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An Evaluation of conventional correlation methods when matching infrared imagery to panchromatic imagery

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U.S. ARMY CORPS OF ENGINEERS
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In this report, a practical method of determining parallax by matching an infrared image to a corresponding panchromatic image using conventional correlation methods is evaluated using digitized aerial images. However, from the results of the study, the method was found to be unsatisfactory.

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PREFACE

The work covered by this Research Note was conducted by the Computer Sciences Laboratory (CSL), U. S. Army Engineer Topographic Laboratories (ETL), Fort Belvoir, Virginia. It is part of an effort carried out in CSL on digital image analysis under Project No. 4A762707A855. Studies were conducted by Michael A. Crombie with computer programing assistance by James Miller. Thomas Hay, Robert Rand, Philip Lem, Charles Haase, and Samuel Barr performed the image scanning.

COL Daniel L. Lycan, CE, was Commander and Director of ETL during the report preparation. Mr. Robert P. Macchia was Technical Director.

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AN EVALUATION OF CONVENTIONAL CORRELATION METHODS WHEN MATCHING INFRARED IMAGERY TO PANCHROMATIC IMAGERY

INTRODUCTION

One of the basic objectives in image processing at the U. S. Army Engineer Topographic Laboratories (ETL) is to develop a method to extract mapping, charting, and geodetic (MC&G) data efficiently from a variety of digital and digitized images. Other objectives, which are associated with this basic objective, are to determine (1) what subset of the MC&G data can be extracted from the digital images, (2) how to collect the information, and (3) whether or not the collection process can be automated efficiently. To accomplish the objectives, methods must be developed to register similar as well as dissimilar images to one another to determine ground coordinates or to transfer control. Methods must also be developed to use basic image information, such as texture, to define images of natural and cultural features found on digital pictures. The purpose of this report is to present an evaluation of conventional image matching techniques when matching infrared (IR) imagery to panchromatic (PANC) imagery. The imagery used in this exercise will also be used in a texture analysis. The texture analyses will be described in other ETL research notes.

IMAGE DATA

The images used in this analysis were exposed on 28 October 1975 and were obtained from the U. S. Geological Survey (USGS). Two aerial cameras, one an IR and the other a PANC, were exposed simultaneously and in such a way that the IR and PANC images almost completely overlapped one another. A brief description of the pertinent geometry is given next followed by a description of the image-scanning process.

Geometric Description ■ Five pairs of IR and PANC were exposed in flight in such a manner that the base-height ratio between successive exposures was 0.3. Three scenes that appeared on all five IR exposures and all five PANC exposures were selected for scanning. The pertinent camera parameters associated with the data are given in table 1.

TABLE 1. CAMERA DATA

	PANC	IR
Scale	1:70000	1:70000
B/H	0.3, 0.6, 0.9, 1.2	0.3, 0.6, 0.9, 1.2
f	153.282 mm	153.122 mm
Spectral Range	0.4 – 0.7 μm	0.7 – 0.9 μm

The five IR images were labeled 52I, through 56I; the fire PANC images were labeled 52P through 56P. Exterior orientation parameters for 52P, 54P, and 56P were provided by USGS.

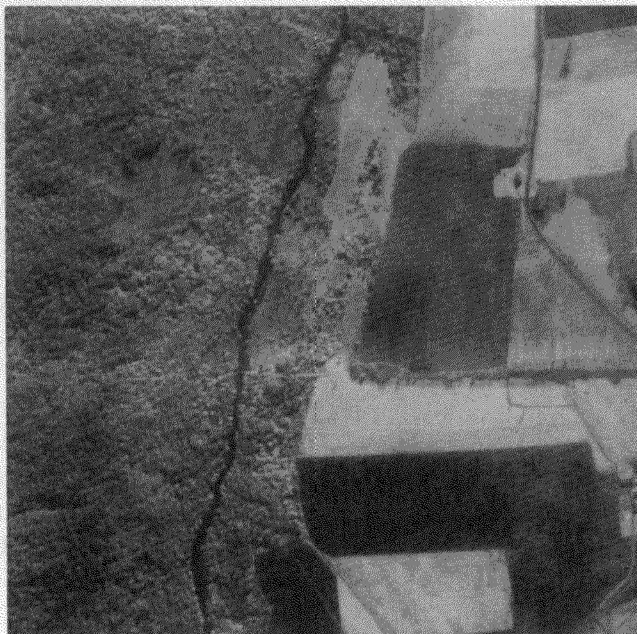
Digitized Data ■ Three scenes that appeared on all 10 (5 IR images and 5 PANC images) exposures were selected for scanning. The upper left corner of each scene was marked in stereo on all 10 exposures prior to scanning on the PDS 1050A Automatic Microdensitometer system. The images were placed in the microdensitometer comparator so that the scan axis was nearly parallel to the base line. The upper left corner of each scene and the four camera fiducial images were measured before and after the scanning process. These data are used to calculate a transformation from pixel space to camera space.

The pixel spacing and the line spacing was 14 μm (micrometers). The pixel diameter was 20 μm; 1024 lines and 1024 pixels per line were measured for each of the three scenes on each of the 10 images. The microdensitometer output was enhanced to produce 8-bit density gray shades and then stored on disc in the image-processing system of ETL. The three scenes (from exposure 54) are shown in figures 1, 2, and 3.

INFRARED

PANCHROMATIC

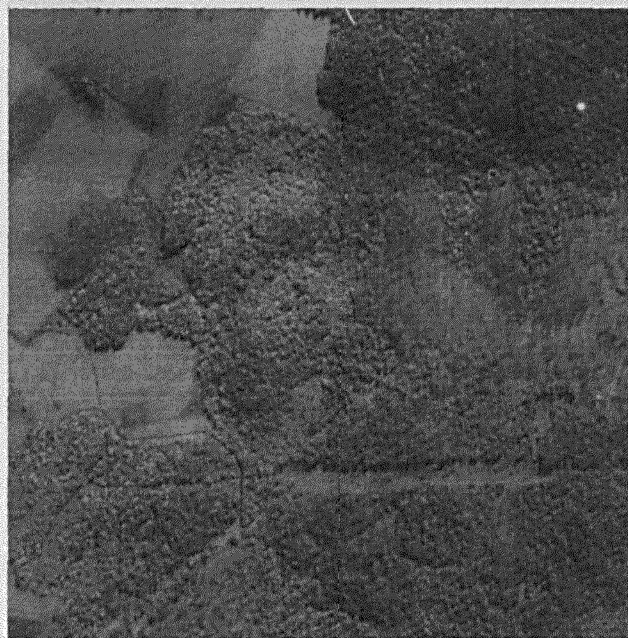
FIGURE 1. Scene A From Exposure 54.



INFRARED

PANCHROMATIC

FIGURE 2. Scene B From Exposure 54.



INFRARED

PANCHROMATIC

FIGURE 3. Scene C From Exposure 54.

NUMERICAL EXPERIMENT

The three scenes were measured on the IR and PANC images to evaluate the linear correlation coefficient as a measure of similarity when matching IR to PANC. The basic measure of effectiveness, P, is defined to be the percentage of successful matches, and the quantities R, C, SP, and B/H were tested for their worth as predictors of a successful match. The criterion for a successful match and the parameters R, C, SP, and B/H are defined below.

Match Process ■ A rectangular grid of points was established on each scene of 541 . The upper left corner on each scene was located at line 80 and pixel 80; 29 lines and 29 pixels per line were specified where the line and pixel spacing was 31. Thus, 29 x 29 = 841 points were defined on each of the three scenes of 541, and the match process attempted to locate the corresponding points on the nine remaining digital images.

A match point was estimated on the dependent image and then refined in the following manner. A 5 x 9 array of correlations values was developed about the match point estimate; the linear correlation coefficient was used as the measure of similarity. The line and pixel location of the correlation maximum was computed and designated as the refined match point. Note that the correlation function was computed at integer pixel and line intersections; whereas, the match point was computed to fractions of line and pixel values. Note also that the longer dimension of the correlation function was in the direction of major parallax.

The largest of the 5 x 9 = 45 discrete correlation values was determined, and if that value was anywhere on the border of the 5 x 9 array of correlation values, the process was halted. Next, the eight correlation values surrounding the largest of the discrete values and the largest correlation value itself were input to a routine that determined (ϵ_x, ϵ_y). The shifts, (ϵ_x, ϵ_y), define the location of the maximum of the correlation function with respect to the largest of the discrete values. The match process was halted at this point if $C \leq 0$, $|\epsilon_x| \geq 1$, or $|\epsilon_y| \geq 1$. The parameter C is the product of the 2-second partial derivatives of the correlation function with respect to x and y, respectively. Both of these values must be negative for the correlation function to be concaved downward.

The following values were output for each successful match:

(X_p, Y_p): Match coordinates

R: Correlation value at the match point

C: Product of the 2-second partial derivatives of the correlation function

Sp: Signal power of match point on the independent image.

Thus C is regarded as a confidence measure in that large values indicate a narrow, well-defined correlation function; whereas, small values indicate a flatter, less well-defined correlation function. Note that if the match was adjudged unsuccessfully, then the match point estimate was output. The match point estimate was estimated from neighboring matches; the match process did not involve image shaping.

The following values were output at the completion of an image matching run:

$\bar{R}$: Average Correlation value

$\bar{C}$: Average C value

$\overline{Sp}$: Average Signal Power

P: Percentage of successful matches

The quantities $\bar{R}$, $\bar{C}$, and $\overline{Sp}$ were averaged over successful matches.

A large number of matching runs were performed to develop statistical variation in the output. Ten matching runs for each of the three scenes were performed when IR was matched to IR and when PANC was matched to PANC. The image matching was organized according to base-height (B/H) ratio. The 10 pairs given in table 2 and the 16 pairs in table 3 were replicated by using two match window sizes, namely 21 by 21 and 31 by 31.

TABLE 2. MATCH PAIRS FOR IR AND FOR PANC

B/H	IMAGE PAIRS			
0.3	54-55	54-53	53-52	55-56
0.6	54-56	54-52	53-55	
0.9	52-55	53-56		
1.2	52-56			

TABLE 3. MATCH PAIRS FOR MATCHING IR TO PANC

B/H					
0.0	52-52	53-53	54-54	55-55	56-56
0.3	54-55	54-53	53-52	55-56	
0.6	54-56	54-52	53-55		
0.9	52-55	53-56			
1.2	52-56	56-52			

Note that 16 matching runs for each of the three scenes were made when IR was matched to PANC. In this case, an extra match run was possible when B/H = 1.2; also, it was possible to acquire five matching runs for B/H = 0.9.

Numerical Results ■ The primary objective of this work effort was to evaluate the process of determining corresponding points between IR and PANC using conventional correlation methods. The match windows were not shaped to reflect local parallax, and no strategies were employed under difficult conditions. If the process failed in any of the ways described previously, than the match was regarded as a failure. The same procedure was used when IR was matched to IR and when PANC was matched to PANC. The purpose of the latter exercises was to provide a numerical comparison for the primary objective. Tables 4 through 9 are averaged values of the results. For example, $\bar{P}$ pertains to the percentage of successes averaged over the appropriate number of image pairs.

TABLE 4. MATCH RESULTS FOR PANC TO PANC – 21 x 21

		SCENES	
B/H = 0.3	A	B	C
$\tilde{P}$	34.10	47.00	72.29
$\tilde{R}$	0.366	0.433	0.525
$\tilde{C}$	0.0051	0.0080	0.0085
$\tilde{S}p$	591	679	974
B/H = 0.6			
$\tilde{P}$	27.78	34.56	38.05
$\tilde{R}$	0.312	0.351	0.411
$\tilde{C}$	0.0047	0.0055	0.0051
$\tilde{S}p$	520	580	943
B/H = 0.9			
$\tilde{P}$	30.20	35.61	32.19
$\tilde{R}$	0.309	0.297	0.315
$\tilde{C}$	0.0044	0.0046	0.0037
$\tilde{S}p$	558	549	817
B/H = 1.2			
$\tilde{P}$	30.44	33.18	21.69
$\tilde{R}$	0.314	0.278	0.238
$\tilde{C}$	0.0045	0.0049	0.0036
$\tilde{S}p$	569	493	783

TABLE 5. MATCH RESULTS FOR PANC TO PANC – 31 x 31

	SCENES		
B/H = 0.3	A	B	C
$\tilde{P}$	34.04	63.11	78.98
$\tilde{R}$	0.399	0.487	0.543
$\tilde{C}$	0.0027	0.0054	0.0056
$\tilde{S}p$	654	747	1059
B/H = 0.6			
$\tilde{P}$	27.35	35.55	36.51
$\tilde{R}$	0.357	0.365	0.420
$\tilde{C}$	0.0025	0.0029	0.0028
$\tilde{S}p$	618	607	996
B/H = 0.9			
$\tilde{P}$	30.14	31.81	31.18
$\tilde{R}$	0.318	0.312	0.344
$\tilde{C}$	0.0020	0.0023	0.0019
$\tilde{S}p$	619	588	942
B/H = 1.2			
$\tilde{P}$	29.01	31.39	1931
$\tilde{R}$	0.338	0.282	0.268
$\tilde{C}$	0.0019	0.0020	0.0018
$\tilde{S}p$	682	505	764

TABLE 6. MATCH RESULTS FOR IR TO IR – 21 x 21

SCENES

B/H = 0.3	**A**	**B**	**C**
$\tilde{P}$	64.06	67.87	74.87
$\tilde{R}$	0.526	0.606	0.609
$\tilde{C}$	0.0063	0.0149	0.0115
$\tilde{S}p$	533	785	884
B/H = 0.6			
$\tilde{P}$	50.89	43.00	42.02
$\tilde{R}$	0.473	0.484	0.459
$\tilde{C}$	0.0049	0.0093	0.0064
$\tilde{S}p$	513	785	898
B/H = 0.9			
$\tilde{P}$	41.14	37.16	28.63
$\tilde{R}$	0.439	0.401	0.350
$\tilde{C}$	0.0042	0.0059	0.0042
$\tilde{S}p$	486	646	647
B/H = 1.2			
$\tilde{P}$	27.47	33.18	24.01
$\tilde{R}$	0.350	0.330	0.289
$\tilde{C}$	0.0039	0.0046	0.0035
$\tilde{S}p$	471	514	672

TABLE 7. MATCH RESULTS FOR IR TO IR - 31 x 31

SCENES

B/H = 0.3	**A**	**B**	**C**
$\tilde{P}$	76.90	70.88	79.61
$\tilde{R}$	0.573	0.637	0.618
$\tilde{C}$	0.0037	0.0112	0.0088
$\tilde{S}p$	622	912	972
B/H = 0.6			
$\tilde{P}$	55.65	43.36	44.19
$\tilde{R}$	0.522	0.522	0.476
$\tilde{C}$	0.0026	0.0064	0.0042
$\tilde{S}p$	586	883	966
B/H = 9.0			
$\tilde{P}$	37.10	37.02	25.45
$\tilde{R}$	0.487	0.429	0.363
$\tilde{C}$	0.0020	0.0035	0.0023
$\tilde{S}p$	621	724	874
B/H = 1.2			
$\tilde{P}$	42.09	31.87	25.99
$\tilde{R}$	0.427	0.349	0.282
$\tilde{C}$	0.0020	0.0025	0.0017
$\tilde{S}p$	568	681	744

TABLE 8. MATCH RESULTS FOR IR TO PANC - 21 x 21

	SCENES		
B/H = 0.0	A	B	C
$\tilde{P}$	33.29	53.03	64.54
$\tilde{R}$	0.273	0.436	0.494
$\tilde{C}$	0.0043	0.0102	0.0102
$\tilde{S}p$	459	674	895
B/H = 0.3			
$\tilde{P}$	38.08	42.79	52.53
$\tilde{R}$	0.316	0.375	0.439
$\tilde{C}$	0.0046	0.0083	0.0071
$\tilde{S}p$	498	627	973
B/H = 0.6			
$\tilde{P}$	32.78	33.69	33.32
$\tilde{R}$	0.278	0.312	0.345
$\tilde{C}$	0.0041	0.0063	0.0046
$\tilde{S}p$	482	698	874
B/H = 0.9			
$\tilde{P}$	35.86	31.51	27.74
$\tilde{R}$	0.262	0.275	0.277
$\tilde{C}$	0.0042	0.0047	0.0038
$\tilde{S}p$	449	507	810
B/H = 1.2			
$\tilde{P}$	26.93	28.72	25.50
$\tilde{R}$	0.210	0.232	0.239
$\tilde{C}$	0.0039	0.0040	0.0036
$\tilde{S}p$	432	575	778

TABLE 9. MATCH RESULTS FOR IR TO PANC - 31 x 31

	SCENES		
B/H = 0.0	A	B	C
$\tilde{P}$	45.49	51.74	72.77
$\tilde{R}$	0.368	0.446	0.496
$\tilde{C}$	0.0053	0.0079	0.0080
$\tilde{S}p$	606	835	945
B/H = 0.3			
$\tilde{P}$	42.98	37.03	53.31
$\tilde{R}$	0.353	0.362	0.418
$\tilde{C}$	0.0059	0.0057	0.0052
$\tilde{S}p$	618	818	1032
B/H = 0.6			
$\tilde{P}$	32.50	32.62	34.28
$\tilde{R}$	0.265	0.314	0.340
$\tilde{C}$	0.0018	0.0037	0.0027
$\tilde{S}p$	563	803	969
B/H = 0.9			
$\tilde{P}$	28.35	30.14	25.99
$\tilde{R}$	0.259	0.267	0.257
$\tilde{C}$	0.0014	0.0023	0.0018
$\tilde{S}p$	547	637	844
B/H = 1.2			
$\tilde{P}$	28.42	24.55	24.64
$\tilde{R}$	0.249	0.211	0.208
$\tilde{C}$	0.0015	0.0018	0.0014
$\tilde{S}p$	508	607	872

STATISTICAL ANALYSIS

Two statistical analyses were performed on the data. The first was an analysis of gray shade and signal power variation to determine if an *a priori* evaluation of signal power or gray shade could be used to identify those scenes most likely to produce good matches from those unlikely to produce good matches. The second analysis was a multiple regression analysis to determine which of the match parameters and which of the geometric parameters were significant in determing a successful match.

Gray Shade and Signal Power Variation ■ Each of the 30 digitized images (3 scenes on 5 IR and 5 PANC exposures) was segmented into 16 blocks where each block was dimensioned 256 by 256. The following five quantities were computed for each of the 480 blocks.

g_{max}: Largest gray shade

g_{min}: Smallest gray shade

$\bar{g}$: Average gray shade

SP : Signal Power or block variance

Ho : Entropy

Several statistical measures were computed within images and over images. It was assumed that the (1,k) block (1 = 1, 4 and k = 1,4), taken from a specific scene, corresponded to the (1,k) block taken from the same scene extracted from a different exposure.

The objective was to compute a variety of scene statistics and then to note whether a relationship between the scene statistics and successful matches could be determined. This portion of the experiment produced little or no predictive information. However, it was noted that the ratio of the scene signal power to a within-estimate signal power showed a reasonable amount of consistency when compared to the percentage of successful matches. The results are summarized in table 10.

TABLE 10. SCENE STATISTICS

SENSOR	SCENE	σ_{z1}^2	σ_{z2}^2	$\sigma_{z1}^2/\sigma_{z2}^2$
	A	1961	1432	1.37
IR	B	2290	1735	1.32
	C	1584	1152	1.38
	A	1791	1541	1.16
PANC	B	2010	1123	1.79
	C	2368	1747	1.36

The scene signal power, σ_{z1}^2, and the within-estimate signal power, σ_{z2}^2, were computed in each of the six cases by averaging the five exposures. The first three and the last ratios are similar in value ($\sigma_{z1}^2/\sigma_{z2}^2 \simeq 1.4$) and, in fact, correspond to the more successful stereo matching situations. The ratio for PANC Scene A was the smallest ($\sigma_{z1}^2/\sigma_{z2}^2 = 1.16$), and the corresponding exposures produced the poorest matches. The ratio for PANC Scene B was the largest ($\sigma_{z1}^2/\sigma_{z2}^2 = 1.79$), and the corresponding exposures produced the next worst match results. These results indicate that a moderate amount of signal power variation over a scene is more likely to produce better match results than either a small or a large amount. It is unlikely that this measure of successful match can be put to use in an automatic process.

Multiple Regression Analysis ■ The objective was to determine which, if any, of the four parameters R, C, SP and B/H could be used to predict whether or not a particular match was successful. The parameters R and C are functions of the imagery and of the match process, SP is a function of the imagery, and B/H is a function of the exposure geometry. A multiple regression analysis of the four parameters on the number of successes was used as a means for making the determination.

In the linear regression equation given in the appendix, it was assumed at the outset that the coefficients were zero. If any of the 90 percent intervals about the coefficient extimates included zero, then the hypothesis of no significance would be supported at the 0.10 confidence level. For example, the hypothesis that the coefficient of R is zero was rejected in five of the six analyses. The data of the IR to IR (31 x 31) supported the hypothesis of no significance in R. The hypothesis that the coefficient of B/H is zero was supported by all the tests. The hypothesis that the coefficient of C is zero was supported by all but the IR to PANC (21 x 21) test. The hypothesis that the coefficient of SP is zero was rejected by the IR to PANC (21 x 21) test and by the IR to PANC (31 x 31) test.

The results of the tests indicate that the linear correlation coefficient R should be a good predictor of a successful match. The signal power SP, associated with the match window, is a fair predictor, especially when IR is matched to PANC. The confidence value C turned out to be of marginal value for predicting successful matches, and the base-height (B/H) ratio turned out to be of no value.

DISCUSSION

The conclusion drawn from the regression analysis that the base-height (B/H) ratio was of no value in predicting a successful match is contrary to experience and also contrary to previous studies.[1] In fact, the six correlation matrices derived from this study (see appendix) show that B/H is negatively correlated with the three variates P (percentage of successes), R (correlation value of match), and C (confidence measure). Note that the correlation value R is a measure of similarity between two points on separate images; whereas, the correlation matrices given in the appendices describe the linear dependence of the variates P, R, C, SP and B/H upon one another. The negative correlation values imply that as B/H increases, the values of P, R, and C decrease. That the regression analyses did not substantiate this observation can be explained by reviewing the percentage of successes as a function of B/H. Consider tables 11 and 12 extracted from tables 4 through 9.

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[1] M. Crombie and L. Gambino, "Digital Stereo Photogrammetry", Presented to *Congress of the International Federation of Surveyors (FIG)*. Commission V, Stockholm, Sweden, June 1977.

TABLE 11. PERCENTAGE OF SUCCESSES (21 x 21 WINDOW)

B/H	PANC--PANC			IR--IR			IR--PANC		
	A	B	C	A	B	C	A	B	C
0.0							33	53	65
0.3	34	47	72	64	68	75	38	43	53
0.6	28	35	38	51	43	42	33	34	33
0.9	30	36	32	41	37	29	36	32	28
1.2	30	33	32	27	33	24	27	29	26

TABLE 12. PERCENTAGE OF SUCCESSES (31 x 31 WINDOW)

B/H	PANC--PANC			IR--IR			IR--PANC		
	A	B	C	A	B	C	A	B	C
0.0							45	52	73
0.3	34	63	79	77	71	80	43	37	53
0.6	27	36	37	56	43	44	33	33	34
0.9	30	32	31	37	37	25	28	30	26
1.2	29	31	19	42	32	26	28	25	25

There is a downward trend in P as B/H increases; however, the slope decreases to zero as $B/H > 0.6$. In fact, the P values for scene A (PANC to PANC and IR to PANC) have little or no slope over the entire range of B/H. These observations, along with the limited number of data points plus the other variables explaining the percentage of success P, mean that the coefficient of B/H in the regression equation being zero is not an unlikely occurrence. The single variable R explained most of the variation in P. Consider the six partial correlation matrices in the appendix. The partial correlation matrix describes the linear dependence among the variates P, R, and C when the signal power (SP) and the base-height (B/H) ratio are constant. The partial correlation between P and R is $0.923 \leq \rho PR \cdot SP, B/H < 0.953$.

There is a very noticable decrease in the percentage of successes as $B/H > 0.3$ for scene B, and especially for scene C. The relatively large signal power of scene C, and to some extene that of scene B, implies an abundance of edges that become obscured when viewed from different aspects. Thus, two exposures of a busy ground scene will be noisy with respect to one another, or common ground detail is obscured owing to different perspectives. Also trying to cancel noise by more measurements (enlarging the matching windows) did not help. In fact, the number of successes decreased as the window size was increased from 21 to 31, when $B/H > 0.3$.

However, there are at least two ways to improve the match process. The first is to shape the image to account for terrain elevation changes and to account for exposure geometry differences. The second is to use only the common information, especially if the images are dissimilar such as when matching IR to PANC. Consider table 13, which shows the relative scale change of a ramp tilted α degree from the datum when viewed from two vertical exposures.[2] The ramp-like object is assumed to be midway between the two exposure stations. It can be seen from the table that for small values of α and B/H, the scale change may not be important. However, as either parameter increases, the relative scale increases nonlinearly. This means that unless one image is resampled to reflect the scale change, the matching windows, even when centered over corresponding points, will not necessarily indicate a match. The beneficial effects of image shaping, especially in steep areas, was demonstrated in another research note.[3]

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[2] M. Crombie and L. Gambine, "Digital Stereo Photogrammetry," Presented to *Congress of the International Federation of Surveyors (FIG)*. Commission V, Stockholm, Sweden, June 1977.

[3] M. Crombie, *Stereo Analysis of A Specific Digital Model Sample From Aerial Imagery*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, VA ETL--0072, September 1976, AD--A033 567.

TABLE 13. IMAGE SCALE CHANGE

B/H	0°	5°	10°	α 15°	20°	25°	30°
0.4	1.00	1.04	1.07	1.11	1.16	1.21	1.26
0.6	1.00	1.05	1.11	1.17	1.25	1.33	1.42
0.8	1.00	1.07	1.15	1.24	1.34	1.46	1.60
1.0	1.00	1.09	1.19	1.31	1.44	1.61	1.81

That the exposures IR and PANC are dissimilar can be demonstrated by a visual examination of the exposure pairs for scenes A, B, and C. Note that the exposure pairs are of nearly the same area, and they were exposed from nearly identical locations with little or no relative tilts. A numerical verification of the same fact is seen in tables 11 and 12, where, when B/H = 0, the percentages of successful matches varies from 33 to 73 percent instead of 100 percent.

The high frequency information appears to contribute more to the match success, when B/H < 0.6, than the low frequency information. This can be shown by noting the sharp increase in success for scene B, and especially for scene C, as B/H < 0.6. Both of these scenes have relatively high signal power; whereas, the low signal power of scene A produces little change in success as B/H varies. It can be shown that high frequency information in an image scene results in a shorter pull in range.[4] This is equivalent to a more spike-like correlation function or equivalently to a large C value. In tables 4 through 9, scenes B and C have much larger C values than scene A for B/H < 0.6.

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[4] M. Crombie and R. Rand, *An Evaluation of the Method of Determining Parallax From Measured Phase Difference*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, VA, ETL--0145, December 1977, AD--A056 006.

The percentage of successes given in tables 11 and 12 are conservative. The success criteria was arbitrarily imposed, and no strategies were used to increase the number of successes. One of the best ways to increase the number of successful matches is to perform a preprocessing operation for each match attempt to remove all adverse effects of geometric distortion and to accentuate image similarities. For similar imagery (IR to IR and PANC to PANC), this would involve image shaping and filtering out increasing amounts of high frequency data on B/H increases. For dissimilar imagery (IR to PANC), this would also involve image shaping; however, the high frequency information should be enhanced so that the common image structure can be registered. Corresponding pixels on IR and PANC, in most cases, will have entirely different illumination values, even when B/H = 0; whereas, image structure (roads, fields, buildings, etc.) appear to be immune to sensor changes. This is not entirely true; for example, note the creek found on scene B of the IR, but hardly noticeable on the PANC.

It is expected that a different algorithm than the conventional algorithm used in this study should be used to develop match points between IR and PANC images. Since it has been asserted here that the principal commonality between the two record types is image structure, then a reasonable approach would be to exploit the similarities between the density gradient functions of the image pairs.[5]

There are at least five parameters that can be used to evaluate a match when the conventional area correlation method is used.

1. R: Correlation value at the match point.
2. C: Product of the two partial derivatives of the Correlation function.
3. SP: Signal Power in the neighborhood of the match point.
4. S_x: Scale difference between corresponding image segments.
5. δ_x: Computed shift in X-parallax.

[5] Richard H. Hudgin, Image Matching Using Structure Information, *SPIE*, Vol. 117, 1977, pp. 126--131.

Parameters R and C are a function of the correlation process, i.e. resampling, window size, etc. The parameter SP is a function of the ground detail and of the sensor; whereas, S_x is dependent upon the terrain and the exposure geometry. The parameter δ_x, which is a model error, reflects unexpected change in terrain slopes, loss or partial loss of correlation, recovery of correlation owing to previous errors, etc. Since the match operation involves a match point estimation followed by a refinement process, small values of δ_x imply a successful match; whereas, larger values imply that something may be amiss. A series of large values of δ_x, especially when the other indicators are suspect, implies that the process is out of control. If S_x, the scale factor, strays too far from unity, then the match process must work with pixel values diluted in resolution. Therefore, S_x values that are significantly different from one indicate match difficulties. The parameter C was used in one study,[6] and the three parameters R, C, and S_x, were used in another study.[7] All five parameters were used in a final study.[8] The three study results pertain to aerial imagery exposed in a panchromatic camera. It was shown in this report that of the three parameters R, C, and SP, the correlation value, R, was the most useful in predicting a valid match. The signal power, SP, turned out to be a fair predictor, especially when matching IR to PANÇ. The parameter C turned out to be of marginal value.

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[6]M. Crombie, *Stereo Analysis of A Specific Digital Model Sample From Aerial Imagery*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, VA, ETL--0072, September 1976, AD--A033 567.

[7]P. Rosenberg, K. Erickson and G. Rowe, *Digital Mapping System: Mathematical Processing*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, VA, ETL--CR--74--6, May 1974, AD--782 230.

[8]D. Panton and M. Murphy, *Digital Cartographic Study and Benchmark*, U. S. Army Engineer Topographic Laboratories, Fort Belvoir, VA, ETL--0168, September 1976, AD--A064 800.

CONCLUSIONS

1. The correlation value, R, is the best indicator of a successful match.

2. The signal power, SP, turned out to be a fair indicator of a successful match, especially when matching IR imagery to PANC imagery.

3. The product of the two partial derivatives of the correlation function, C, turned out to be of marginal use.

4. Match successes decrease rapidily as the base-height (B/H) ratio increases; this is especially true for scenes with large signal power.

5. Image structure should be exploited when registering IR imagery to PANC imagery.

6. Algorithms other than the conventional area correlation procedure must be developed and tested for the successful registration of IR imagery to PANC imagery.

APPENDIX. Multiple Regression Results

The data given in this appendix are results from six regression analyses. The six sets pertain to the three match situations IR to IR, PANC to PANC, and IR to PANC, and to the two window sizes used in the match process. The regression equation in all cases was the following:

$$P = \mu + a \times R + b \times C + c \times SP + d \times B/H + e$$

where

- P: Percentage of successful matches
- μ: $\bar{P} - [a \times \bar{R} + b \times \bar{C} + c \times \overline{SP} + d \times \overline{B/H}]$
- R: Average correlation of the successful matches
- C: Average confidence value of the successful matches
- SP: Average signal power of the successful matches
- B/H: Base-height ratio
- e: Model Error. The expected value of e is zero and the variance of e is σ^2.

There were 30 observation equations for each of the IR to IR matches and for each of the PANC to PANC matches. There were 48 observation equations for each of the IR to PANC matches.

The regression analysis results were computed and the F–statistic was used to determine whether or not the regression coefficients a, b, c, and d were significantly different from zero.[9] The initial hypothesis was that each coefficient was zero, i.e. the corresponding parameters were not linearly related to match success.

[9] Donald F. Morrison, *Multivariate Statistical Methods*, McGraw--Hill Book Company, New York, 1976, pp. 107.

There are two correlation matrices associated with each of the six sets of results; each are presented in upper triangular form. The first is the 5 by 5 correlation matrix of the input data, and the second is the 3 by 3 partial correlation matrix, wherein signal power (SP) and base-height (B/H) are held constant. The next set of data includes the regression coefficients and their 90 percent confidence bounds. The last two values in each of the six sets is the square of the multiple correlation coefficient and the standard error of estimate.

IR to IR (21 x 21)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.924 & 0.639 & 0.336 & -0.854 \\ & 1.000 & 0.807 & 0.476 & -0.913 \\ & & 1.000 & 0.650 & -0.640 \\ & & & 1.000 & -0.388 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.953 & 0.716 \\ & 1.000 & 0.843 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients and 90% bounds

$$\begin{aligned} \mu &= -57.4 \\ a &= 242 \pm 127 \\ b &= -1361 \pm 1828 \\ c &= -0.0038 \pm 0.0270 \\ d &= 7.73 \pm 52.1 \end{aligned}$$

Multiple Regression Coefficient Squared

$$P^2 = 0.889$$

Standard Error of Estimate

$$\sigma = 6.3$$

PANC to PANC (21 x 21)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.896 & 0.852 & 0.599 & -0.499 \\ & 1.000 & 0.841 & 0.612 & -0.593 \\ & & 1.000 & 0.426 & -0.596 \\ & & & 1.000 & -0.106 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.929 & 0.878 \\ & 1.000 & 0.880 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients and 90% bounds

$\mu = -30.5$
$a = 99 \pm 93$
$b = 3933 \pm 4191$
$c = .0124 \pm 0.0281$
$d = 5.7 \pm 16.0$

Multiple Regression Coefficient Squared

$P^2 = 0.854$

Standard Error of Estimate

$\sigma = 6.9$

IR to PANC (21 x 21)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.884 & 0.833 & 0.594 & -0.580 \\ & 1.000 & 0.782 & 0.677 & -0.574 \\ & & 1.000 & 0.514 & -0.542 \\ & & & 1.000 & -0.167 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.927 & 0.889 \\ & 1.000 & 0.855 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients and 90% bounds

μ = 1.5
a = 80 ± 54
b = 1905 ± 1595
c = 0.0025 ± 0.0021
d = −2.54 ± 8.79

Multiple Regression Coefficient Squared

$P^2 = 0.835$

Standard Error of Estimate

$\sigma = 6.5$

IR to IR (31 x 31)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.867 & 0.568 & 0.130 & -0.859 \\ & 1.000 & 0.726 & 0.241 & -0.912 \\ & & 1.000 & 0.650 & -0.635 \\ & & & 1.000 & -0.330 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.923 & 0.614 \\ & 1.000 & 0.740 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients and 90% bounds

$\mu = 57.7$
$a = 69 \pm 191$
$b = 597 \pm 3477$
$c = -0.0251 \pm 0.0577$
$d = -36.5 \pm 49.4$

Multiple Regression Coefficient Squared

$P^2 = 0.799$

Standard Error of Estimate

$\sigma = 9.7$

PANC to PANC (31 x 31)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.910 & 0.879 & 0.541 & -0.610 \\ & 1.000 & 0.876 & 0.632 & -0.784 \\ & & 1.000 & 0.531 & -0.655 \\ & & & 1.000 & -0.412 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.937 & 0.918 \\ & 1.000 & 0.920 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients and 90% bounds

$\mu = -59.2$
$a = 211 \pm 133$
$b = 3948 \pm 5472$
$c = -0.0074 \pm 0.0016$
$d = 17.2 \pm 21.8$

Multiple Regression Coefficient Squared

$P^2 = 0.884$

Standard Error of Estimate

$\sigma = 7.3$

IR to PANC (31 x 31)

Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.889 & 0.640 & 0.536 & -0.624 \\ & 1.000 & 0.686 & 0.574 & -0.709 \\ & & 1.000 & 0.385 & -0.592 \\ & & & 1.000 & -0.272 \\ & & & & 1.000 \end{pmatrix}$$

Partial Correlation Matrix

$$\begin{pmatrix} 1.000 & 0.929 & 0.748 \\ & 1.000 & 0.785 \\ & & 1.000 \end{pmatrix}$$

Regression Coefficients

$\mu = -13.4$
$a = 151 \pm 67$
$b = 331 \pm 1527$
$c = 0.0037 \pm 0.0026$
$d = 0.75 \pm 13.3$

Multiple Regression Coefficient Squared

$P^2 = 0.794$

Standard Error of Estimate

$\sigma = 8.8$