Measurements on Digitized Hardcopy Images

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ABSTRACT: Aerial photographs, for which pointing precisions in the *x*, *y*, and *z* coordinates are known, have been digitized with effective square apertures ranging from 6.25 μm to 100 μm. The digitized data were reproduced as hardcopies and observed on a stereoplotter in order to determine precisions of observations. A comparison of these pointing precisions with those derived from the original aerial photographs reveals the magnitude of the aperture required for digitizing to ensure that the quality of the visual observations is maintained. Systematic errors in the positions of po:·.ts observed in the images are determined by computer simulation and are related to pixel sizes. The studies indicate that visual observations to standard aerial photography are unaffected by digitizing if the pixel sizes are less than or equal to 25 μm. However, the RMS of systematic errors in the digitized data attributed to the digitizing process can be about one-fifth of the pixel size.

INTRODUCTION

TECHNOLOGY IN PHOTOGRAMMETRY is moving rapidly towards the use of digital cameras to obtain digital images, and the digitizing of aerial photographs for processing the derived data by stereocorrelation, pattern recognition, and feature detection techniques. Studies of the appropriate pixel size for digitizing to enable such tasks to be carried out have also been made. Parallel with these developments is the introduction of forward motion compensation (FMC) into aerial cameras, enabling the use of high resolution, slow speed aerial film materials for the photography. The resolution of the resulting images from such cameras is significantly higher than that derived with cameras without FMC, being on the order of 60 line pairs/mm in some cases (Meier, 1984; Zeth and Voss, 1984). Estimates were given for the measuring precisions for targets on this new generation high quality photography of approximately 1μm in the *x* and *y* directions and 1/10,000 of the flying height in height (Trinder, 1984, 1986).

With the advent of the use of digital data in photogrammetry, it is appropriate to investigate the effects of digitizing on the quality of visual observations on hardcopies of digitized images. As the image quality of photography improves, the pixel sizes of digitizing required to maintain the quality of photography must be reduced, leading to an increasing volume of digital data to be stored and processed. This paper will investigate the pixel sizes which should be used for digitizing aerial photography in order to ensure that the quality of visual observations on the digital images is not adversely affected by the digitizing process. Further, it will investigate the geometric quality of digitized images by studying the systematic errors introduced by the digitizing process.

IMAGE QUALITY OF DIGITIZED IMAGES

Funkhouser (1978) demonstrated the well known test of digitizing sector stars with apertures varying from 12.5 μm to 100 μm. He indicated that, according to sampling theory, it can be expected that, in order to resolve 5, 10, 20, or 40 line pairs/mm on digitized images, apertures of 100, 50, 25, and 12.5 μm, respectively, would be required. Konecny *et al.* (1979), however, claim that in practice the digitization of data is influenced by Moiré effects which are dependent on the phase position of sampled points in relation to the signal. They found that the equivalent photographic resolving power of a scanner system is determined by multipling the picture element size by a factor 2.5 to 3 times, which is the Kell factor. Doyle (1982) states that, to relate pixel size of an electro-optical system to photographic resolving power, 2.5 pixels (expressed as m/pixel) are required to present the same information as 1 photographic line pair (expressed as m/line pair). Using the Kell factor quoted by Konecny above, Funkhouser's estimates should be modified to read apertures of 80, 40, 20, and 10 μm are required to resolve 5, 10, 20, or 40 line pairs/mm, respectively.

Makarovic and Tempfl (1979) made a study of the relationship between pixel sizes and resolution using the concept of transfer functions. In their study, variables considered were not only the pixel size D, but also the interval Δ at which sampling of the data was made; D may be greater than, less than, or equal to Δ, but in this paper D equals Δ in all cases. The transfer function describes the fidelity of the digitized data compared with the original data for different spatial frequencies. They showed that the spatial frequencies of digitized data for which a fidelity of 50 percent is obtained would be 24, 12, and 6 line pairs/mm for sampling intervals of 12.5, 25, and 50 μm, respectively. In addition, they demonstrated that the spatial frequencies determined by sampling theory and the Kell factor are reproduced with low fidelities. This indicates that these methods of determining the most suitable aperture sizes for digitizing would overestimate the quality of image obtained. Makarovic and Tempfl (1979) estimate that, for photography with a resolving power of 40 line pairs/mm, an aperture size of 8 μm is required, whereas the Kell factor would indicate a marginally larger aperture of 10 μm is necessary.

If the scanning aperture were selected as 10 μm, the data accumulated for a 230-mm square photograph would be 5.3×10^8 pixels. It is, therefore, necessary to determine the maximum pixel size which can be used for digitizing photography in order to limit the amount of data collected, but ensure that the quality of the photography is not adversely affected.

Any processing of photography, whether it involves copying to another emulsion or digitizing using a square aperture, will cause a deterioration in the quality of the resulting hardcopy of the picture. The effects of additional processing steps can be investigated by combining the modulation transfer functions (MTFs) of the image prior to processing with that of the additional process. The approximate MTF of the digitizing procedure can be derived from the Fourier transform of a square wave function, the so-called sampling function, which is identical to that used for image movement.

An example is taken for this paper of photography with an MTF equivalent to a Gaussian spread function with a 2σ-width of 25 μm, which is typical of photography studied by Trinder (1984). MTFs of digitization are shown in Figure 1. The MTF of the original photograph together with MTFs of the images following digitization are shown in Figure 2, in which there is clearly a deterioration in quality which becomes more significant as the aperture size increases beyond 25 μm. The results of observations by Trinder (1984) indicate that for marginal re-

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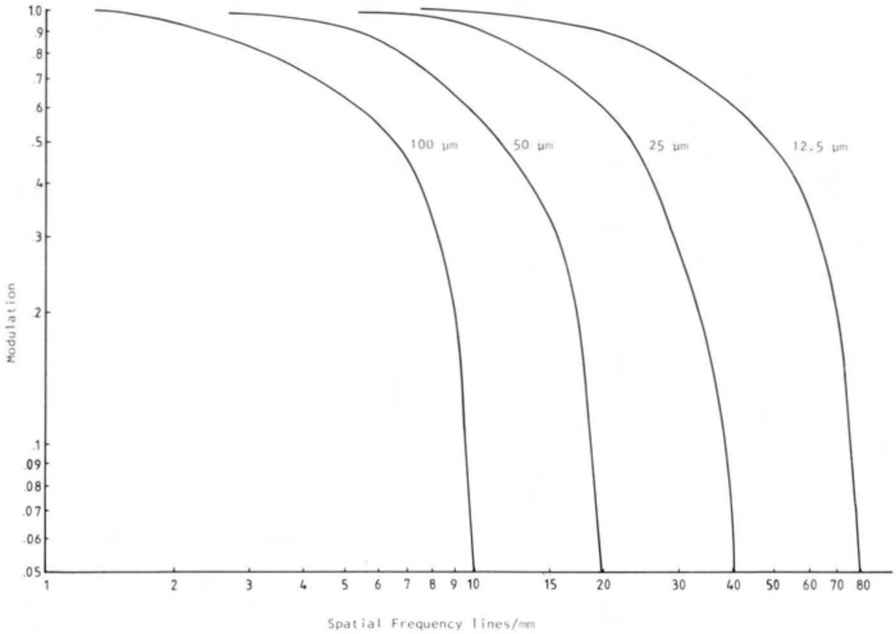


FIG. 1. Approximate MTFs of digitizing process with pixel sizes as shown on each curve.

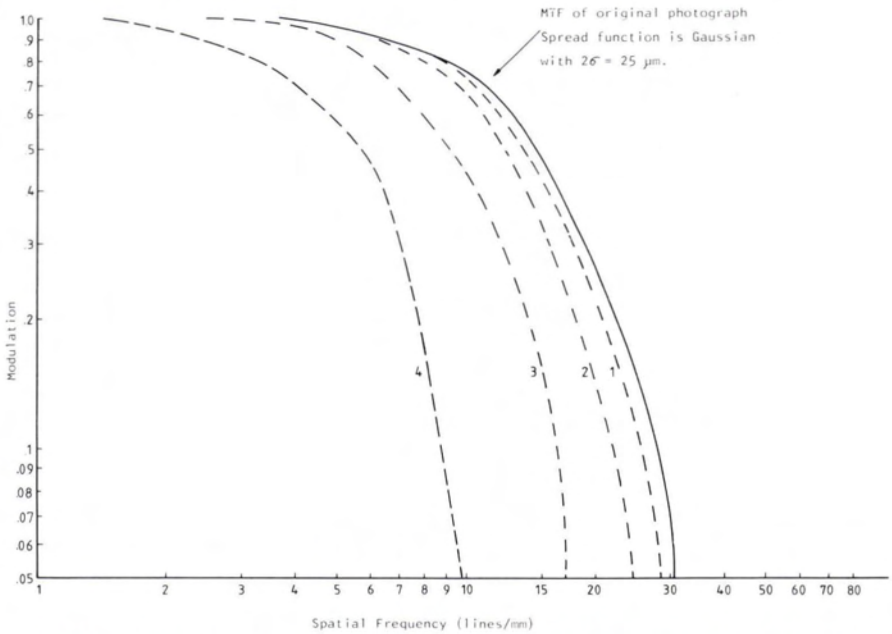


FIG. 2. MTF of original photograph shown by the solid line, and those shown by curves 1 to 4 of the hard copies of images following digitizing with apertures of 12.5, 25, 50, and 100 μm, respectively.

ductions in image quality measured by a 10 percent increase in spread function width, which is the case when an aperture 25 μm in size is used, there should be only a small deterioration in measuring precisions for observations to well defined targets. However, for apertures greater than 25 μm, there would be an increasing deterioration in measuring precisions for details on the photography, as shown by curves 3 and 4 on Figure 2. If it is required that a minimal loss in image quality should occur following digitization, aperture sizes of 12.5 μm or smaller must be used. According to Makarovic and Tempfl (1979), for example, an aperture of approximately 10 μm should be used for this photography.

STUDIES OF OBSERVATIONS TO DIGITIZED IMAGES

Konecny *et al*. (1982), who studied the effects of digitizing images with different apertures on the interpretability of details on aerial photography, found that images digitized at 25-μm intervals were considered by the observers to be the same as the originals. Interpretation was also possible for images digitized with 50- and 100-μm pixel sizes,though results were not as good as for the originals. Stereoscopy was possible even for images digitized with pixel sizes of 200 μm and 400 μm, but interpretation was affected, and contouring was not possible. Thurgood and Mikhail (1982) studied measuring precisions to targets on hardcopy images of synthesized aerial photographs with multi-pixel and single pixel targets superimposed. They obtained monocular precisions of 7 μm and 4 μm in the x and y directions, respectively, for single pixel targets, with little dependence on pixel sizes, but for multiple pixel targets, the precisions deteriorated rapidly, especially for large pixel sizes. Precisions of measurement were 7.6 μm and 5.4 μm in the x and y directions, respectively, for 50-μm pixel sizes, and 16.9 μm and 11.7 μm in the x and y directions for the 100-μm pixel size. Because the images were simulated, systematic errors in the observations could also be computed; these will be discussed later in this paper.

The study in this paper was undertaken because of the availability of a wealth of data previously obtained on pointing to targets on aerial photography (Trinder, 1984). Two pairs of overlapping photographs at scales of 1:8,000 and 1:16,000, each with images of 22 ground targets made up of five sizes of circular and three sizes of cross-type, were digitized with pixel sizes of 25, 50, and 100 μm on an Optronics Photomation, and hardcopies were subsequently produced. In addition, 5× enlargements of sections of these images were also digitized, and the hardcopies were photographically reduced so that effective aperture sizes of 6.25 μm and 12.5 μm were obtained. The hardcopies derived by digitizing with 50- and 100-μm apertures were full 230-mm format, but for those obtained with 25-μm aperture and smaller, only sections of the photographs were available because of the limited computer storage. Areas of the images obtained varied from about 120-mm square for the 25-μm aperture to 30-mm square for the 6.25-μm effective aperture size.

Pointing precisions in the x, y, and z coordinates were obtained by repeated observations on two circular and two cross-type targets on each pair of photographs oriented in a Wild A8 stereoplotter. The observation procedure was identical to that described by Trinder (1984) and Trinder (1986) and, therefore, will not be repeated in this paper. A comparison between results for circular targets, obtained on non-digitized photographs in this earlier study, and those for digitized photographs with different apertures, can be made directly in Figure 3 for x and y observations and Figure 4 for height observations. In these figures the overall precisions for non-digitized photographs from the previous study are shown by solid line and those from the digitized images by symbols indicated in the legend.

Predictably, for the apertures of 6.25, 12.5, and 25 μm, there was no significant deterioration in the measuring precision in the x and y directions. However, for 50- and 100-μm apertures, the precisions of x and y measurement were erratic but generally deteriorated by 10 percent and 20 percent, respectively, for 50- and 100-μm aperture sizes. This deterioration is less than might have been expected considering the appearance of some of the photographs, as shown for example in Figure 5. Some targets on the images digitized with an aperture of 100 μm were almost nonexistent and could not be observed; the results in Figures 3 and 4 only reflect precisions for targets which were visible. The stereoscopic mode of observations would have assisted the observer in making these measurements in cases where one image of the stereopair was not well defined. There was no apparent difference in the quality of the observations for circular and cross-type targets.

The ability in stereoscopic observations to, as it were, smooth out some of the effects of dissimilarities of image qualities between the two photographs of overlapping pairs was demonstrated by Julesz (1965). He found that, in stereoscopic observations of random dot images in which one was blurred and the other sharp, the fused image appeared to be sharp. For the study described in this paper, the absence of portions of the target in one image only marginally affected the pointing precision. The results in this test tend to agree with the experiences on interpretability of Konecny *et al.* (1982), referred to previously.

For the stereoscopic height precisions given in Figure 4, which are expressed as ‰ of the projection distance, the pointing precisions follow a similar pattern in terms of pixel sizes to those obtained for the x and y observations. The overall quality of the results is somewhat better than those shown in Trinder (1986) because the observer had gained more experience in stereoscopic observations, but the pattern is still the same. A similar deterioration occurred in the stereoscopic height precisions as the pixel size increased beyond 25 μm.

SYSTEMATIC ERRORS IN DIGITIZED IMAGES

Systematic errors in the digitized images as a result of the digitization process may result from two sources.

- *Source 1* — Errors in the mechanical construction of the scanner digitizer.
- *Source 2* — Shifts in the position of points because of the location of the target within the pixel pattern.

On Source 1 errors, Optronics specifications for the Photomation state that the equipment is calibrated to precisions of ±2 μm/cm in read and write mode and overall ±10 μm anywhere on the film in write mode. For the full format images derived by digitizing with apertures of 50 and 100 μm for this study, the precision of any target is, therefore, assumed to be on the order of 10 μm or better.

To test the effects of Source 2 errors in the digitized images, coordinates referred to the fiducial center were observed on an analytical platter for all 22 targets recorded on the original photographs of the two sets of photography. The fiducial mark coordinates derived for the original photographs were then used as fixed data for the inner orientation by affine transformation for a similar set of observations on the digitized photographs. Digitized photographs, derived using pixel sizes of 50 and 100 μm only, were observed because of the absence of fiducial marks on the sets of digitized photographs derived with smaller pixel sizes. Differences between the image coordinates on the original and digitized photographs were then computed, and a root mean square (RMS) error was computed from the differences.

Systematic errors expressed by the root mean square errors varied significantly, with some being as large as 68 μm for the 100-μm pixel size. However, after deleting the unusually large errors, systematic errors were on the order of 15 to 17 μm for the 50-μm pixel size and 31 to 33 μm for the 100-μm pixel. These errors are significantly larger than the Source 1 errors referred to above. Similar, though not as large, errors were reported by Thurgood and Mikhail (1982) in their study on accuracies of targets on digitized photographs, although they believed the errors were caused by instabilities in the film-writer, i.e., Source 1.

To investigate the magnitude of Source 2 errors, a simulated study was carried out on the digitization process of features. Digitizing determines a measure of the total intensity of the section of the photograph contained in the area of the pixel, for a particular pixel location. To determine the intensity value after digitizing by computation, for a particular set of pixel positions and target intensity distribution, the intensity profile of the target being studied must be scanned with a pixel of appropriate size. The volume, for a two-dimensional object, or area, for a one-dimensional object, enclosed by the pixel dimensions and the intensity profile of the object then gives the required intensity value. To simplify the problem, a one-dimensional object was scanned by a pixel, as shown in Figure 6. Furthermore, because the pixel will be located in random unknown positions with respect to the intensity of the target, it is necessary to scan the target with the pixel in different starting positions in order to determine the dependence of the intensity of the digitized image on pixel position. Typical causes of systematic errors in digitized images are demonstrated in Figure 7.

The computation involved selecting targets ranging in sizes from 50 to 65, 100, and 200 μm. Convolutions were computed of these targets and Gaussian spread functions with 2 σ-widths of 10, 25, and 40 μm in order to give typical target intensity profiles that would be recorded on photographs. As mentioned earlier, a Gaussian spread function with 2 σ-width of 25 μm is typical of the quality of photography used for the earlier part of this study. The resulting profile was then scanned with aperture widths of 12.5, 25, 50, 100, and 200 μm, and the area enclosed by the target profile and aperture dimensions was

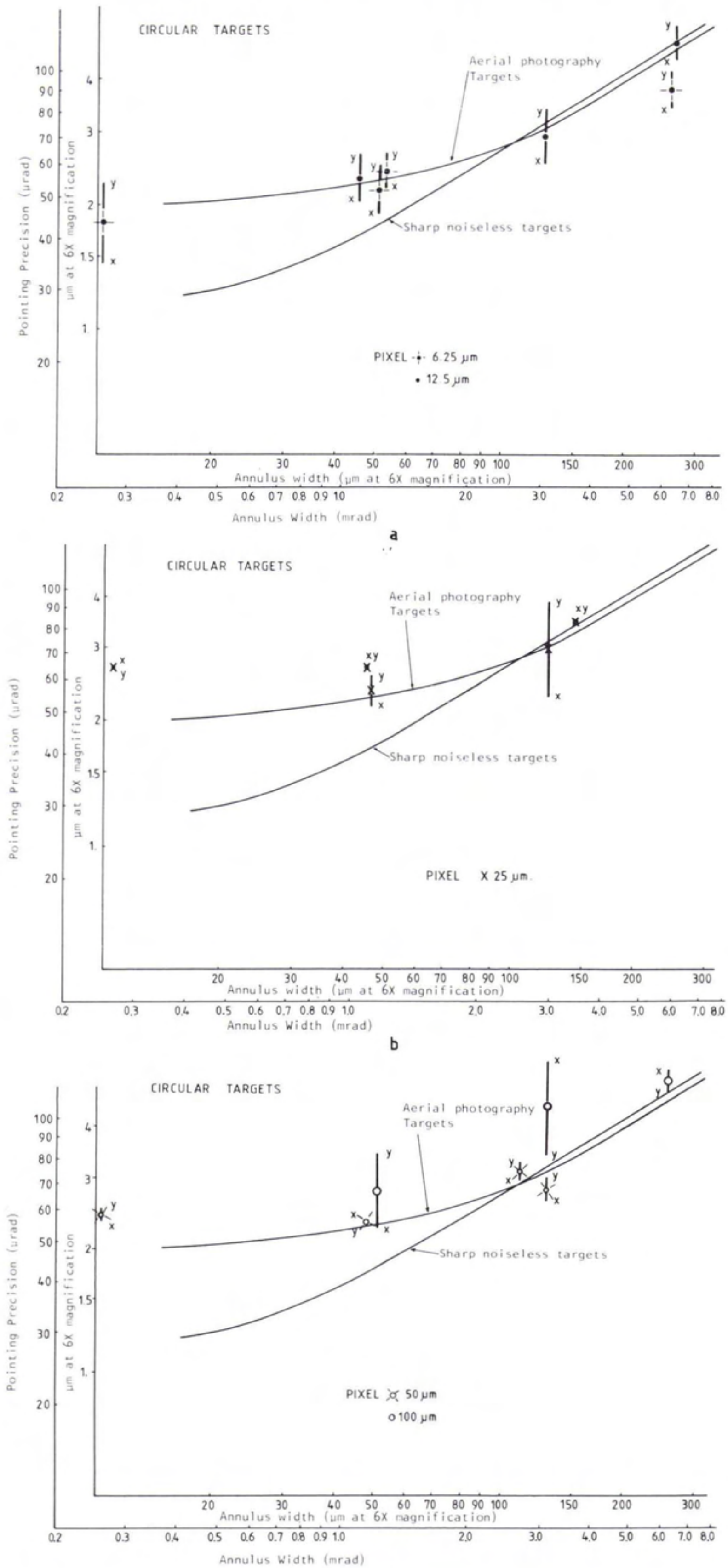
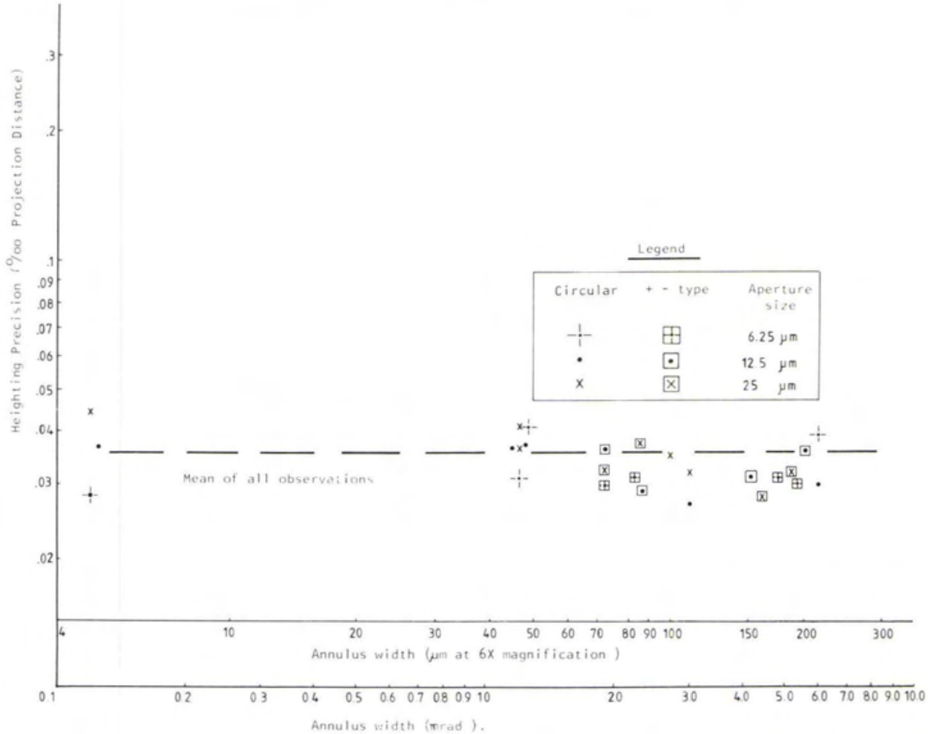
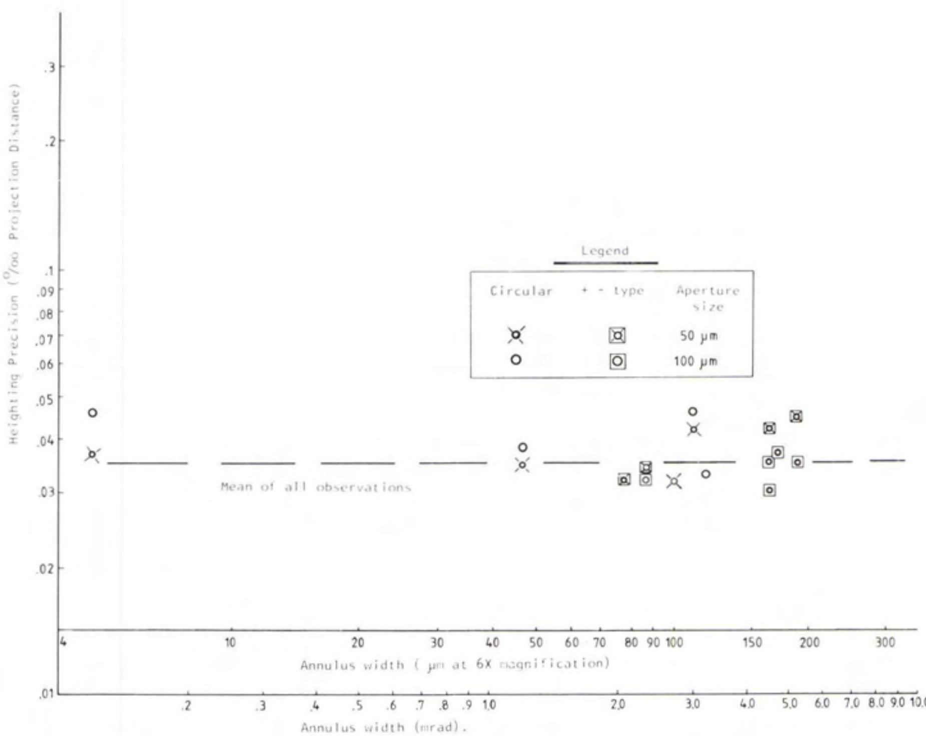


FIG. 3. Precisions of pointing for circular targets on hard copies of images digitized with (a) 6.25- and 12.5-µm pixels, (b) 25-µm pixels and, (c) 50- and 100-µm pixels. Annulus size between the edge of the measuring mark and target is shown on the abscissa scale in both circular measure (mrad) and µm for observations at 6× optical magnification, while pointing precision is shown on the ordinate scale. The range of precisions between the *X* and *Y* directions is shown by appropriate symbols.



a



b

FIG. 4. Precisions of height measurement on circular and +-type targets measured as a proportion of the flying height for (a) pixel sizes of 6.25, 12.5, and 25 μm; and (b) 50 and 100 μm.

computed. The resulting profile was then plotted in a similar fashion to those shown in Figure 7. In addition, successive displacements, each of one-tenth of the aperture size, were introduced into the position of the aperture, and the target was rescanned. For each target, therefore, ten separate scans were obtained. Estimates of where an observer would measure as the center of the target on the "digitized" profiles of the simulated targets were generally made to the pixel for which maximum intensity was recorded, or in the middle of two pixels if they had the same or nearly the same intensity. There did remain some uncertainty in some cases as to where the observer might measure to the target. Because the center of the target was always known in the computation, systematic errors in the digitized targets could then be determined from the difference be-

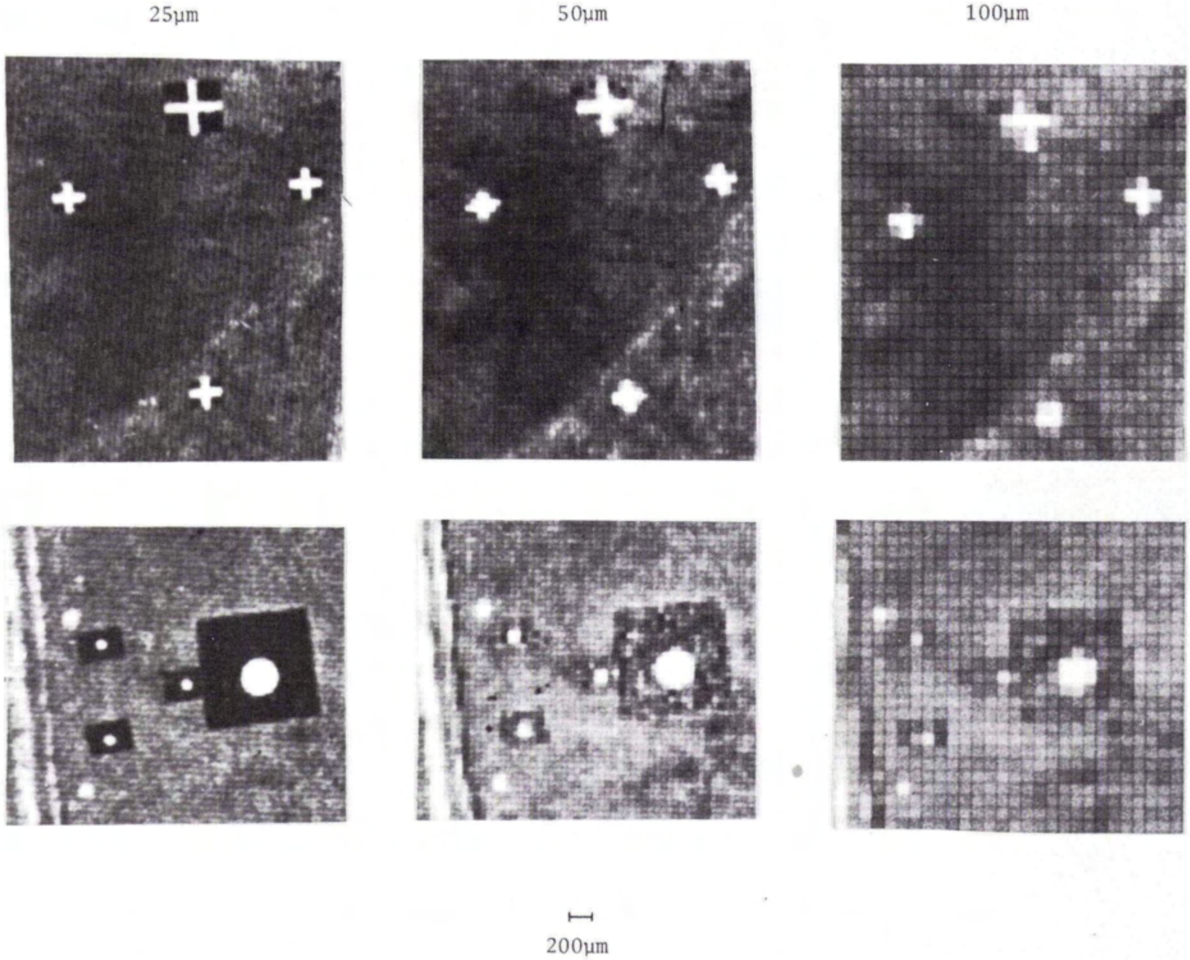


FIG. 5. Typical examples of images of small targets following digitizing with apertures as shown.

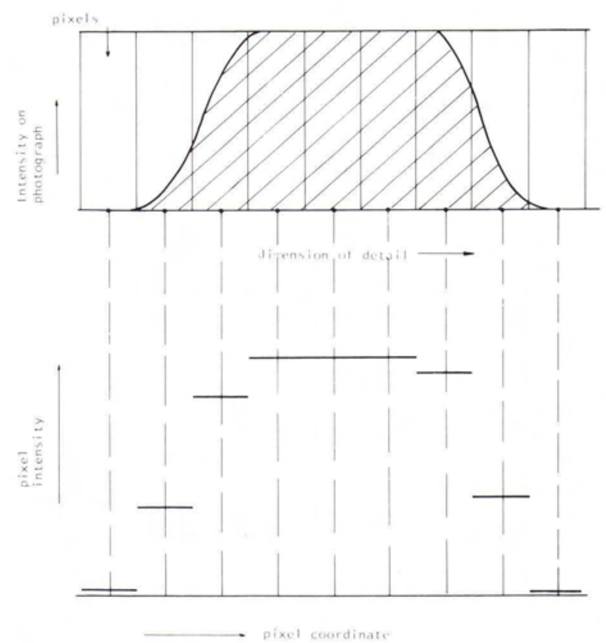


FIG. 6. Simulation of digitizing process by scanning the intensity profile of a target. Pixel intensities resulting from this process are also shown.

tween the position estimated by an observer and the correct center.

In Table 1 are shown the estimated root mean square errors in the positions of the digitized targets of sizes 50 to 200 µm for different image qualities, expressed by the 2 σ-width of the spread function and pixel sizes from 12.5 µm to 200 µm. Because the errors were independent of image quality, systematic errors for the overall RMS values for each pixel size can be expressed by the simple expression

> RMS error in target position = 0.18× pixel size, unless the pixel size approaches that of the target, in which case the error will be even greater.

Referring again to the systematic errors obtained in the observations on the digitized photographs, the fiducial marks on the digitized photographs as well as the targets would be subject to systematic errors. On the Wild photography observed, the fiducial marks are 65 µm in diameter. According to the above formula, systematic errors for such points would be 8 µm for a 50-µm pixel and substantially more for 100-µm pixel; i.e., on the order of 25 µm. Therefore, estimated RMS errors for photography scanned by 50-µm and 100-µm pixel sizes caused, respectively, by the errors in fiducial mark locations (8 and 25 µm), observation errors (3 and 3 µm), target positions (8 and 22 µm), and the Photomation (5 and 5 µm) are 13 µm and 33 µm, respectively. These values agree well with the RMS of systematic errors actually obtained on the aerial photography.

Errors of this magnitude can degrade the geometric quality of the photography very significantly. It is, therefore, clear that, if precise measurements are to be made on the photography, even a 25-µm pixel size may be too large because it could introduce an error of about 4 µm into detail positions. If digitized photography is to be used for stereocorrelation, the RMS error in elevations based on parallax measurements would be 2.4

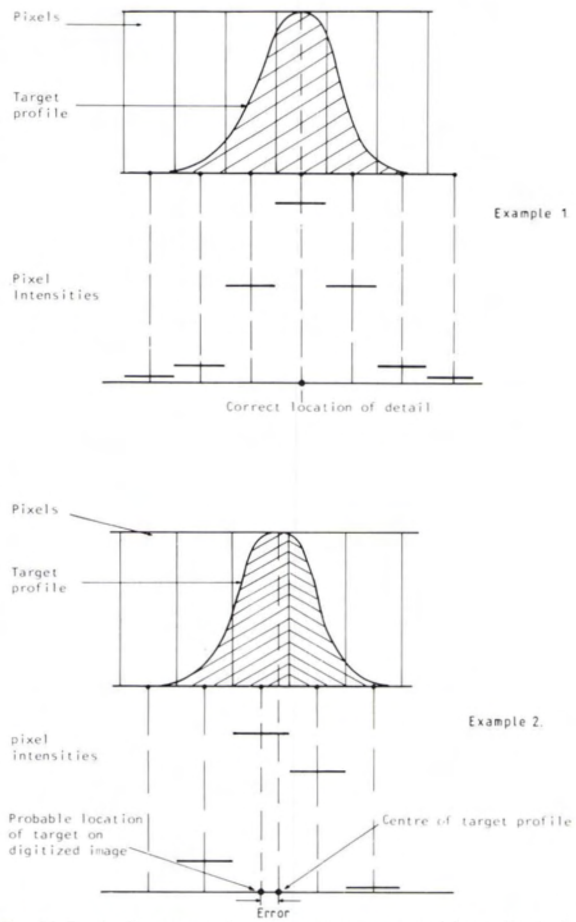


FIG. 7. Typical causes of systematic errors. In Example 1, the pixel distribution is symmetrical with respect to the target intensity, and, therefore, no systematic error in the location of the target will occur. In Example 2, the pixel distribution is asymmetric with respect to the target, and, hence, an error in the location of the target will occur.

TABLE 1. RMS ERROR (μm) IN TARGET LOCATION FOR TARGET SIZES AS SHOWN, PRESENTED IN TERMS OF PIXEL SIZE AND IMAGE QUALITY PARAMETER 2 σ.

Target size (μm)		50			100			200		
Spread function	2σ(μm)	10	25	40	10	25	40	10	25	40
Pixel size (μm)										
12.5		2.4	2.4	2.3	2.0	2.3	2.3	—	—	—
25		3.8	4.2	4.6	3.3	2.2	6.9	4.6	4.0	5.4
50		10.9	10.7	10.9	9.1	7.9	7.9	9.1	9.1	7.8
100		—	—	—	21.7	21.7	21.7	18.3	19	18.3
200		—	—	—	—	—	—	43.5	43.5	43.5

times the RMS of detail coordinates for wide angle photography. This would amount to 5.4 μm and 9.6 μm, respectively for, 12.5-μm and 25-μm pixel sizes. These figures are much larger than, for example, the precision of about 1 μm for target location by correlation of digital images reported by Forstner (1984). The influence of pixel size on such computations must, therefore, be noted and the appropriate size selected on the basis of the geometry required from the digital data. Considering the estimates of appropriate pixel sizes by Makarovic and Tempfl (1979) and the errors in geometry of the photograph brought about by the digitization, pixel sizes of 10 μm or less must be considered as necessary for photogrammetric operations.

CONCLUSIONS

The results reported in this paper indicate that, for operations in photogrammetry such as pointing observations and interpretation tasks, a pixel size of 25 μm for digitizing photographs is adequate if a marginal reduction in precision can be tolerated. However, even this pixel size will result in a large data storage problem if complete photographs are to be digitized. Of more serious concern, however, are the systematic errors which result from digitizing caused by the location of the target in the pattern of pixels. RMS errors introduced by this error are on the order of 0.18× pixel size. RMS errors of 4 μm in detail position and 10 μm in elevation can be expected on photography digitized with pixel sizes of 25 μm. If the precision of geometry of photography is to be maintained, pixels size of 10 μm or less must be chosen.

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