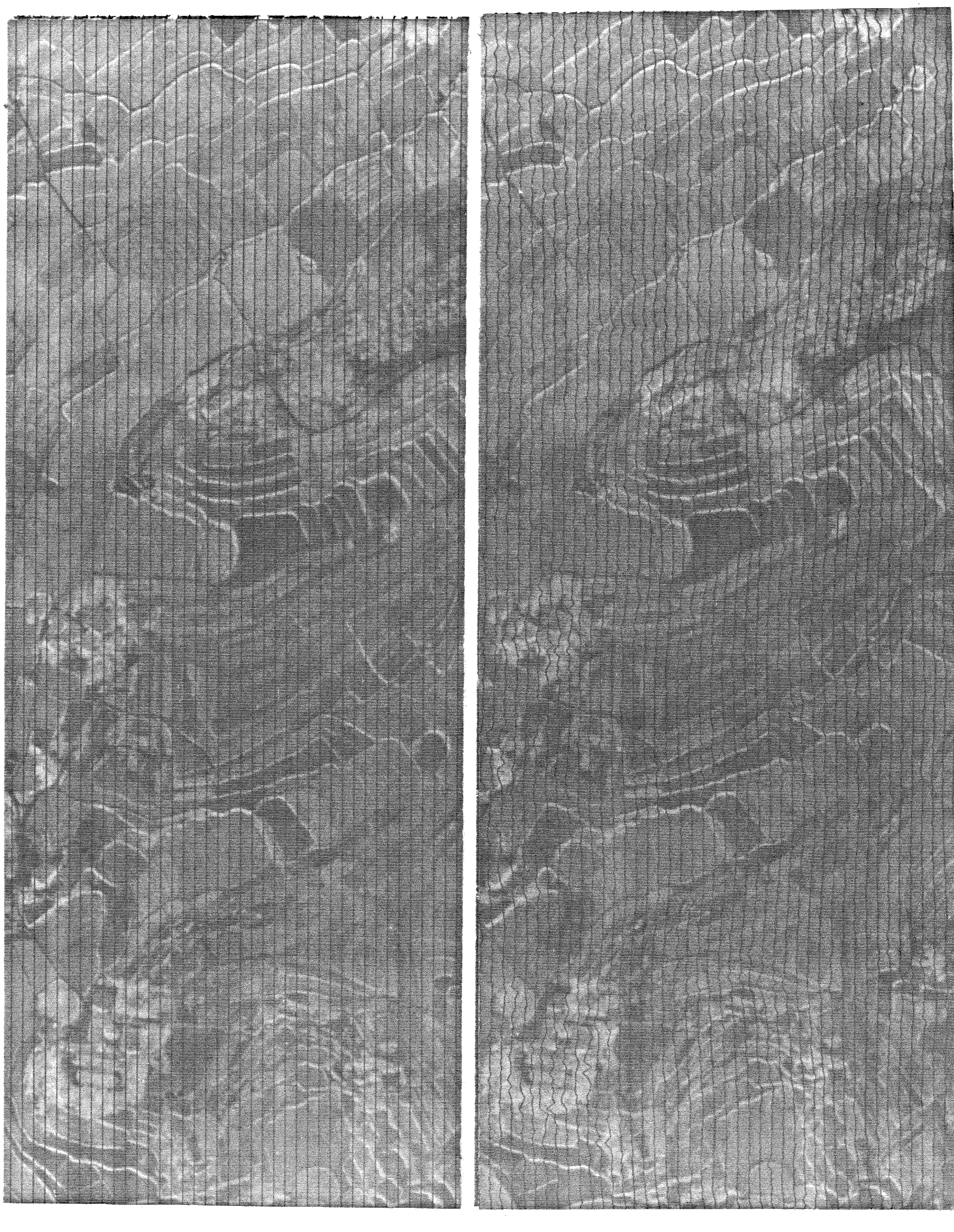

Fig. 11

and correction of blunders is a very important postprocessing process for improvement of the quality of digital correlation. At this stage, both the infermations of the gray values of images and also of the parallaxes are available and a joint consideration of buth of them is very beneficial.

3) As a result of a post detection of blunders, the requirement for the digital correlation operation could be reduced to a certain level. As for the example here, the image data shaping has not been carried out, yet a satisfid rosult of matching at mountain slopes has still been achieved.

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