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Automatic Reseau Measurement with a Simple Optical Correlator

The reseau to be measured is optically matched to a reference reseau with the aid of digital signal processing.

INTRODUCTION

A MAJOR DISADVANTAGE of employing reseau photography in photogrammetry is that hundreds of reseau points must be measured manually. This is a very tedious and time-consuming procedure. Although equipment has been developed for automatic reseau measurement,[1,2] such equipment is presently rather expensive. In this article, an automatic reseau measurement technique, based on using a simple, noncoherent optical correlator for reseau mark detection and noncoherent optical correlation—low frequency background noise—is solved by performing digital high-pass filtering on the sampled output of the optical correlator. A digital computer is employed to perform the digital signal processing and to control the automatic reseau point measurement process. Digital filtering significantly enhances the performance attainable with the correlator. Digital computer control of the reseau point measurement process—specifically the correlation function

ABSTRACT: *A technique has been devised for using a simple, noncoherent optical correlator for reseau mark detection and measurement. The approach uses a digital computer to perform the signal processing and control of the automatic reseau point measurement process. The concept has been implemented on an experimental photogrammetric facility. Experiments show that the system produces very repeatable measurements and reliable detection if the signal-to-noise ratio (SNR) is sufficiently high. Digial filtering enhances system measurement repeatability and its ability to detect reseau marks in the presence of high-signal-level background imagery. Various analytical instruments could be readily retrofitted with equipment to implement the noncoherent optical correlation capability.*

measurement is described. A major problem associated with mechanical scanning hardware. The technique has been verified experimentally on a photogrammetric research facility at Bendix Research Laboratories (BRL) under a program supported by the U.S. Air Force, Rome Air Development Center (RADC)[2].

BACKGROUND

The simplicity of noncoherent optical correlation techniques makes them very attractive solutions to photographic image-matching problems. Optical correlation scanning—eliminates the need for special techniques have received considerable attention in the field of optical character recognition. They have also been studied as possible methods for extracting parallax information from stereo phtographs. The degree of success achieved in applying simple optical correlation techniques to an image-matching problem depends on the nature of the specific problem. Simple optical correlators cannot tolerate large amounts of differential image distortion between the two photographic images being matched. They are, therefore, not well suited to the task of

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matching imagery in highly distorted stereo photographs. For the tasks of reseau detection and measurement, however, optical correlation techniques are well suited and offer benefits of high system signal-to-noise ratio (SNR) and simplicity of equipment design.

For image-matching in general , the ease with which photographic images can be multiplied and integrated in optical systems makes optical processing particularly suitable for processing photographic image information to determine two-dimensional cross-correlation functions. The outstanding features of optical correlators are that image processing is done in parallel at essentially the speed of light, and that system noise is minimal. The primary noise sources in a noncoherent optical correlator are photograph grain, light source noise, and photodetector noise. Of these noise sources, the light source noise and photodetector noise are contributed by the optical correlator. The grain noise is inherent in the photograph.

With an incandescent lamp powered by a well-regulated DC power supply, the light source noise is negligible. Noise contributed by the photodetector of the optical correlator is small because the output bandwidth of the correlator is very narrow. The bandwidth need only be wide enough to pass the relatively slow time variations of the ouput correlation signal. The narrow photodetector bandwidth results in a very high photodetector SNR. The basic limitation of the optical correlation process is, therefore, the SNR of the photograph itself.

A particular type of noncoherent optical correlator suitable for reseau detection and measurement is shown in Figure 1. Light from the incandescent lamp light source is condensed by a lens and passes through the first photo. The light intensity pattern passed by the first photo is imaged on the second photo by the imaging lens. This imaging process inverts the image. The image inversion is shown in the figure as an inversion of the sense of the x and y photo axes. As the light from the first photo passes through the second photo, the light intensity pattern of the first photo is multiplied by the transmission function of the second photo. The light intensity pattern in a plane immediately beyond the plane of the second photograph is therefore proportional to the product of the transmission functions of the two photographs.

The aperture plate immediately beyond the second photograph passes the product function over a selected area A. Light emerging from the aperture is collected by

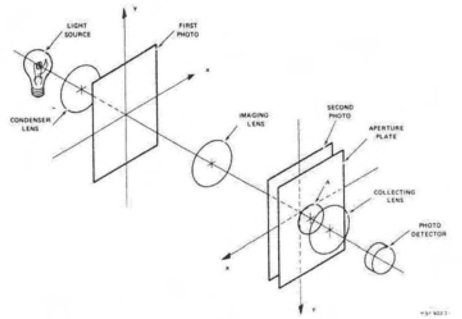

FIG. 1. Noncoherent optical correlator.

the collecting lens and concentrated on the light-sensitive surface of the photodetector. If the position of the first photograph is shifted in its x, y plane, the image of the first photo is also shifted in the plane of the second photo. The result of this shifting is that the product function will be proportional to the transmission function $T_2(x,y)$ of the second photo times the transmission function $T_1(x + \eta, y + \xi)$ of the shifted first photo. The combined effects of the aperture plate and collecting lens are to integrate the product function $T_1(x + \eta, y + \xi)\ T_2(x,y)$ over the aperture area A. The output of the photodetector, which is porportional to the output light intensity of the optical system, can, therefore, be characterized by

$$C(\eta,\xi) = k \iint_A T_1(x + \eta, y + \xi)\ T_2(x,y)\ dx\ dy$$

which is proportional to the correlation of the two-dimensional photograph transmission functions $T_1\ (x,y)$ and $T_2\ (x,y)$.

The system does not actually compute normalized correlation, but for the purpose of positional measurement, unnormalized correlation can be used. In the equation, η and ξ are the x and y shift variables, and k is a constant which is proportional to the input light intensity, the optical system light efficiency, and the photodetector conversion constant. If the transmission functions of the first and second photos are identical except for a positional shift, the positional shift can be measured by searching in x and y for a maximum of the optical correlator output correlation function. Matched filter detection is accomplished by comparing the maximum output value with a suitably chosen detection threshold. If the output exceeds the detection threshold, the probability is high that the maximum value found is the desired maximum and not a side lobe of the correlation function.

In the optical correlator described here, it is desirable to use a fairly large aperture area. In general, the aperture diameter should be at least several times larger than the main lobe of the correlation function. If the aperture is too small, side lobes of the correlation function easily can exceed the main lobe in intensity. For reseau measurement, however, the aperture size requirement is not a problem. The width of the correlation function main lobe is about twice the width of the reseau mark cross arms. The reseau mark cross arm width is typically from 10 to 50 μm, and the aperture diameter can typically be 10 to 100 times the width of the correlation main lobe. Since reseau marks are generally uniform in size and shape, differential image distortions are not a problem.

Automatic measurement of reseau points on aerial photographs is an application for which noncoherent optical correlation techniques are well suited. The objective of reseau measurement is to determine the locations of reseau marks which were placed on the photograph at some point in the photographic processing procedure. If reseau mark locations are measured, film shrinkage and other distortions introduced in subsequent photographic processing can be corrected.

In order to apply the optical correlator to reseau measurement, the second photo of Figure 1 is made to be a reference reseau mark. This reference mark consists of a clear reseau of the same dimensions as the expected dimensions of the reseau mark on the photographs. The reference background is opaque. The first photo is the photograph containing the reseau marks to be measured. It is assumed that the rotation and approximate locations of these marks are known. Reseau mark location measurement consists in moving the photograph in directions normal to the reseau axes until the correlation peak is obtained. The location of the correlation peak is then the location of a reseau mark. Automatic reseau point measurement is accomplished by using a computer to search for the correlation peak (utilizing computer control of the photocarriage) and recording the photo-coordinates of the peak.

Experimental Reseau Measurement System

In order to demonstrate the automatic reseau measurement technique and to evaluate its effectiveness, an experimental system was developed. The system was implemented on an experimental photogrammetric facility at the Bendix Research Laboratories. This facility is essentially an analytical stereo-comparator, consisting of a two-stage viewer, a PDP 11/35 computer, and various standard computer peripheral devices. Optical correlation equipment was added to the manual viewing optics of one stage of the viewer. The photocarriage and objective lens of this stage forms part of the optical correlator. Experimental computer programs were developed for correlation scanning, digital signal processing, and data recording. The reference reseau mark masks used in the optical correlator were clear crosses with opaque backgrounds, and allowed measurement of both light and dark reseau marks or grid intersections.

Figure 2 shows how the photogrammetric facility is configured for the reseau point measurement system. During automatic measurement, photograph scanning motion is generated by the computer programs. Photograph position commands are transmitted to the stage by way of the servo interface. The optical correlator, consisting of the photo stage, reference reseau mark, and associated optics, computes correlation as a function of the relative position of the photograph reseau mark with respect to the reference reseau mark. A photomultiplier tube (PMT) detects the light output of the optical correlator. The output current of the PMT, which is proportional to unnormalized correlation, is converted to a voltage and transmitted to the analog-to-digital (A/D) conversion interface.

The A/D interface unit converts analog correlation voltage samples to digital values for computer input. The entire collection of equipment external to the computer can be thought of as a correlation function generator. The computer programs transmit independent variables x and y to the external equipment, and the external equipment returns a

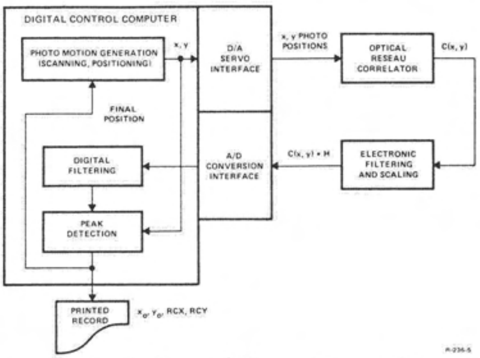

FIG. 2. Optical correlation *reseau* point measurement system.

value of correlation for each x,y pair of coordinate values. By searching (or scanning) in various directions, the programs find the point of maximum correlation. The x,y values which result in maximum correlation are then defined to be the measured coordinates of the photographic reseau point. Both light and dark reseau marks can be measured by the system. In the case of dark reseau marks, a correlation function minimum defines the reseau point.

Optical modifications to the photogrammetric facility for reseau mark correlation are shown in Figure 3. The illuminator, photograph stage, mirror, imaging lens, and reference mark are all part of the normal viewing optics. The beam splitter, reference reseau mark, and PMT assembly were added for reseau correlation. The beam splitter introduced in the normal optical path reflects some of the light at a right angle to the normal optical path. This reflected light comes to focus at a second image plane which is the same distance from the beam splitter as the viewer reference mark. The reference mark reticle and PMT assembly are both mounted on a mechanical device (not shown) which allows rotation and translation of the reference mark and PMT. This positioning device is used to position the reference reseau in the proper image plane, rotate the reference reseau axis into alignment with the photograph reseau axis, and align the center of the reference mark with the optical axis. It facilitates removal of offsets between manual and automatic reseau measurements and allows some flexibility by not requiring that the photograph reseau axes be perfectly aligned with the photograph stage axes.

As described earlier, optical correlation is performed by imaging the photograph reseau mark on the reference mark. Light from

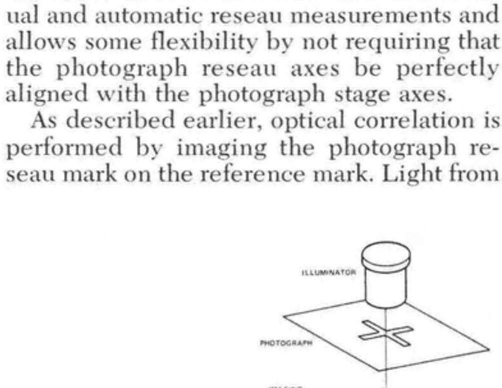

FIG. 3. Photogrammetric facility modifications for optical *reseau* mark correlation.

the illuminator passes through the photograph and is reflected by the mirror to the imaging lens. Light passing through the imaging lens is partially reflected to the reference mark. The lens images the photographic reseau mark onto the reference mark, and the product image is formed immediately behind the reference mark. Product image light is integrated over the photocathode of the PMT to form an output signal current proportional to the cross correlation of the image reseau mark with the reference mark. The beam splitter allows some of the light from the photograph to pass down the normal optical path for viewing of the photograph. Both manual and automatic *reseau* point measurements can, therefore, be made without having to reconfigure the optics.

In the computer, program modules for reseau point measurement provide a multiple scan sequence for automatic measurement, a single scan mode for determining a single one-dimensional correlation function, and special recording capabilities for recording correlation functions and point measurements on either a printer or punched tape.

The scanning sequence performed to automatically measure a reseau point is done in two parts. The first part is a fast search to find the approximate location of the reseau mark. The second part is a slow search over a more limited range to make the final measurement. When automatic measurement is initiated, the system moves a certain distance to the left of a starting point and scans rapidly in the positive x direction. It then scans in the negative x direction. The average of the two x coordinates determined from these scans is stored as the approximate measured x coordinate. This sequence is repeated for the y direction, and when completed the system moves to the approximate measured reseau point position. Starting from this approximate position, the x and y scanning sequences are repeated at a slower velocity and over a more limited range. The x and y photo coordinates determined from this second scan sequence are the final measured coordinates of the reseau point. The system is driven to the final measured position, and reseau point coordinates are recorded. On the experimental system, this two-part scanning procedure requires a total time of slightly over eight seconds. This time could be reduced by using higher data sampling rates. (The present system samples at a rate of 100 per second.)

The method used to determine x or y position during scanning is peak detection. As the system scans the photograph, relative to the reference reseau mark, the optical correlator transmits the correlation function to the computer. The computer samples and stores correlation values and corresponding commanded photo coordinates. When the scan is completed, a computer program searches the set of correlation values for the maximum (or minimum for dark reseau marks). The photo coordinate value for which maximum (or minimum) correlation was obtained is selected as the measured reseau point coordinate. The experimental system did not have the capability of automatically indexing to the approximate positions of successive reseau points; however, such a capability would be implemented on any operational system. At the beginning of an automatic reseau measurement procedure, a file containing calibrated (expected) reseau point locations would be read into the computer. When one reseau point is measured, the computer can then drive the photo stage to the approximate location of the next reseau point, reducing the amount of searching required to find that point.

Experimental System Evaluation

Experiments performed with the reseau point measurement system revealed that the accuracy and repeatability attainable with this technique are very good. Comparison of manual and automatic measurements of calibration grid points showed differences of about 2 μm rms. Repeatability of automatic measurements was better than that of the manual measurements; about 0.5 μm rms for the automatic system compared with 1 to 2 μm rms for manual measurements of the grid plate. In the course of the experimental evaluation, it was discovered that the ability of the system to properly detect reseau marks could be greatly enhanced by performing digital high-pass filtering of the correlation data in the computer prior to peak detection. It was also discovered that a certain amount of digital low-pass filtering was useful in reducing measurement noise. The paragraphs which follow discuss experimental procedures and results in more detail.

The reseau point measurement system was evaluated using four different photographs. For accuracy evaluation, a grid plate containing 20- μm-wide grid lines was used. Repeatability was evaluated over three photographs containing reseaus. The first photo contained dark reseau grid lines having generally good signal-to-noise ratio (SNR). The second photo contained light cross-type reseau marks of fair SNR. The third photo contained thin dark reseau crosses with fair to poor SNR. The reseau point measurement system had no difficulty in measuring the grid plates and the first two photo reseau marks. On poor reseau marks of the third photo, however, the system would occasionally fail to correctly measure the reseau point.

Accuracy evaluation was performed by comparing manual and automatic measurements of grid intersections on the grid plate. The overall error obtained from several evaluations appears as the first item in Table 1. Individual evaluations varied from about 1.5 μm to 2.5 μm rms. This variation is most likely due to variations in operator repeatability from one day to another. The figures in Table 1 for manual and automatic grid plate measurement repeatability show that automatic measurement repeatability is clearly superior. Comparisons of automatic and manual reseau point measurements were not made for the photographic reseau marks. Resources available at the time were not sufficient for doing any meaningful study of differences between manual and automatic measurements in the presence of background image noise.

One factor which affects the comparison of automatic repeatability and manual repeatability is photocarriage servo backlash. Automatic measurements are made in such a way that backlash is cancelled out in computing reseau point location. Manual measurements are probably corrupted somewhat by servo backlash. The reseau point measurement system provided a convenient vehicle for measuring backlash. Such measurements indicated that y axis backlash was about 2 μm and x axis backlash was about 3 to 4 μm. The larger backlash in the x axis is probably the reason for the higher x axis manual measurement repeatability error compared with the y axis. (See Table 1.)

Tests of automatic measurement repeatability were made over three photographs. The first photograph was entitled Ft. Sill and contained dark grid lines. The grid lines were apparently applied to the photo during photo copying. They have good contrast with respect to the background imagery and are about 20 to 30 μm in width. The second photo was a panoramic photo of the Arizona test area with light cross-type reseau marks. These reseau marks also appear to have been applied during photo copying. The contrast of the light reseau marks was generally not as good as the dark Ft. Sill photo grid lines, particularly in bright areas of the photograph. The light reseau marks were about 25 to 35 μm in width. The third photo was enti-

TABLE 1. EVALUATION RESULTS

Evaluation	x_{rms}	y_{rms}
Grid Plate Manual-to-Auto Accuracy Evaluation	2.1 μm	1.9 μm
Grid Plate Manual Repeatability	1.9 μm	1.0 μm
Grid Plate Auto Repeatability	0.4 μm	0.5 μm
Ft. Sill Photo Auto Repeatability	0.5 μm	0.5 μm
Arizona Panoramic Photo Auto Repeatability	0.9 μm	0.7 μm
Sudbury Photo Auto Repeatability	1.1 μm	1.1 μm

tled Sudbury and contained short, thin reseau crosses which were placed on the film at the time of exposure (in the camera). The general quality of these reseau marks is fair to poor compared with the quality of the Ft. Sill photo reseau marks. Many of the poor quality reseau marks were, in fact, barely discernable in the viewing optics. The width of the Sudbury photo reseau marks was about 15 to 20 μm.

Results of repeatability tests for the three photos (and grid plates) are shown in Table 1. The repeatability error generally tends to be higher for poorer quality reseau marks; however, reseau cross arm width may have been a contributing factor to the errors obtained. For the Ft. Sill photo, the 20 to 30 μm photo reseau cross arm width was matched fairly well to the 24 μm width of the reference reseau cross arm. For the panoramic photo, photograph reseau cross arm width varied from about 25 to 35 μm, and was somewhat larger than the 24 μm reference. The Sudbury reseau cross arms were about 15 to 20 μm wide and were measured using a 22 μm reference.

If the reseau cross arms were of perfectly rectangular density cross section, the correlation function would be flat-topped when they were not matched in width. One might, therefore, expect that large errors would result from not having the reseau marks matched. Actual reseau marks, however, are not generally perfectly rectangular in density cross section, and the correlation functions are usually rounded on the top. Experience with the optical correlator indicates that matching the reference reseau cross arm width to that of the photographic reseau mark is not as critical as was originally anticipated. If the mismatch is large, of course, measurement errors are likely to be greater; however, the measurement repeatability errors obtained for all three of the test photos were below 2 μm rms. It is, therefore, expected that a range of photographic reseau marks could be accommodated by the judicious selection of a single reference.

In addition to the accuracy and repeatability tests, tests were performed to determine the percentage of reseau marks on each photo which could be correctly located. For the Ft. Sill and Arizona panoramic photos, all reseau marks which were tried were correctly located. For the Sudbury photo, however, a certain percentage of the reseau marks tried were not correctly located. These results are shown in Table 2. Approximately 86 percent of the reseau marks tried were located correctly. About 14 percent were not. The 14 percent consisted of 10 percent which were correctly identified as bad measurements and 4 percent which were not identified as being bad measurements. It should be noted here that the Sudbury photo was used as an extreme example. Some of the reseau marks on this photo were barely discernable by the human operator. Even so, the automated system could often make consistent measurements of marks which the operator had difficulty measuring. Nevertheless, the fact that the system produced 4 percent undetected bad measurements demonstrates that it presently does have limitations. Methods of improving system performance are discussed later.

During system optimization, it was discovered that noise on the correlation function could be reduced significantly by low-pass filtering the digital correlation data in the

TABLE 2. RESEAU POINT MEASUREMENT TEST RESULTS

	Ft. Sill	Arizona	Sudbury
Good Measurements	100%	100%	86%
Detected Misses	0	0	10%
Undetected Misses	0	0	4%
Rejected Good Measurements	0	0	0

computer. Low-pass filtering is essentially an averaging process which rejects high frequency signal components. In this application it was used to reject high frequency noise generated primarily by the PMT and interface electronics. This low-pass filtering was applied only to the correlation data from the second, slow scanning sequence which is used to determine the final reseau point position measurement. The digital low-pass filtering improved measurement repeatability from about 1 μm rms to about 0.5 μm rms when using the grid plates as input material.

Figures 4 and 5 show the effect of the low-pass filtering. These figures show the shape of a dark reseau mark correlation function in the vicinity of the minimum point. As seen in Figure 4, the data contain some noise. Figure 5 is a filtered correlation function of the same reseau mark. As can be seen, the noise has been greatly reduced without significantly affecting the shape of the correlation function.

An inherent property of the noncoherent optical correlator is that the low frequency background tramsmission characteristics of the two photographs appear in the output correlation function. This background transmission can occasionally produce a higher output value than the reseau mark correlation peak. The low frequency background imagery can modulate the film more fully than the high frequency reseau mark imagery because of the modulation transfer function of the film (and other system components). The transfer function is generally high for DC and low frequencies, and tapers off as frequency increases. Since the reseau point measurement system uses the maximum (or minimum in the case of dark reseau marks) value of the correlation function to determine reseau point location,

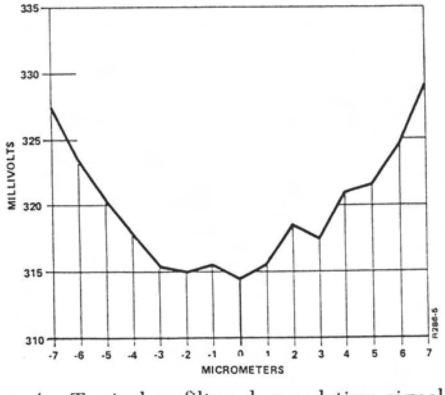

Fig. 4. Typical unfiltered correlation signal in vicinity of minimum point.

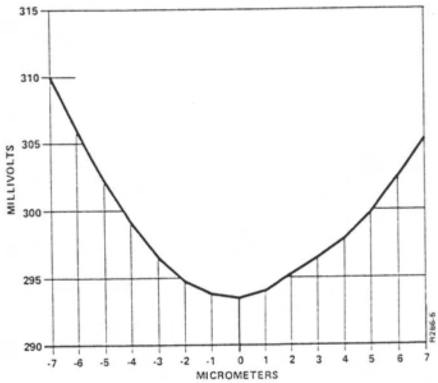

Fig. 5. Typical low-pass filtered correlation signal in vincinity of minimum point.

a background signal which exceeds (or is lower than) the reseau mark correlation peak (or minimum) will produce an incorrect measurement.

An output correlation function having a dominant background signal level is shown in Figure 6. The correlation function exhibits a background signal with a strong upward linear trend toward the left of the plot and a background peak which is higher than the correlation peak. Such correlation functions occurred quite often in the Arizona panoramic photo for reseau marks with bright reseau point identification numbers beside them. The background peak in Figure 6 is, in fact, due to one of these bright numbers. The reseau measurement system would not (when first tested) find the reseau for situations such as that of Figure 6. Figure 7 shows the effect of high-pass filtering the correlation function. High-pass filtering essentially removes the DC and low frequency signal components. The figure shows that the background signal has been greatly suppressed and the reseau mark correlation peak is much higher than the remanents of the background signal.

The high-pass filter concept was also applied in computing a correlation quality measurement. During the slow, final scan

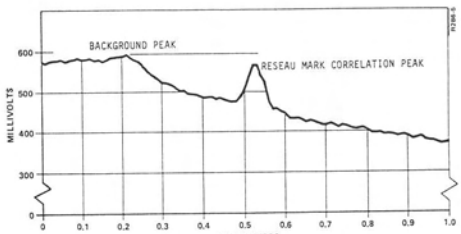

Fig. 6. Unfiltered correlation function.

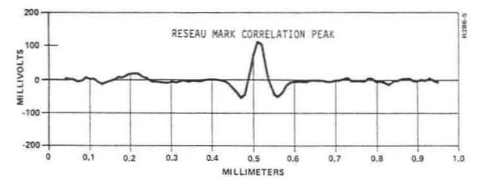

FIG. 7. High-pass filtered correlation function.

sequence, high-pass filtering is applied at the maximum (or minimum) correlation point in the correlation data set. The correlation quality is computed using

$$C = C(i_{max}) - \tfrac{1}{2}\left[C(i_{max} + 40\ \mu m) + C(i_{max} - 40\ \mu m)\right]$$

A correlation value is computed for both the x and y correlation function scans. These correlation values indicate the height of that part of the composite correlation function which is due primarily to the reseau mark alone. The effect of background is removed. This measure of reseau mark correlation quality was fairly effective in determining whether or not a reseau mark had been found correctly, but as indicated by the 4 percent bad measurements of Table 2, it was not infallible.

SUMMARY OF RESULTS AND POSSIBLE IMPROVEMENT

Reseau point measurements made with the Ft. Sill and Arizona photographs demonstrate that very reliable detection of reseau marks can be achieved if reseau mark SNR is sufficiently high. All of the marks measured on these photographs were correctly detected as reseau marks. On photographs having poor SNR, however, automatic reseau detection was not entirely reliable. An operational system must, therefore, incorporate additional discrimination techniques to ensure that reseau marks are correctly detected.

The problem of incorrect detection of reseau marks is due primarily to background imagery which has high contrast with respect to that of the reseau mark and also has sufficiently sharp edge transition to produce a predominant false correlation peak. Additional techniques are available for dealing with this problem. Discrimination against incorrect measurements can be improved by comparing the measured reseau point position with the calibrated position. If the distance is above some threshold, the probability is high that the measurement is bad and should be rejected.

Another possible technique is to examine the shape of the correlation function in more detail. Correct reseau correlation functions should be fairly symmetric and have approximately a particular width. Correlation functions which are highly asymmetric and/or have a width significantly different from that which is expected indicate that measurements resulting from these correlation functions are probably bad.

An obvious way to decrease the chances of bad measurements is simply to raise the correlation detection threshold. This was tried to some extent during experimental evaluation of the system and was found to be rather ineffective. Although the number of bad measurements was reduced somewhat, the number of good measurements rejected increased significantly. In an operational system these rejected good measurements would have to be measured manually and, if a large percentage were rejected, the usefulness of the automated system would become questionable.

The problem can, of course, be avoided altogether by ensuring that reseau marks are placed on the photos in such a way that a high SNR is achieved. In general, this requires that the reseau marks be wide enough to fully modulate the film. They can also be made to have longer cross arms, which would increase the space-bandwidth product of the correlation function. This would enhance the detectability of the reseau marks. This approach could be carried farther by including some additional reseau imagery in the vicinity of the cross as part of the reseau mark. The pattern would, of course, also appear in the reference mark. This would cause the correlation function to have a stronger central peak which would enhance reseau mark detectability.

A significant result of the experimental work was the discovery that restrictions imposed by having a fixed reseau cross arm size were not as severe as had originally been expected. The reseau point measurement system was fairly tolerant of differences in photographic and reference reseau cross arm widths. It is therefore possible to select a single reference reseau mark which will permit measurement of reseau marks with a range of cross arm widths rather than just a single width.

CONCLUSIONS

The experimental work described above demonstrated the feasibility of utilizing noncoherent optical correlation in conjunction with digital computer processing and control to implement automatic reseau point measurement on an existing analytical comparator-type instrument. The outstanding performance of the experimental reseau point measurement system is due in large measure to the control and processing capabilities provided by the digital control computer. Digital filtering of output data from the optical correlator greatly enhanced the system measurement repeatability and its ability to detect reseau marks in the presence of higher-signal-level background imagery. Digital computer control of the photograph scanning motion minimizes the complexity of the optical/mechanical correlation hardware and permits easy modification of scanning parameters.

Although the experimental work was performed on a particular instrument, a range of presently available instruments could be retrofitted for automatic reseau point measurement. Analytical instruments such as the US-1, AS-11, and TA3/P1, for example, already have most of the key system components required. The optical correlation optics and A/D conversion electronics required for automatic reseau measurement on these instruments would be fairly modest additions.

To equip an existing manual monoscopic comparator for automatic reseau measurement, computer controllable servo systems would have to be added to allow the measurement stage to be driven by a digital computer. Although the experimental system used a PDP 11/35 computer, the requisite functions for automatic measurement could be performed by a microcomputer-based system. The cost of acutal digital computer hardware can, therefore, be almost negligible compared with other system components such as the comparator instrument itself and, for one-of-a-kind systems, the computer program development.

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