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Deformations of Estar-base Aerial Films

A strict control of procedures and conditions during printing and processing can reduce the linear homogeneous deformations considerably.

THE PHYSICAL properties of Estar base aerial film are quite well known from a number of earlier publications (e.g., Calhoun, Adelstein and Parker [1961], Adelstein and Leister [1963], and references cited there). The dimensional changes of these films under routine processing and also under simulated service conditions were studied by several authors (e.g., Adelstein, Josephson and Leister [1966], Carman and Martin [1968] and references cited there).

ABSTRACT: *Three rolls of Estar-base film from the same master roll were contact-printed from a glass grid in a continuous manner. Sections of each roll were processed in three separate laboratories. The samples showed with a remarkable consistency those properties of the materials that pertain to their linear homogeneous deformations. The results agree well with findings from other experiments performed with different methods and techniques. A strict control of procedures and conditions during printing and processing can reduce deformations considerably. More serious attention should be given to the use of reseaus in aerial cameras.*

The results discussed in this paper are from an interlaboratory film stability test which was conducted as part of a larger project concerning accuracy problems and limiting factors in photogrammetric techniques. The main goal of this part of the investigation was to establish, in the presence of nonlinear homogeneous, nonhomogeneous and random deformations, the linear homogeneous behavior of the film under routine processing, handling and storage conditions. The term deformation is used in the sense that the changes in the medium alter relative distances between points. The homogeneous deformations are those that can be described by functions whose parameters are independent from the position of the points in the medium. These functions may be linear or nonlinear. The description of nonhomogeneous deformation requires the use of functions whose parameters depend on the position of the point in question. These nonhomogeneous deformations are often treated as random deformations, and indeed it is difficult to draw a clear dividing line between the two. In this paper the deformations were treated as plane deformations, consequently a two-dimensional mathematical model was at the base of the numerical data processing.

THREE ROLLS of Kodak Plus-X Aerographic film, 0.1 mm Estar base, type 2401, from the same master roll, were used in a grid-comparator experimental procedure. For this purpose a master grid was made by exposing an annulus shaped mark on a glass plate (6.35 mm thick) at distances of approximately one centimeter in a 24-by-24 array. From the original negative master grid a positive master grid was contact printed and used for reference throughout the test. This positive master grid was printed along the entire length of the three rolls (approximately 1 frame every 60 cm). The printing was performed on a parallel-light printer at 32 per-

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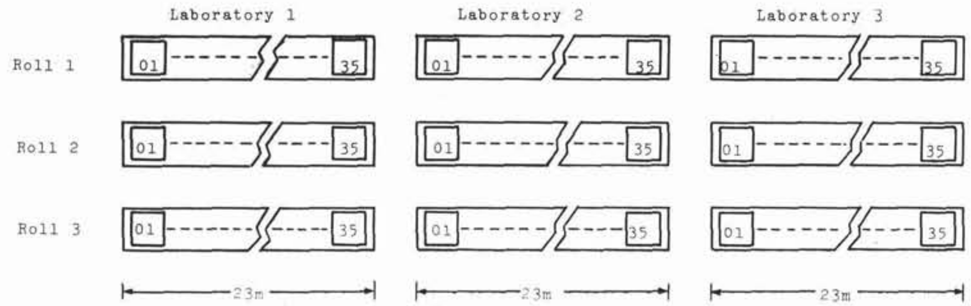

FIG. 1. Schematic illustration indicating how three rolls of film were printed and then each of them cut into three sections. Three corresponding cuts from the three rolls were processed by the three laboratories.

cent R.H. and 70°F. At the time of printing a constant stress was applied before the exposure; thus a nonlinear, shrinkage-like deformation of the initial pattern was introduced. This was done to facilitate investigations other than the one described here.

Subsequently each roll was cut in three parts approximately 23 m long. From these 9 cuts (each of them containing 35 frames) three corresponding cuts from the three different rolls (Figure 1) were selected and processed by three laboratories. The data pertaining to processing are shown in Table 1.

After processing, all nine cuts were stored in rolls at 32 percent R.H. and 70°F. One week after processing, five frames (numbers 03, 10, 17, 24 and 32) evenly distributed along the cut, were printed on glass plates from each of the 9 cuts (total of 45 diapositives). Three frames, (numbers 03, 17 and 32) from the three cuts of the roll No. 3, were printed on plates 1 week, 2 weeks, 3 weeks and 6 months after the first printing (total of 36 diapositives). The relative humidity and the temperature during the printing of all these diapositives was the same as quoted for the storage. Precautions were taken to avoid, as far as possible, any deformation during the printing.

Therefore the first group of 45 diapositives was supposed to contain the deformation introduced at the initial printing of the positive master grid on film, the deformation due to processing, the deformation due to the inherent properties of different rolls of film and the deformation introduced at the time of diapositive printing. The second group of 36 diapositives was supposed to contain, besides these deformations, the deformation due to aging.

The measurements of all 81 plates were performed on the NRC Monocomparator. (The inner diameter of the master grid annulus was made to be 10 μm larger than the average diameter of the measuring marks on the comparator's multi-measuring mark plate). The coordinates of a 12-by-12 array of 144 points with 2 cm spacing were measured on all the diapositives. Since the positive master grid is not an exact centimeter grid (the positions of the annuli deviate from their nominal values up to 0.2 mm) the reference coordinates of the selected 144 points were determined as the mean from 10 sets of repeated measurements of the grid points with the master plate kept in the same position in the comparator. (The residuals after the orthogonal transformation of each of these 10 sets of measurements into the reference mean indicated, on the average, a mean square error of ± 1 μm in both x- and y-directions).

The diapositive plates were placed in the comparator as close as possible to the position in which the master grid was measured. Consequently the same measuring mark and practically the same position of the micrometer screws were utilized for the measurement of a particular point during the entire measuring process. Also the sequence of coordinate measurements on the master grid and on all diapositives was the same. Inasmuch as only the relative changes were of interest in this part of the experiment, or, in other words, the fidelity with which the original pattern was

TABLE 1. PROCESSING SCHEME

Laboratory	*1*	*2*	*3*
Processing Machine	Rewind Tank	Continuous	Continuous
Developer and Fixer Temperature	68°F	80°F	85°F
Drying Temperature	70°F	95°F	150°F

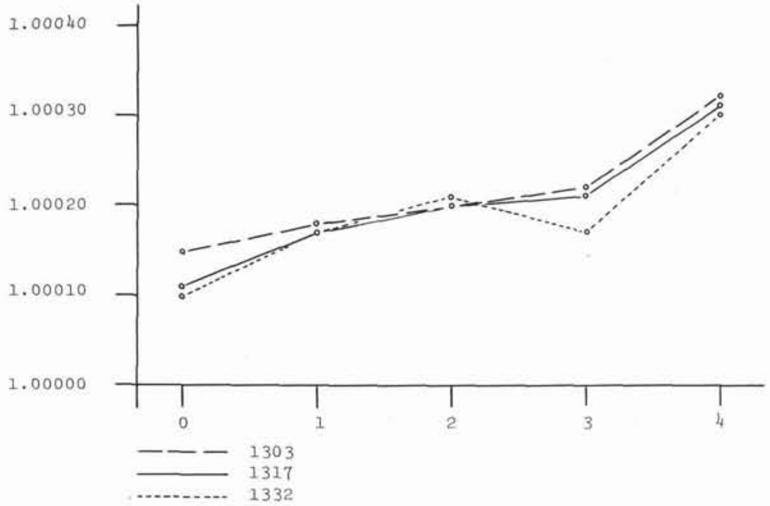

FIG. 2. The overall scale changes of three films processed by Laboratory 1 plotted as a function of time and based on a similarity transformation. The scale factor is the ordinate and the time interval is the abscissa. The first three time intervals are one week whereas the last one represents 21 weeks. See Table 2 below.

TABLE 2. NUMERICAL DATA CORRESPONDING TO FIGURE 2 ABOVE
The first row of each set of three frames shows the scale factor plotted in the figure. The mean-square errors of differences in micrometers are shown for Δx in the second row and Δy in the third row

1.00015	1.00018	1.00020	1.00022	1.00032
1303	4	3	3	6
	3	3	3	4
1.00011	1.00017	1.00020	1.00021	1.00031
1317	3	3	4	4
	3	4	4	4
1.00010	1.00017	1.00021	1.00017	1.00030
1332	3	3	3	4
	3	4	3	4

preserved on the film throughout processing and storage, all values under analysis were differences between the master grid measurements and the diapositive measurements. These differences may be assumed to be free of the comparator's systematic errors. (Multimeasuring-mark plate errors were completely excluded, and the cumulative and periodic screw errors contributed a negligible influence).

THE 81 SETS of 144 coordinate pairs were transformed into the reference master grid coordinates by a program for orthogonal, similarity and affine transformation. The parameters of these transformations were determined by a least-square solution from all 144 points and the residual errors after transformation were computed. The final output of these computations are the printouts containing the values of the parameters and the residuals after transformation, and a plot of these residuals for each transformation. As the figure is not altered by the orthogonal transformation, the output of this transformation represents the original deformation of the pattern registered on the film. The two other transformations were used, respectively, for the determination of overall scale changes of the patterns, and for different scale changes along two axes which are not necessarily perpendicular. From the analysis of these parameters and residuals, inference was sought on the linear homoge-

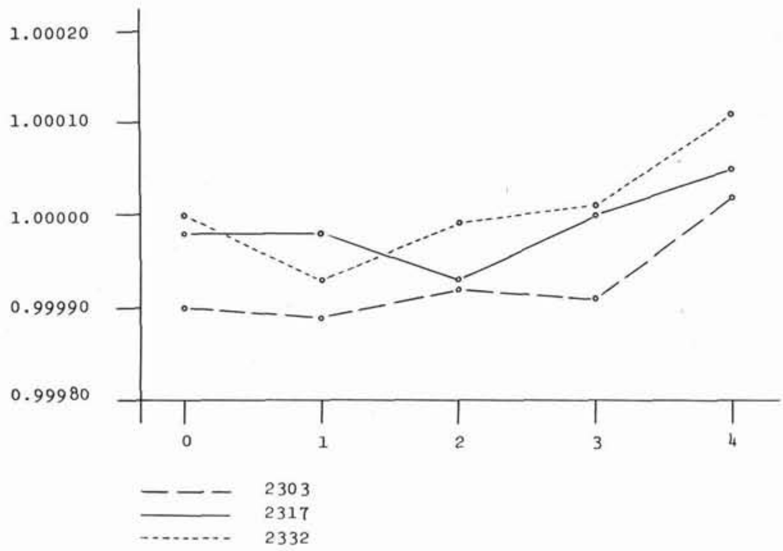

FIG. 3. The overall scale changes of three frames processed by Laboratory 2, similar to Figure 1. See Table 3.

TABLE 3. NUMERICAL DATA CORRESPONDING TO FIGURE 3. SEE TABLE 2

0.99990	0.99989	0.99992	0.99991	1.00002
2303	4	4	3	6
	4	3	3	4
0.99998	0.99998	0.99993	1.00000	1.00005
2317	5	4	10	6
	5	5	10	6
1.00000	0.99993	0.99999	1.00001	1.00011
2332	5	5	6	5
	4	5	5	4

neous deformation of the 81 samples.

The overall scale changes of the three frames from the cut of the roll No. 3, processed by the Laboratory 1, are presented in Figure 2. On the ordinate the scale factor λ, determined by the similarity transformation into the control, are shown. The abscissa is the time scale t. The last interval on the abscissa (3 to 4) stands for a compressed time interval of 21 weeks, the others represent one week intervals. The scale factors λ are also listed in the adjacent tables, for each of the three frames. The values in the second and third rows, related to the particular frame, are the mean-square errors of differences Δx and Δy in μm. These differences were obtained by subtracting the residuals derived after the transformation of the frame printed at $t=0$, from the residuals after the transformation of each subsequent print of the same frame for $t=1, 2, 3$, and 4. If only pure overall scale changes had occurred during the aging period, these mean-square errors should be approximately equal. The slight increase in these values with time suggests some nonhomogeneous or, at least, nonlinear disturbances, which may be attributed to aging. The more probable sources of these disturbances are the influences introduced at the time of printing. The maximal dispersion of λ for different frames printed at the same time does not exceed 0.005 percent. The aging effect is apparent and amounts to an average shrinkage of 0.02 percent over six months.

The results from the cut of the same roll but processed by Laboratory 2 are shown in Figure 3. The dispersion of λ for different frames printed at the same time is larger than in the previous case and amounts to 0.01 percent. The aging effect is again visible

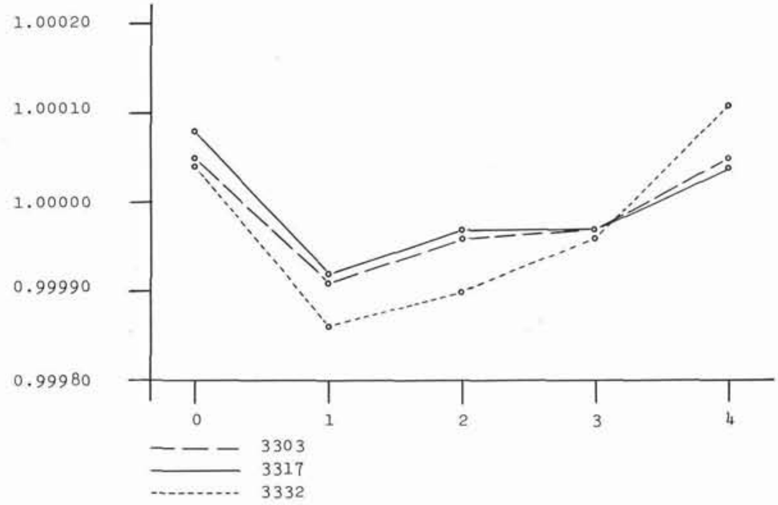

FIG. 4. The overall scale changes of three frames processed by Laboratory 3, similar to Figure 2. See Table 4.

TABLE 4. NUMERICAL DATA CORRESPONDING TO FIGURE 4. SEE TABLE 2

1.00005	0.99991	0.99996	0.99997	1.00005
3303	4	5	3	5
	5	5	4	5
1.00008	0.99992	0.99997	0.99997	1.00004
3317	4	4	4	4
	3	3	3	3
1.00004	0.99986	0.99990	0.99996	1.00011
3332	5	4	6	8
	5	3	4	6

but somewhat less pronounced. In places, considerable irregularities are indicated by quite high values of mean square errors.

In Figure 4 the same effects are presented for the cut processed by Laboratory 3. The maximal dispersion of λ is again of the same order as for Laboratory 1. The shrinkage due to aging is, when observed in the interval from $t=1$ to $t=4$, comparable to that indicated by the results from Laboratory 1. The irregularities are less pronounced than in the case of Laboratory 2. If the frames are ordered according to the magnitude of the scale factors, in all three instances they show a different sequence; this indicates an apparent independence of the deformation patterns from the position of the frame on the roll.

THE AVERAGES of overall scale changes λ, in function of time, for the three laboratories are presented in Figure 5. It should be noted that only the cut processed by Laboratory 1 was kept at the same relative humidity and temperature during the entire experiment. The cuts processed by the two other laboratories were brought into the same environment after processing. Consequently, the first week interval on the graph (0–1) represents the record of a mixture of reversible and permanent dimensional changes. From the end of the first week the aging effect is obviously showing the same trend for all three cuts. From the differences of average scale factors λ for $t=4$ and for $t=1$ the following average relative dimensional changes are found: -0.014 percent for Laboratory 1, -0.013 percent for laboratory 2 and -0.017 percent for Laboratory 3.

In Figures 6 to 9 and in adjacent tables the results obtained from affine transformations are presented. The organization of these diagrams is the same as for the ones presenting

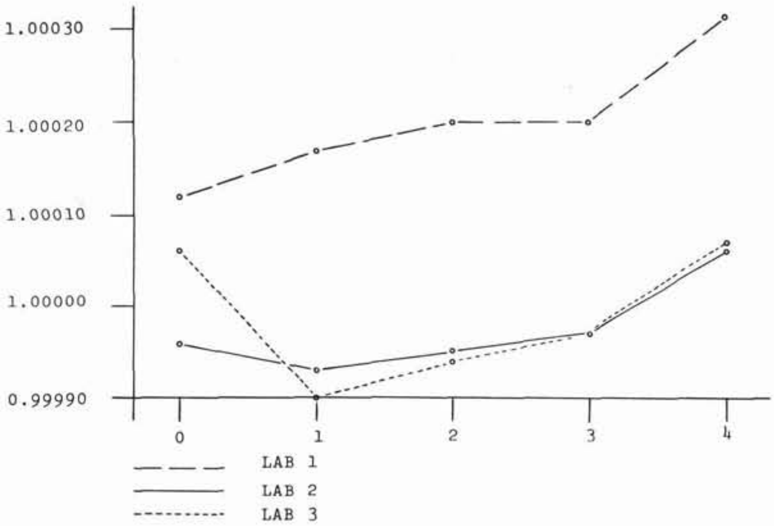

FIG. 5. The averages of the overall scale changes from the three laboratories plotted as a function of time, similar to Figure 2. See Table 5.

TABLE 5. NUMERICAL DATA CORRESPONDING TO FIGURE 5. SEE TABLE 2

1.00012	1.00017	1.00020	1.00020	1.00031
LAB 1	3	3	3	5
	3	4	3	4
0.99996	0.99993	0.99995	0.99997	1.00006
LAB 2	5	4	6	6
	4	4	6	5
1.00006	0.99990	0.99994	0.99997	1.00007
LAB 3	4	4	4	6
	4	4	4	5

the overall dimensional changes, with the exception that λx represents the scale factor along the rolls and λy the scale factor across the rolls. In the tables the numerical values of λx are listed in the first row and those of λy in the second row. The meaning of data in the third and fourth rows is the same as in the tables for overall scale changes. In all these figures the linear influence of the initially introduced deformation (at the time of master grid printing), which was predominant in the y-direction, is obvious.

For Laboratory 1 (Figure 6) the dispersion of scale factors in both directions is below 0.01 percent. For Laboratory 2 (Figure 7) the dispersion of the results, as could have been expected, is larger. The maximal dispersion of 0.015 percent (derived from values λy at $t=0$) can be explained by the fact that the conditioning of the film to the new environment was not completed. The maximum of 0.015 percent (from values λx at $t=3$) and the irregularities shown on the graph for Frame 2317, are difficult to explain. They may be attributed to some adverse influences present at the time of printing or measuring, except that the printing procedure was the same for cuts from all three laboratories, and rechecking the measurements did not reveal any significant difference in comparison to other samples. The mean-square error in the last column, which corresponds to the frames printed at time $t=4$, indicates the presence of slight irregularities in the dimensional changes. Generally the same trends may be observed in Figure 8 which is representing the results obtained from the cut processed by Laboratory 3.

The averages of the results from all three laboratories are shown in Figure 9. The diagrams for λx and λy indicate a remarkable consistency in behavior in both x- and y-direction, especially for those observed from the first week ($t=1$) onward. The relative dimen-

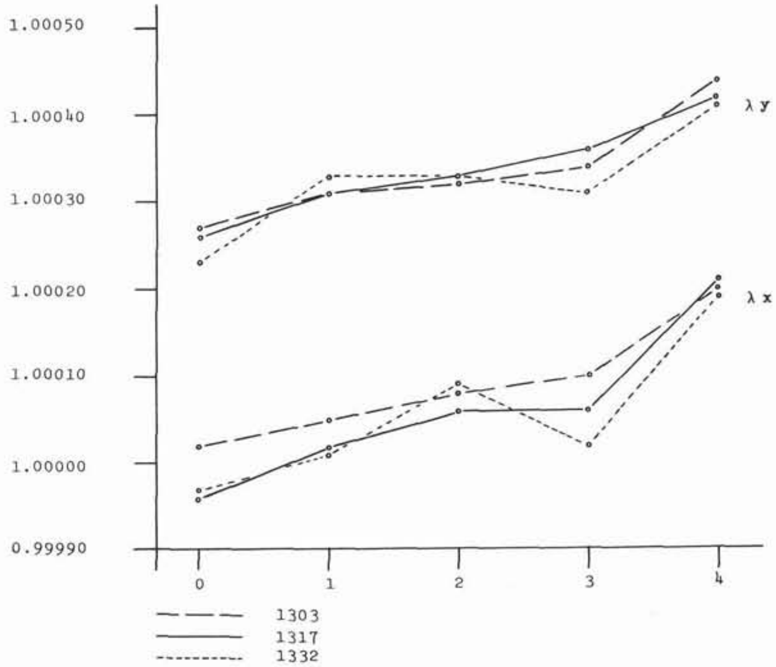

FIG. 6. The dispersion of the scale factors of the three films for Laboratory 1 plotted as a function of time and based on affine transformations. See Figure 2 and Table 6.

TABLE 6. NUMERICAL DATA CORRESPONDING TO FIGURE 6.
The first and second rows are the scale factors in x and y, respectively

1.00002	1.00005	1.00008	1.00010	1.00020
1.00027	1.00031	1.00032	1.00034	1.00044
1303	3	3	3	5
	2	3	3	4
0.99996	1.00002	1.00006	1.00006	1.00021
1.00026	1.00031	1.00033	1.00036	1.00042
1317	3	3	3	3
	3	3	4	3
0.99997	1.00001	1.00009	1.00002	1.00019
1.00023	1.00033	1.00033	1.00031	1.00041
1332	2	3	2	3
	3	3	3	3

sional changes in the x-direction, derived from differences of λx for $t=4$, are: -0.017 percent for Laboratory 1, -0.015 percent for Laboratory 2, and -0.018 percent for Laboratory 3. The relative dimensional changes in y-direction, derived from corresponding λy values are: -0.010 percent for Laboratory 1, -0.010 percent for Laboratory 2 and -0.015 percent for Laboratory 3.

THE RESULTS discussed up to now were from the group of 36 diapositives made from the cuts of the same roll. They were, as already explained, selected to show primarily the aging effect. It is obvious that, for this part of the experiment, the originally recorded pattern on the film was of no consequence, because the results reduced to the ones obtained from the first printing ($t=0$) show only how well this originally printed pattern was preserved on the film through the six-month period. The following results belong to the group of 45 diapositives indicating the behavior of cuts from different rolls when processed by the same laboratory.

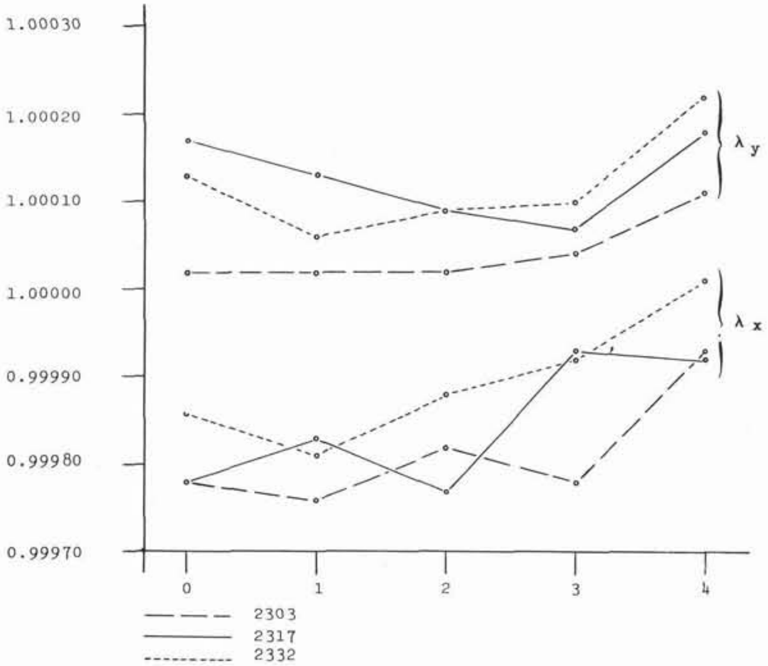

FIG. 7. The dispersion of the three scale factors for Laboratory 2, as in Figure 6. See Table 7.

TABLE 7. NUMERICAL DATA CORRESPONDING TO FIGURE 7. SEE TABLE 6

0.99978	0.99976	0.99982	0.99978	0.99993
1.00002	1.00002	1.00002	1.00004	1.00011
2303	3	3	3	6
	4	3	3	4
0.99978	0.99983	0.99977	0.99993	0.99992
1.00017	1.00013	1.00009	1.00007	1.00018
2317	4	3	4	4
	3	4	4	3
0.99986	0.99981	0.99988	0.99992	1.00001
1.00013	1.00006	1.00009	1.00010	1.00022
2332	4	4	4	5
	4	4	3	3

EACH OF the nine vector diagrams, presented in Figure 10, represents the averages of residual errors from five frames belonging to the same cut. Since this particular set of nine patterns was derived from the results of orthogonal transformations (corrective deformation of the original pattern not applied) the vectors are representative of the combined influences of all the sources of errors. Upon inspecting the figure, the coincidence of the patterns for cuts from different rolls processed by the same laboratory is quite prominent, although scarcely any coincidence of patterns is evident for cuts from the same roll processed by different laboratories. The apparent similarity of patterns for Laboratories 2 and 3 reflects the similar processing conditions in these two laboratories (see Table 1).

The scale factors λ, determined by similarity transformation and representing the overall dimensional changes of all 45 frames from nine cuts, are listed in Table 10. (The frame numbers (see Figure 1) indicate the position of the frame on the particular cut). The coherence of these factors through the

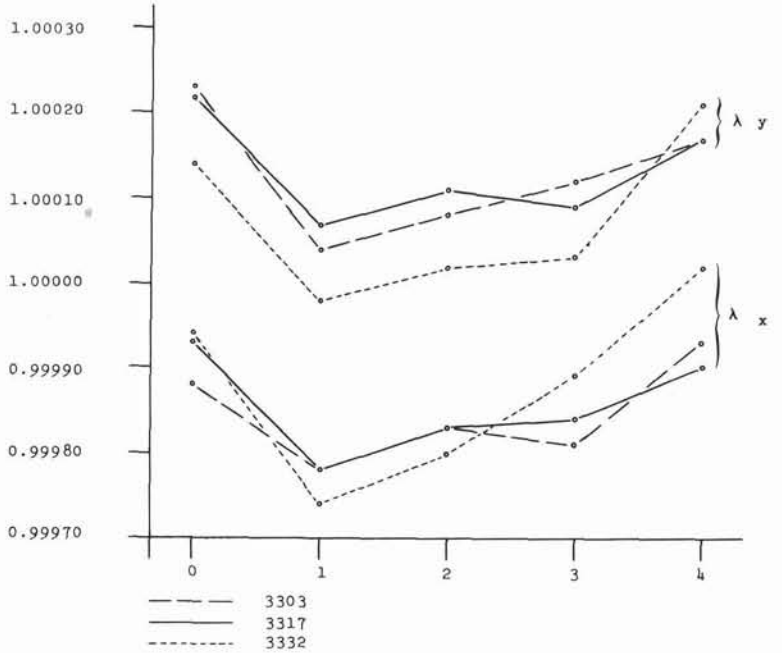

FIG. 8. The dispersion of the three scale factors for Laboratory, as in Figure 6. See Table 8.

TABLE 8. NUMERICAL DATA CORRESPONDING TO FIGURE 8. SEE TABLE 6

0.99988	0.99978	0.99983	0.99981	0.99993
1.00023	1.00004	1.00008	1.00012	1.00017
3303	3	4	3	4
	4	4	3	3
0.99993	0.99978	0.99983	0.99984	0.99990
1.00022	1.00007	1.00011	1.00009	1.00017
3317	3	3	4	4
	2	3	3	3
0.99994	0.99974	0.99980	0.99989	1.00002
1.00014	0.99998	1.00002	1.00003	1.00021
3332	5	3	5	8
	4	2	3	5

columns suggest the absence of significant fluctuations in overall dimensional changes for frames belonging to cuts from different rolls and processed by the same laboratory.

The last two rows in the table contain the mean scale factor for each laboratory and the corresponding mean square errors derived from the discrepancies between the mean factors and the factors for individual frames. Considering that a change of 1 percent R.H. causes a relative dimensional change of approximately 0.0025 percent and that a change of 1°F causes a relative dimensional change of approximately 0.001 percent, and taking into account all potential sources of errors acting upon the film during the experiment, these mean-square errors may be regarded as satisfactory. The average scale factors indicate an overall shrinkage of -0.014 percent for the cuts processed by Laboratory 1 and negligible overall scale changes for those processed by Laboratories 2 and 3.

SOMEWHAT BETTER insight into the linear homogeneous deformations is offered by the results of affine transformations listed in Table 11. The mean of scale factors λx for Laboratory 1 indicates that practically no

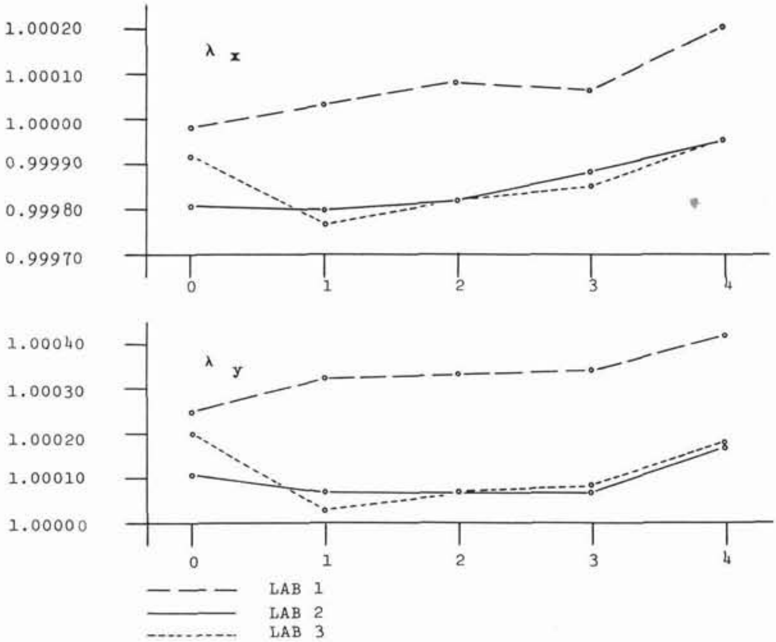

FIG. 9. The average dispersions for the three laboratories, as in Figure 6. See Table 9.

TABLE 9. NUMERICAL DATA CORRESPONDING TO FIGURE 9. SEE TABLE 6

0.99998	1.00003	1.00008	1.00006	1.00020
1.00025	1.00032	1.00033	1.00034	1.00042
LAB 1	±3	±3	±3	±4
	±3	±3	±3	±3
0.99981	0.99980	0.99982	0.99988	0.99995
1.00011	1.00007	1.00007	1.00007	1.00017
LAB 2	±4	±3	±4	±5
	±4	±4	±3	±3
0.99992	0.99977	0.99982	0.99985	0.99995
1.00020	1.00003	1.00007	1.00008	1.00018
LAB 3	4	3	4	5
	3	3	3	4

scale change took place in the *x*-direction of frames from the cuts processed by this laboratory. The mean for λy factors indicates a relative shrinkage of 0.028 percent. For Laboratories 2 and 3 an expansion is evident in the *x*-direction and shrinkage in the *y*-direction (these shrinkages are smaller than the ones found for Laboratory 1). The differences in relative dimensional changes between the *x*- and *y*-directions, derived from the means of corresponding λx and λy, are: 0.027 percent for Laboratory 1 and 0.031 percent for Laboratories 2 and 3. These differences are mainly the consequence of the affine deformation introduced at the time of master grid printing.

A comparison may be of interest of the intervals in which the fluctuations of dimensional changes for all 81 frames took place. For the group of 36 diapositives these intervals are derived from the maximal and minimal values of the corresponding scale factors. The intervals for the overall dimensional changes are: 0.022 percent for Laboratories 1 and 2, and 0.025 percent for Laboratory 3. For affine deformations they are: 0.025 percent in *x*- and 0.021 percent in the *y*-direction for Laboratory 1, 0.025 percent and 0.020

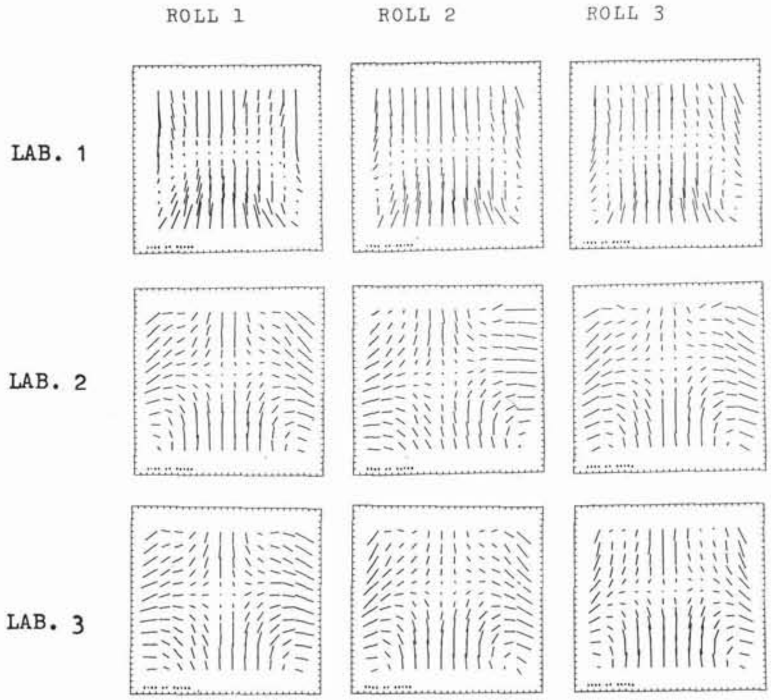

FIG. 10. Vector diagrams representing the average residual errors for five frames belonging to the same cut.

percent for Laboratory 2, and 0.028 percent and 0.025 percent for Laboratory 3. For the group of 45 diapositives the intervals of the same order of magnitude are indicated by the mean square errors listed in Tables 10 and 11.

FROM THE analysis and discussion of the results, it is evident that, in spite of different and sometimes quite unfavorable conditions to which the film was exposed, they reproduce with remarkable consistency those properties of Estar-base aerial films that pertain to their linear homogeneous deformations. These results also agree well with findings from other experiments performed with methods and technique different from those used in this test. From a preliminary analysis of other than linear homogeneous deformations in these samples, it seems that their detection and correction can be successfully handled in practice by techniques based on grid-comparator methods. It is also obvious that a strict control of procedures and conditions during printing and processing can considerably reduce the deformations. In this sense the main difficulty remains with the control of conditions in the camera and its environment during the actual photographic mission. This has been clearly demonstrated by Carman and Martin [1968]. In analyzing the difficulties that have to be overcome in order to bring the quality of geometrical information recorded on film to a par with the potential geometric accuracy attainable by present day photogrammetric equipment,

TABLE 10. SCALE FACTORS AFTER A SIMILARITY TRANSFORMATION

Roll No.	*Frame No.*	*LAB 1* λ	*LAB 2* λ	*LAB 3* λ
1	03	1.00017	0.99999	0.99986
	10	1.00016	1.00000	0.99998
	17	1.00018	1.00004	1.00000
	24	1.00011	0.99999	1.00002
	32	1.00014	1.00003	1.00000
2	03	1.00021	0.99998	0.99995
	10	1.00013	1.00000	1.00002
	17	1.00017	0.99998	0.99996
	24	1.00015	0.99993	1.00005
	32	1.00011	1.00000	1.00001
3	03	1.00015	0.99990	1.00005
	10	1.00010	0.99999	1.00006
	17	1.00011	0.99998	1.00008
	24	1.00011	0.99995	1.00002
	32	1.00010	1.00000	1.00004
Average		1.00014	0.99998	1.00001
S		±0.00003	±0.00004	±0.00005

TABLE 11. SCALE FACTORS AFTER AFFINE TRANSFORMATIONS

Roll No.	*Frame No.*	*LAB 1* λ*x*	λ*y*	*LAB 2* λ*x*	λ*y*	*LAB 3* λ*x*	λ*y*
1	03	1.00006	1.00029	0.99981	1.00016	0.99972	1.00001
	10	1.00004	1.00028	0.99982	1.00018	0.99983	1.00013
	17	1.00007	1.00029	0.99990	1.00018	0.99986	1.00015
	24	1.00000	1.00023	0.99984	1.00014	0.99984	1.00020
	32	0.99996	1.00031	0.99987	1.00019	0.99978	1.00021
2	03	1.00006	1.00035	0.99984	1.00012	0.99983	1.00006
	10	0.99996	1.00030	0.99985	1.00015	0.99987	1.00017
	17	1.00003	1.00030	0.99988	1.00008	0.99981	1.00012
	24	1.00001	1.00029	0.99976	1.00010	0.99989	1.00021
	32	0.99993	1.00030	0.99982	1.00018	0.99985	1.00017
3	03	1.00002	1.00027	0.99978	1.00002	0.99988	1.00023
	10	0.99998	1.00021	0.99988	1.00010	0.99994	1.00018
	17	0.99996	1.00026	0.99978	1.00017	0.99993	1.00022
	24	0.99997	1.00026	0.99978	1.00013	0.99984	1.00019
	32	0.99997	1.00023	0.99986	1.00013	0.99994	1.00014
Average S		1.00001 ±0.00004	1.00028 ±0.00004	0.99983 ±0.00004	1.00014 ±0.00005	0.99985 ±0.00006	1.00016 ±0.00006

methods and techniques, it seems that more serious consideration should be given to the proposals put forward by Blachut [1966].

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Notice to Contributors

1. Manuscripts should be typed, double-spaced on $8\frac{1}{2}\times 11$ or $8\times 10\frac{1}{2}$ white bond, on *one* side only. References, footnotes, captions—everything should be double-spaced. Margins should be $1\frac{1}{2}$ inches.
2. *Two* copies (the original and first carbon) of the complete manuscript and two sets of illustrations should be submitted. The second set of illustrations need not be prime quality.
3. Each article should include an abstract, which is a *digest* of the article. An abstract should be 100 to 150 words in length.
4. Tables should be designed to fit into a width no more than five inches.
5. Illustrations should not be more than twice the final print size: *glossy* prints of photos should be submitted. Lettering should be neat, and designed for the reduction anticipated. Please include a separate list of captions.
6. Formulas should be expressed as simply as possible, keeping in mind the difficulties and limitations encountered in setting type.