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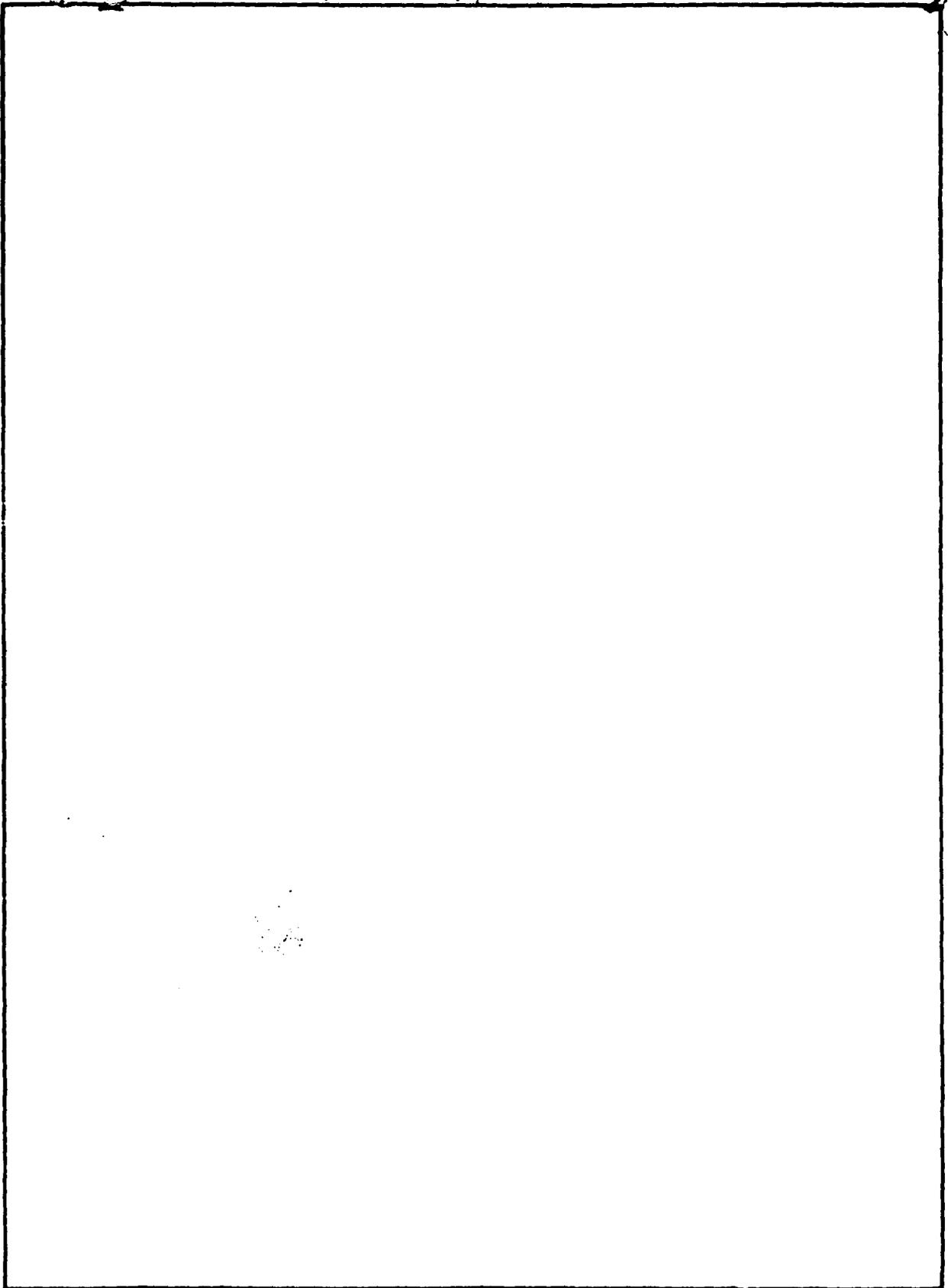
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MENSURATION TESTS USING DIGITAL IMAGES

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ABSTRACT

Digital image files were written on photographic film using 25, 50, and 100 micrometer pixels. The resulting images were then measured monoscopically and stereoscopically. Measurement precisions associated with images having 25 and 50 micrometer pixel sizes were comparable. 100 micrometer pixel size had an adverse effect on measurement precision.

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INTRODUCTION

Digital images are slowly becoming more common in the photogrammetric community. Sometimes images are acquired in digital form as, for example, multispectral scanner images. Other times, photographs may be digitized to permit digital image processing or for image transmission. Whether originally digital or digitized, analog presentations of digital image files (which are called digital images) typically contain a distinct block structure associated with individual picture elements or pixels. The main objective of this paper is to determine the effect of such structure, if any, on mensuration tasks.

Two experiments which examine how various parameters characteristic of digital images, affect the capability to photogrammetrically exploit them are described. In one experiment a stereo pair of photographs having reseau grids was digitized and reimaged several times. The reseau intersections were measured monoscopically and stereoscopically on both the original images and derived digital images. In the second experiment a series of digitally synthesized aerial photographs were measured to evaluate originally digital images.

MENSURATION OF DIGITIZED PHOTOGRAPHS

Two overlapping mapping quality aerial photographs taken near Phoenix, Arizona were selected for the experiment. A test area was then identified on both photographs. The test area is about 8 x 8 cm square on each photograph.

The test area on each photograph was digitized three times with scanning apertures of 12.5, 25, and 50 μm , using an Optronics drum microdensitometer. Following digitization, each digital image file was reimaged using the same Optronics device. Images digitized at 12.5 and 25 μm were reimaged at 25 μm pixels, while the 50 μm digitized data was reimaged with 50 μm pixels. The selection of scanning and reimaging apertures was dictated by the Optronics equipment. The equipment digitizes at 12.5, 25, and 50 μm and writes 25, 50 and 100 μm .

The result of this process was four sets of stereo pairs. The original photographs are referred to as the host images, (H). The three sets of stereo pairs at digitized 12.5, 25, and 50 μm are referred to as (A), (B) and (C), respectively.

The reseau marks in the test area are arranged to form a staggered grid with a nominal spacing of one centimeter. Each of the two images of the test area contains 64 (8 rows and 8 columns) reseau intersections, which were used for measurements. It should be noted that the reseau intersections cannot be viewed in stereo.

All the measurements, both monoscopic and stereoscopic, were made by a single person using a Bendix AS11-B1 Analytical Stereo-Plotter. ~~The observer was a~~ photogrammetrist skilled in the use of the plotter. No specific pointing procedures were imposed on the observer.

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MONOSCOPIC MEASUREMENTS

The measurements were first screened for blunders. We will denote the left and right images of each pair by the subscripts, 1 and 2 respectively. Following this screening there were measurements for the following reseaus: 63 on images A_1 and A_2 , 61 on image B_1 , 62 on image B_2 , 29 on C_1 and, 39 on C_2 . The reduced amount of data for images related

to stereopair C (the 50 μm case) resulted from the circumstance that many of the reseau intersections were so degraded that they could not be measured.

Coordinates measured on the digitized images were then transformed into the measurement coordinate system of the corresponding host image. A linear affine model was used for this purpose. This model was selected because it compensates for a slight rectangularity present in digital image pixels as well as a slight skewing caused by small systematic errors in alignment of adjacent rows of pixels.

The X residuals from the adjustment of A_1 to H_1 were combined with the X residuals from the adjustment of A_2 to H_2 and a sample standard deviation was computed. A similar procedure was performed for the Y residuals. Likewise, the same computations were performed for B to H and C to H. These results are shown in Table 1 under the heading "Pooled Standard Deviation."

The pooled standard deviations contain the combined noise from host and digitized image measurements. Because of the constraint on image orientation which was enforced prior to measurement, these noise components are expected to combine according to the model shown as Equation 1. In the equation σ_P is the pooled standard deviation, σ_H is the standard deviation of the host image measurements, S is the adjustment scale factor (shown in Table 1) and σ_D is the standard deviation of the digitized image measurements. The equation may be applied to either coordinate.

$$\sigma_P^2 = \sigma_H^2 + S^2 \sigma_D^2 \quad \text{Eq. 1}$$

The available data does not permit the pooled standard deviation to be reliably factored into the desired components. However, photogrammetrists who have experience measuring similar reseau grids estimate that $\sigma_x = 5 \mu\text{m}$ and $\sigma_y = 8 \mu\text{m}$ might be expected for the host image measurements. With this information, Equation 1 was used to estimate the standard errors for the digitized image measurements shown in Table 1.

Table 1. Precision Data for Monoscopic Measurement.

Adjustment By Stereo Pair	Sampling		Scale (S)	Pooled Standard Factor Deviation		Est. Std. Dev. For digitized Image	
	Read	Write		σ_x	σ_y	σ_x	σ_y
A -H	12.5 μm	25 μm	1/2	6 μm	12 μm	7 μm	15 μm
B -H	25	25	1	8	13	6	10
C -H	50 μm	50 μm	1	12 μm	13 μm	11 μm	11 μm

The data show no strong dependence between measurement precision and pixel size. If precisions for the host image measurements were correctly estimated, the measurements on digitized images were three or four micrometers noisier than the host image measurements. The added noise could be caused by pixel structure or by other factors, such as photo read and photo-write distortions, film distortions, and reduced image resolution. In the authors' judgement, the other factors present more plausible explanation for any additional measurement noise in the digitized images than the pixel structure factor.

STEREO MEASUREMENTS

Stereoscopic measurements were also made on the host pair and on digitized pairs A and B. Stereo measurements from pair C, while desirable, were not obtained for lack of time.

Once a stereo model was established, the observer visited a preselected reseau intersection on photograph 1 of the pair. The measuring marks were then positioned "on the ground" at the reseau intersection and model coordinates recorded. On the host pair a total of thirty one sets of model coordinates were collected this way (every other reseau intersection was measured to conserve instrument time). Prior to removing the images from the plotter, the instrument settings were recorded so that the stereo-model could be reestablished.

The plan was to use the established instrument settings for the host pair also with the digitized stereo pairs. In this way, all measurements would be referenced to the same coordinate system. However, because of distortions in the digitized images (differential x-y scaling and non-perpendicularity), the models formed this way were not parallax free. Therefore, the instrument settings for each digitized stereo pair had to be adjusted slightly. As a result, slightly different model coordinate systems were established for each stereo pair of photographs.

Since each of the three sets of stereo measurements were in slightly different coordinate systems, a three dimensional similarity transformation was performed to bring the model coordinates for the digitized images into registration with coordinates from the host stereo-model. All applicable model coordinates were used in these transformations. The calculated transformation residuals showed systematic trends in the horizontal components which are characteristic to scale errors. After some investigation, the observed systematic trends were linked to known rectangularity of pixels which is characteristic of the digitized imagery. The corrections were applied to the residuals to remove the trends.

Sample standard deviations computed using the trend corrected residuals are shown in Table 2. These results seem to indicate that digitization effects were not of primary importance to stereoscopic pointing capability.

Table 2. Precision Data for Stereoscopic Measurements.

Residual Source	Sample Standard Deviations (μm)		
	σ_x	σ_y	σ_z
Transformation From - To			
A-H	11	12	13
B-H	12	12	16

MENSURATION OF SYNTHETIC PHOTOGRAPHS

The second experiment involved the measurement of synthetic aerial photographs. The image synthesis capability, described in references 1 and 2, was used in the following manner. An orthophoto of an area (approx. 5.3 km by 8.3 km) near Ft. Sill, Oklahoma, USA, was digitized using a sample interval of 4.8m on the ground. Then each pixel in the digital orthophotograph was associated with an elevation value from a specially prepared digital terrain elevation model. The combined elevation and image data was then processed using the photograph synthesis computer programs to construct digital image files having the desired perspective geometry. This process is analogous to inverse digital orthophoto production. Synthetic photographs generated in this manner have the desirable properties that object space is perfectly known and that image geometry is subject to rigid control.

For this experiment, digital image files for three stereo pairs of synthetic photographs (A, B, & C), of the Ft. Sill site were constructed. Each stereo model imaged the same terrain and had a base to height ratio of 0.69. All photographs are perfectly vertical relative to the horizontal datum. The three sets of files were different from one another in resolution. The average ground separation between adjacent image pixels was 2.4 meters, 4.8 meters and 9.6 meters for photographs of stereo pairs A, B, and C respectively. Each digital image file was then written to film three times using the three different pixel sizes of 25 μm , 50 μm and 100 μm to yield a total of 9 synthetic stereo digital images. These test photographs are described in Table 3.

Table 3. Synthetic Stereo Photography for Mensuration.

Stereo Pair	Pixel Size	Photograph Resolution*	Photograph Scale
A100	100 μm	2.4 meter	1:24000
A050	50	2.4	1:48000
A025	25	2.4	1:96000
B100	100	4.8	1:48000
B050	50	4.8	1:96000
B025	25	4.8	1:192000
C100	100	9.6	1:96000
C050	50	9.6	1:192000
C025	25 μm	9.6 meter	1:384000

*Average ground Distance separating adjacent pixel centers.

Two types of targets were placed in the synthetic photographs to facilitate measurement. One type of target was a cross shaped figure "painted" on to the digital terrain. Figure 1 shows the marking scheme. Since control point markings were processed through the synthesis algorithm as ordinary ground surface features, this marking method is analogous to paneling control points derived by ground survey prior to flying mapping photography. Since interior and exterior orientation of synthetic images is defined and therefore precisely known, accurate image coordinates can be computed directly from the recorded control coordinates. In general the computed image coordinates do not coincide with image pixel centers.



Figure 1 Ground Model Modification Scheme for Marking Control Points (Each square represents a brightness value stored in the ground description).

The other targets were specially darkened pixels on photograph two of the stereo pairs. These targets are analogous to artificially (or PUG) marked points.

Both types of targets were controlled. That is, the image space and object space coordinates of each target were recorded during image synthesis and may be regarded as perfectly known.

The Targets were placed to fall on flat and sloping terrain as well as image areas with sparse image detail and plentiful image detail. Additionally two settings of viewing magnification were used in the measuring process. These four descriptive factors were associated with targets. These factors are summarized in Table 4.

Table 4. Target Factors.

FACTORS	Level 1	Level 2
1. Target Type	single pixel target	cross target
2. Relief	flat terrain	sloping terrain
3. Contrast	sparse image detail	plentiful image detail
4. View Magnification	7X	14X

In all 32 targets were defined on each stereo pair; two targets of each possible combination of Target Factors. By design, the same targets have the same ground location in each stereo pair. In this sense, the same targets appear in each stereo pair.

Three ~~skilled~~ photogrammetrists measured the identified targets on each of the stereo pairs using OMI-Nistri TA3P stereo comparators. In all, 864 target measurements (32 targets/stereo pair x 9 stereo pairs x 3 observers each pair), were collected.

All measurements associated with a single stereo pair by an observer were executed in a measuring session. Sessions were constrained to begin and end in the same work shift. Each observer conducted nine sessions, one for each of the nine stereo pairs.

At the beginning and end of each measuring session, four or five specially marked "fiducial" pixels were measured on each synthetic photograph. These fiducial measurements were used to establish the transformation from the comparator coordinate system to the image coordinate system. The redundant measurements were also used to confirm stability of the comparator setup during the measuring session as well as precision associated with centering the measuring mark on selected pixels.

Each of the thirty two selected targets were stereoscopically measured in each session. The execution of a single stereo measurement was a relatively complex process which produced five separate sets of (X, Y) coordinates. First, the measuring mark associated with photo 2 of the pair was monoscopically centered on the target to be measured. Once this was accomplished, the stage for photo 2 remained fixed for the remainder of the measurement sequence. Next, the measuring mark for photo 1 was positioned using stereo perception to position the mark "on the ground" and stage coordinates (for both comparator stages) were recorded. Photo 1 measuring mark was moved off target, repositioned, and stage coordinates were again recorded. Then, dove prisms in the optical train were adjusted so that the imagery appeared in pseudo stereo. The photo 1 measuring mark was positioned again "on the ground" and stage coordinates recorded. Finally, the photo 1 measuring mark was decentered, recentered, and stages coordinates again recorded. Thus, one (X, Y) coordinate pair was recorded for each point on photo 2 and four (X, Y) coordinate pairs recorded the stereo transfer to photo 1.

All measurements were transformed into the camera system then analyzed for measurement accuracy and precision. Accuracy measures reflect the agreement between measured target coordinates and apriori known target coordinate which are known from image synthesis. Precision indicates repeatability either by single observer or between observers.

Each fiducial pixel was measured twice by each observer. These measurements were analyzed for precision associated with centering on a pixel by a single individual. An average precision (68% confidence level) of 2.6 μm in either the x or y coordinate component was found to best estimate this quantity. Potential factors which might influence this precision are pixel size, the observer, the coordinate component (x, y), and comparator stage. Table 5 shows precision computed as a function of these factors. The differences in precision shown in the table have little practical statistical significance.

Table 6. Pixel Centering Precision (The capability of an observer to repeat himself).

SOURCE	LEVEL	dof*	rms
TOTAL	ALL	504	2.6 μm
PIXEL SIZE	100 μm	168	3.3
	50 μm	168	2.2
	25 μm	168	2.0
OBSERVER	# 1	168	2.9
	# 2	168	2.1
	# 3	168	2.7
COORDINATE (STAGE)	X(1)	126	2.8
	Y(1)	126	2.8
	X(2)	126	2.5
	Y(2)	126	2.1 μm

* dof is statistical degrees of freedom in rms computation

Pixel size and target type were found to significantly affect precision and accuracy of monoscopic measurements. Table 6 shows accuracy and precision for each target type and each monoscopically measured synthetic photographs. Additionally, pooled accuracy and precision figures for digital images with 100 μm pixels and smaller pixels are shown. The accuracies are the result of root sum squared computations from measurement errors. Precisions were computed by introducing a mean error (measurements by 3 observers) correction at each target.

Precision for single pixel targets measure the repeatability between different observers associated with centering on a pixel. The precision value for the X component is significantly larger than that associated with an observers ability to repeat himself.

Table 6. Precision and Accuracies Associated with Monoscopic Measurements of Synthetic Photographs.

STEREO PAIR	SINGLE PIXEL TARGETS				"CROSS" TARGETS			
	Precision		Accuracy		Precision		Accuracy	
	x	y	x	y	x	y	x	y
A (100 μm pixels)	7.5 μm	3.9 μm	9.1 μm	6.5 μm	14.2 μm	11.9 μm	17.7 μm	16.4 μm
A (50 μm pixels)	7.2	3.2	7.9	4.4	9.4	6.8	10.4	7.0
A (25 μm pixels)	5.9	3.7	13.8	4.9	5.1	4.7	12.3	4.7
B (100 μm pixels)	7.5	4.4	11.4	9.0	14.8	15.6	26.9	25.1
B (50 μm pixels)	5.2	4.6	7.4	6.6	5.5	6.4	12.0	11.6
B (25 μm pixels)	6.3	3.0	9.0	3.8	5.4	3.5.	10.2	6.0
C (100 μm pixels)	7.4	5.5	32.4	8.8	20.8	4.9	35.0	19.5
C (50 μm pixels)	5.7	3.6	5.4	4.1	9.4	6.4	12.9	11.4
C (25 μm pixels)	6.6	4.3	7.6	4.5	9.0	4.0	9.4	5.4
All 100 μm pixels	7.5 μm	4.7 μm	20.5 μm	8.2 μm	16.9 μm	11.7 μm	27.5 μm	20.6 μm
All 50x25 μm pixels	6.2 μm	3.8 μm	8.9 μm	4.8 μm	7.6 μm	5.4 μm	11.3 μm	8.2 μm

The accuracy values for the single pixel targets reflect measurement precision plus errors introduced by film distortion and metric infidelity associated with the photo write device. Clearly, these additional error sources are particularly important when 100 μm pixels are used.

Measurements of the larger sized cross targets have lower precisions and accuracies than for single pixel targets. Measurement precision is particularly low for crosses on the 100 μm pixel sized images. Both accuracy and precision are probably reduced due to image distortions associated with image synthesis.

Accuracy and precision data were also computed for measurement by stereo transfer to photograph one of the stereo pair. This data is shown in Table 7. The most striking fact associated with the data in Table 7 is that much more noise is associated with the process of stereo transfer than that of monoscopic pointing. The second most significant result is that target type affects precision differently in stereo transfer than in monoscopic pointing. We should note that the single pixel targets did not appear in

stereo. Therefore observers had to rely on unrelated image detail in the neighborhood of the target to position the measuring mark. On the other hand, cross targets, like other ground detail were viewed in stereo. For this reason the large noise component is associated with single pixel targets rather than the cross targets. Measuring precision associated with cross targets is essentially the same in both monoscopic and stereoscopic measurement. But, precision associated with stereo transfer for single pixel targets is much lower than either stereo transfer with cross targets or monoscopic measurement of the single pixel targets.

Table 7. Precisions and Accuracies Associated with Stereoscopic Transfer Using Synthetic Photographs.

Stereo Pair	Single Pixel Targets				"Cross" Targets			
	Precision		Accuracy		Precision		Accuracy	
	x	y	x	y	x	y	x	y
A (100 μm pixel)	152 μm	91 μm	187 μm	101 μm	32 μm	15 μm	35 μm	20 μm
A (50 μm pixel)	22	23	24	24	11	12	12	12
A (25 μm)	13	18	13	20	6	9	7	10
B (100 μm pixel)	64	27	68	30	42	18	47	26
B (50 μm pixel)	16	9	15	12	7	10	13	14
B (25 μm pixel)	15	13	13	13	7	8	8	10
C (100 μm pixel)	40	12	45	13	26	9	31	20
C (50 μm pixel)	15	12	18	11	11	8	15	11
C (25 μm pixel)	12	10	13	10	7	8	8	11
All 100 μm pixel	98	55	118	61	34	14	39	22
All 25x50 μm pixel	16 μm	15 μm	17 μm	16 μm	8 μm	9 μm	11 μm	11 μm

Each target was also associated with levels of the four factors shown in Table 4. Except for target type these factors did not greatly affect precision of monoscopic measurements. They do, however, affect precision of stereo transfer in a rather complex way. The observed precision of stereo transfer depends greatly on combinations of (interactions between) the factors as well as the factors of display resolution and pixel size. Table 8 shows some of these interactions as measured on 100 μm pixel sized images. The 100 μm pixel was selected because the effects are largest in magnitude. Similar phenomena are present in the other images. From the table it is clear that some factor combinations are preferable to others.

In the preceding analysis, precision was expressed in micrometer units at image scale. Since synthetic photographs with a wide range of image scales were measured, precision data must be scale normalized to determine capability to extract ground information. Table 9 shows the precision data from Tables 7 and 8 normalized by simple ratio to an image scale of 1:96000. From this data it is clear that ability to extract information increases with photograph resolution. For monoscopic pointing, it appears that large pixel sizes are preferable to small pixel sizes. For stereo transfer, on the other hand, the 50 μm pixel sizes appears to be preferable.

Table 8. Precision of Stereo Transfer Using Digital Images with 100 μm Pixels as a Function of Factor Combinations

FACTOR 1	FACTOR 2	Precision		Factor 2	Precision	
		x (μm)	y (μm)		x (μm)	y (μm)
Single Pixel Target	Sloping Relief	125	69	Flat Relief	60	14
Cross Target	" "	35	37	" "	32	15
Single Pixel Target	Poor Contrast	130	76	Good Contrast	49	17
Cross Target	" "	38	14	" "	28	14
Single Pixel Target	14X Magnification	126	70	7X Magn.	57	35
Cross Target	" "	33	13	" "	34	15
Sloping Relief Target	Poor Contrast	120.2	68	Good Contrast	49	18
Flat Target	" "	62	37	Good Contrast	29	13
Sloping Target	14X Magnification	121	70	7X Magn.	48	20
Flat Target	" "	50	23	" "	47	32
Poor Contrast	14X Magnification	122	70	7X Magn.	56	33
Good Target	" "	47	13	" "	32	18

Table 9. Precision Data Scale Normalized to 1:96000.

STEREO PAIR	RESOLUTION	PIXEL SIZE	ORIGINAL SCALE	NORMALIZED		PRECISION	
				MONOSCOPIC (all targets)		STEREO-TRANSFER Dot	
				x	y	x	y
A100	2.4 meter	100 μm	1:24000	3 μm	3 μm	38 μm	23 μm
A050	"	50	1:48000	5	4	11	12
A025	"	25	1:96000	6	5	13	18
B100	4.8 meter	100	1:48000	6	6	32	14
B050	"	50	1:96000	6	6	16	9
B025	"	25	1:192000	12	7	30	26
C100	9.6 meter	100	1:96000	16	6	40	12
C050	"	50	1:192000	16	10	30	24
C025	"	25	1:384000	31 μm	17 μm	48 μm	40 μm

CONCLUSIONS

In summary, the experimental data presented here support the following conclusions:

- a. Digital image having pixel sizes of 50 μm or smaller are not substantially different from continuous tone images for mensuration purposes.
- b. In selecting a sample rate for digitization only the capability to resolve desired image detail (mensuration targets) need ~~by~~^{be} considered.
- c. Stereo-transfer is the primary source of measurement noise.
- d. Noise associated with Stereo transfer is related to factors of terrain relief, target type, density of image detail (contrast) and viewing magnification. Measurement precision deteriorates rapidly when unfavorable levels of two or more of these factors occur.
- e. The results from the two experiments are in agreement; namely, using both digitized and originally digital (synthesized) images.

The results given in this paper are the first step in a continuing research effort at Purdue University to evaluate the metric aspects of digital images. While significant findings have been found, it is our intention to ascertain these results with further experiments. Not only static mensuration tasks, but also dynamic tasks, such as continuous profiling, are being investigated. Furthermore, pertinent operations in digital image processing as well as considerations of soft-copy image mensuration are planned for future work.

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