Nonuniform Dimensional Changes in Topographic Aerial Films[*]

P. Z. ADELSTEIN[†] AND D. A. LEISTER[†]
Eastman Kodak Co.

ABSTRACT: *A study has been made of the nonuniform dimensional changes which can occur in aerial film negatives. The method of measurement employs the principle of moiré. A 300-line halftone pattern is exposed onto the aerial film by contact from a glass plate. After processing, the film negative is reregistered with the plate. Dimensional changes are measured from the resulting moiré pattern and any nonuniformity is quantitatively determined. Precision of the method is such that the standard deviation is 0.002% size change. Distortions are expressed as standard deviations of the processing dimensional change within a 9″×9″ frame.*

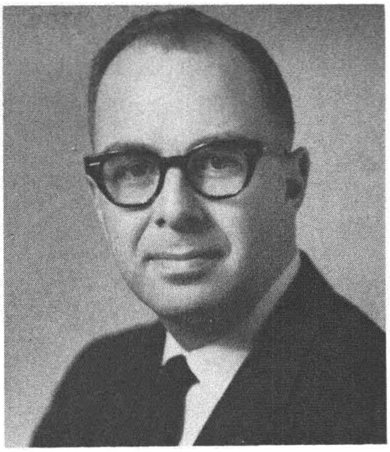
Measurements were made of the dimensional behavior due to processing in a tray, in a rewind mechanism, and in a continuous machine. Nonuniform dimensional changes in a single frame of topographic aerial film on cellulose acetate butyrate base can result in a standard deviation of 0.03% size change. This could account for a random linear displacement of 30 microns in some cases. Estar polyester base topographic aerial films show a much higher degree of dimensional uniformity, and random linear displacements are usually less than 5 microns.

Dimensional errors may result when film is dried only to sensible surface dryness after processing. This is manifested both by the overall film size and by dimensional distortion.

INTRODUCTION

IN PHOTOGRAMMETRIC work, the importance of high precision has been well recognized. Much work has been done over the years to improve camera design, to minimize lens distortion, and to provide better plotting instruments. A very important component of the photogrammetric system is the photographic film, and this has been receiving increasing attention in recent years.

One of the earliest studies of the dimensional changes of photographic aerial film was by Davis and Stovall (1) in 1937 and Carver (2) in 1938. This was followed by the work of Carman (3) in 1946 and by an extensive discussion of this subject the following year by Calhoun (4). This latter paper presented comprehensive laboratory data on the size changes due to humidity, temperature, processing and aging. Moreover, the importance in photogrammetric work of minimizing dimensional differences between the length and width directions was emphasized. In fact it is usually more important for the length-width differences in size or "differential distortions" to be kept to a minimum rather than for the overall size change to be small. The latter can be corrected by a change in magnification. The magnitude and importance of length-


P. Z. ADELSTEIN

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[†] Manufacturing Experiments Division, Eastman Kodak Company, Rochester 4, New York.

width differential changes was also reported by Atwell (5) and Filmer (6).

However, in the Calhoun paper, the work was concerned with overall or average size changes. Results were not available on possible nonuniform dimensional changes or "local distortions." These latter effects can be as important as length-width size change differences, since they would result in errors in the photographic image, as has been emphasized by Eden (7) and Sadler (8).

Over the past ten years there has been considerable activity investigating possible nonuniform dimensional changes of film. Most of this work has consisted of exposing a reseau or grid on the film, and subsequently comparing the intersections of this grid with the glass master, using an optical comparator. In 1951, McNeil (9) reported that the displacement of the grid intersections could amount to 30 microns. He found that these displacements were fairly systematic. In 1956, a similar study was done on spectroscopic glass plates (10) and displacements of 5 to 15 microns were observed near the edges of the plates. These were attributed to distortions of the gelatin emulsion.

One of the most comprehensive studies was made in the same year by Brucklacher and Luder (11) using the grid and optical comparator method. They found that nonuniform dimensional changes amounted to ±2.4 microns* for plates and 4.3 microns* for the film-plate combination. They did report a value as high as 25 microns in one experiment. These authors observed no effect due to film aging but some effects due to uneven heating during drying or uneven illumination.

Altman and Ball (12) used a similar experimental technique but were concerned primarily with photographic plates. They did limited work with photographic film and observed nonuniform dimensional changes of 3.5 microns.

In a recent study, Calhoun, Keller and Newell (13) departed from the grid-optical comparator system because of the laborious nature of the procedure. Instead they exposed the film to a 50-per cent halftone pattern on a glass plate. The halftone pattern was like that of a checkerboard where each square was 2.38 mil (60 microns) on a side. The spacings between these halftone squares in any one row were measured with a recording microdensitometer. The relative position of these squares compared to the glass master was electronically computed and gave a measure of the nonuniform dimensional changes. The limit of detectability of nonuniform dimensional changes using this method was about three microns. No evidence of local distortions larger than this value was found in aerial films that were processed and handled carefully. Local distortions caused by waterspots were observed which were as large as 18 microns. It should be noted that in this work the nonuniformity of dimensional change could only be measured over a relatively small length. This method is not suited to study changes over a complete aerial film frame.

These authors also described a second method to detect small random dimensional changes in film using a moiré pattern. This method also required the exposure of a halftone pattern onto the aerial film. After processing, the film negative was registered with the original glass halftone. Any difference in dimension between the glass plate and the film, due to shrinkage or swell of the latter, caused a moiré pattern. Nonuniformities in dimensional change showed up as distortions in the moiré pattern, and their magnitude could be determined. This procedure has the advantage of being quite rapid, and is capable of detecting nonuniform dimensional changes which might be missed in the grid method. Calhoun et al observed distortions in the moiré pattern due to waterspots, excessive heating, and high film tensions during processing. Limited work under normal handling conditions showed no evidence of nonuniform dimensional changes.

Subsequent to this study, a preliminary comparison was reported (14) between cellulose acetate butyrate base and Estar‡ polyester base aerial films using the moiré method. This showed lower overall size change for the Estar base film and greater uniformity between the different directions compared to the cellulose acetate butyrate base film. This agreed with the findings of Harman (15) on polyester base film.

The present paper reports the continuation of the investigation of nonuniform dimensional changes in aerial film using the moiré pattern method. A more comprehensive comparison between cellulose acetate butyrate base and Estar base films has now been made, and the effect of normal processing and handling has been studied.

DEFINITIONS

In studies on the dimensional stability of aerial film, many terms have been used to

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* Lineal displacements.

‡ "Estar" is a registered Trade Mark of the Eastman Kodak Company.

describe some of the dimensional distortions that can occur. To avoid confusion, it is advisable to briefly define the various types of distortion that will be referred to in this paper.

"*Differential distortion*" is the difference in the average dimensional change between any two film directions. This may or may not be the length and width directions.

"*Local distortion*" is considered a nonuniformity in film dimensional change that is confined to a relatively small area (roughly one-half inch square). Previous work (13) has indicated, for example, that these can be caused by waterspots.

"*Unidirectional distortion*" is a term used in this paper to describe the nonuniformity in film dimensional change within a given film direction. In other words, this describes the distortion when the lengthwise dimensional change in one area of the frame differs from the lengthwise change in another area.

"*Overall distortion*" is the nonuniformity in film dimensional change between all areas and all directions of the frame. It includes the differential and unidirectional distortions.

Experimental Procedure

"Moiré" is the name given to the pattern formed by superimposing two halftone photographs (Figure 1). It applies to the pattern of light and dark areas formed by the interference of the light and dark areas in the two halftones. It is actually a mechanical interference pattern. An explanation of the moiré pattern, and the calculations that can be made from such patterns, was described in detail in earlier papers (13, 16). The salient features of this technque are briefly reviewed.

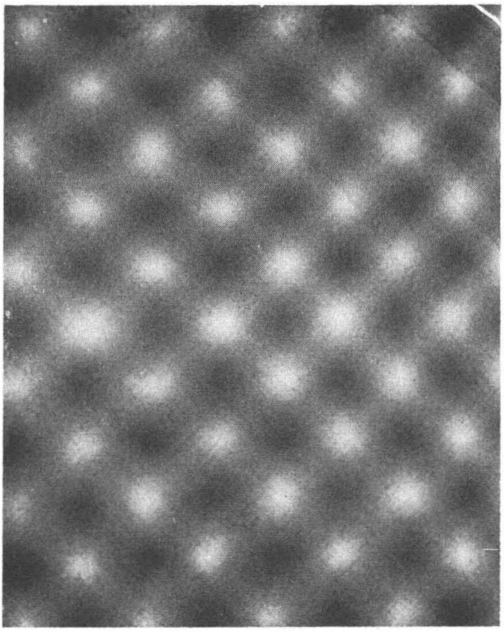

FIG. 1. Continuous tone photograph of a typical moiré pattern.

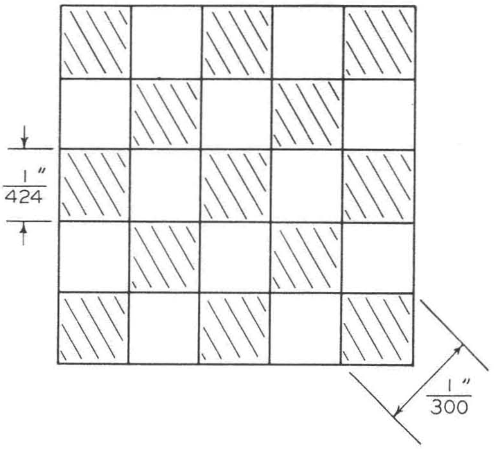

FIG. 2. Illustration of a 300-line per inch, 50% halftone pattern.

In this study, all exposures were made from a 300-line halftone print. This consists of an opaque and clear area checkerboard pattern in which the opaque areas comprise 50% of the total. As shown in Figure 2, there are 424 squares-per-linear-inch in the directions parallel to the edges and 300 squares-per-linear-inch in the diagonal directions. Visually, without magnification, the halftone has a uniform gray density.

When two identical halftone prints are superimposed so that their rows of squares are parallel, either of two extreme conditions can occur. If an opaque area of one halftone is directly above an opaque area of the second halftone, then the sandwich has an overall gray appearance, since about 50% of the light is transmitted. However, if an opaque area is directly above a clear area, then the overall appearance is opaque. The light transmitted through the sandwich can be varied from 0 to 50% depending on the degree of overlap of the opaque areas in the two halftones. Since the size of the squares in the two is identical, the sandwich will only appear as various shades of gray. A moiré pattern will not result.

However, if one halftone print has been allowed to shrink relative to the other, then the size of the squares in the two is obviously not the same. When these prints are superimposed without rotation so that the rows of squares are parallel, the relative degree of registration varies from one edge of the print to the other. Assume for example

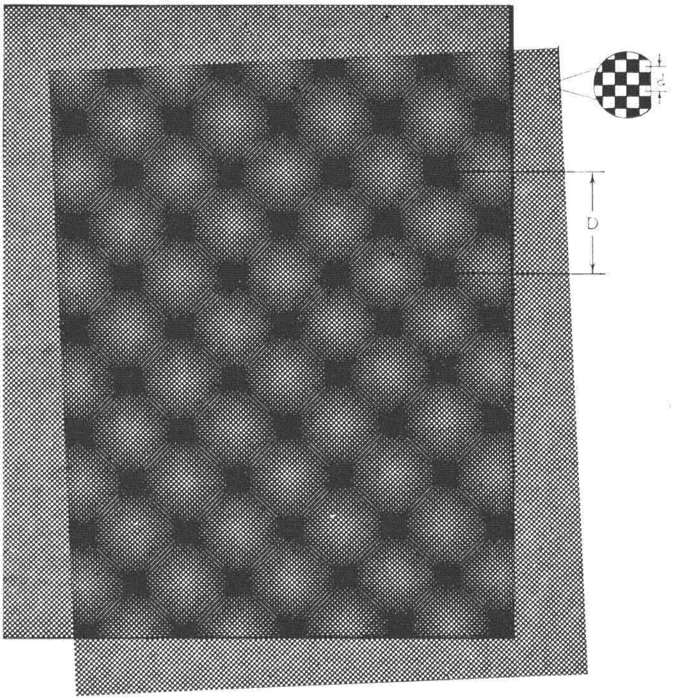

FIG. 3. Moiré pattern formed by two superimposed halftone prints.

that the clear areas are in register at one edge of the print, then at some distance from the edge of the pattern the clear areas are completely out of register. This results in zero per cent light transmission through the sandwich and the appearance of a "moiré dot." When the total shrinkage of one of the halftone prints equals the spacing of one clear and one opaque halftone square, a moiré dot is formed in the center of the area. In other words, the distance between moiré dots can be used to quantitatively calculate the shrinkage of the film print. The greater the shrinkage, the closer is the spacing between the moiré dots.

Figure 3 illustrates a typical moiré pattern formed by superimposing two halftone prints which are out of size. The percent dimensional change can be calculated from the formula

$$\% \text{ dimensional change} = \frac{d}{D} \times 100$$

where

d is the distance between two opaque areas in the halftone pattern, and
D is the distance between two moiré dots.

The larger the magnitude of D, or the smaller the value of d, the greater is the precision of this method. In this study, the value of D is limited by the size of the aerial film negative, that is, $9\frac{1}{2}$ inches. The 300-line halftone pattern pictured in Figure 2 is the finest that is currently available which meets the necessary requirement of pattern uniformity. Therefore, a single moiré dot spacing is formed when the relative shrinkage of the two halftone prints is 0.05%. However, measurements of the nonuniformity of dimensional change require at least three or four moiré dot spacings in each film dimension, and this would only occur if the overall size difference amounts to 0.2%. To improve the precision of this system, the halftone print was registered with a second print that was deliberately made "off size." The steps involved in this process are illustrated in Figure 4. Two master halftone glass plates were used which differed in magnitude by 0.17%. Otherwise these two halftone plates were identical. The aerial film negative (or other photographic plate or film) under study was then contact printed with one of the glass plate masters, and after processing, it was registered with the second. This produces a satisfactory moiré pattern.

The contact printing of the film negative from the glass master, and the subsequent registration was accomplished using a vacuum frame. The film was "sandwiched" between

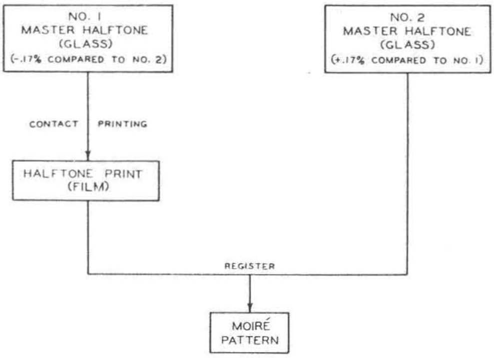

FIG. 4. Steps in moiré pattern method used to measure uniformity of dimensional change.

two microflat glass plates ($\frac{1}{4}''$ thick), one containing the master halftone, and a vacuum was applied as shown in Figure 5. Use of this vacuum printing frame ensured close plate-film contact. Permanent records of the moiré patterns were made by photographing the plate-film sandwich through the printing frame. All measurements of moiré dot spacings were made directly from the photographic record.

PRECISION OF THE METHOD

To determine the overall error involved in this method, the steps outlined in Figure 4 were made with the master glass halftone being exposed onto another glass plate. The glass plate material used was specially made Kodalith Ortho Type 3 on $\frac{1}{4}''\times 12''\times 12''$ glass with a surface flatness of .00002 in./in.* The moiré pattern produced by registration of the processed Kodalith plate with the second glass plate master is shown as a high contrast print in Figure 6. The uniformity of the moiré pattern was quantitatively evaluated by measuring the distances between moiré dots.

In each of the length, width and the two diagonal directions of a 9-inch frame, there are usually about eighteen distances which can be measured between adjacent pairs of moiré dots. Therefore, in each of the four directions of the moiré pattern, eighteen values of size change were obtained. For each direction, the average size change and the standard deviation, s, is given in Table I. The standard deviation is a measure of the "unidirectional distortion" in that particular direction. Both the size change and the standard deviation values were extremely small. This will be more evident when corresponding values for photographic film are presented.

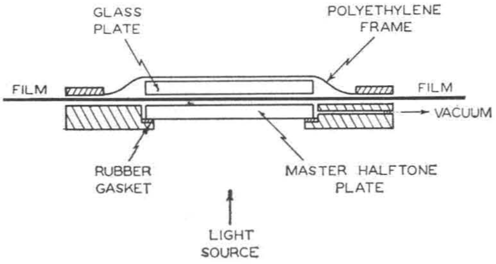

FIG. 5. Vacuum frame used for either printing or registration of film negative.

TABLE I

COMPOSITE ERROR IN THE SYSTEM—USING GLASS PLATE IN PLACE OF AN AERIAL FILM NEGATIVE

Direction	*Size Change, %*			
	Average	*Std. Dev.,* s	*Mean Std. Dev.,* $\bar{s}$	*Overall Std. Dev.,* s_o
Length	−.0003	.0018	.0020	.0021
Width	−.0005	.0018		
Diagonal 1	+.0008	.0024		
Diagonal 2	+.0002	.0021		

The mean standard deviation value, $\bar{s}$, is the mean of the standard deviations for the four different directions. This value indicates the average standard deviation between measurements of size change in any particular

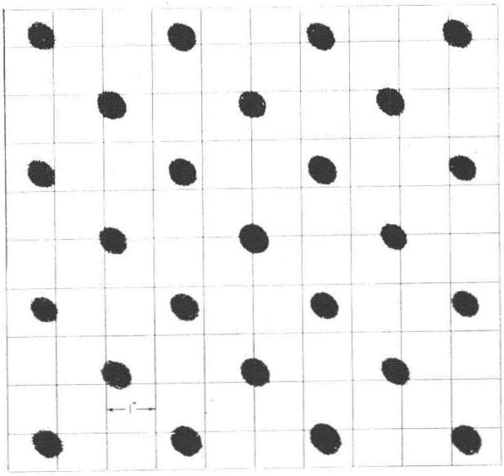

FIG. 6. High contrast print of moiré pattern formed by two halftone patterns on glass plates which were offsize by 0.17%.

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* A standard means of indicating surface flatness. The units are inches per linear inch on the plate.

direction. It can be considered as a measure of the average "unidirectional distortion" for the frame. The value of 0.002% for the glass Kodalith negative indicates excellent uniformity of size change in any one direction.

The overall standard deviation, s_o, is calculated from all 72 measurements of moiré dot spacings made on the moiré pattern. This value not only reflects the variation in size change in any one direction, but also the variation between different directions. It is a measure of both the "unidirectional distortion" and "differential distortion," and therefore can be considered indicative of the "overall distortion."* Since the distance between moiré dots varies from two to three inches, the values of s_o would not reflect any "local distortions" if these are present. However, such "local distortions" would show up as a density variation in the moiré pattern as described earlier (13).

The very low s_o measurement of 0.002% for the glass negative shows the high uniformity of the moiré dot pattern produced by this experimental procedure. This value is considered the limit of the precision of this system and proves to be more than adequate for a study of photographic film. The measurements reflect the difference in the halftone pattern of the two glass plate masters; the nonuniform dimensional changes in the emulsion on the Kodalith glass negative due to processing; and the errors in the measurement of the moiré dot spacings. The last is believed to be the dominant factor.

The reproducibility of this system was also evaluated using photographic film. Six successive moiré patterns were made by reregistering a single frame of film and a glass master positive. Subsequent measurements of the moiré dot spacing showed that the differences in overall standard deviation (s_o) of all six patterns were less than 0.002% size change.

INTERPRETATION OF THE METHOD

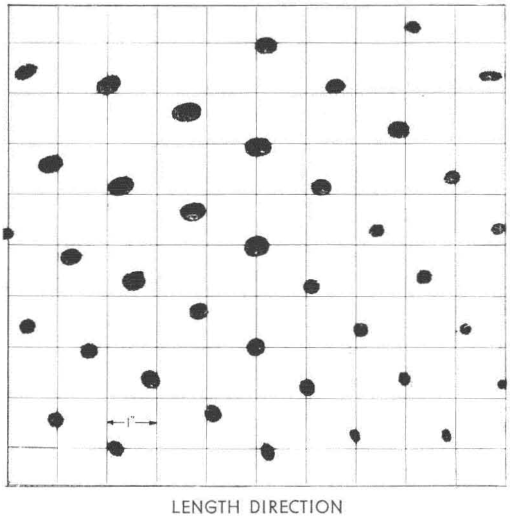

FIG. 7. High contrast print of moiré pattern formed from halftone print on distorted film and master halftone glass plate. (This illustrates distortion obtainable on cellulose acetate butyrate base film used under uncontrolled temperature and humidity conditions.)

Table I illustrates that ten numerical values are used to describe the uniformity of a moiré dot pattern. These are the average size change of the film in each of four directions; the standard deviation of this size change in these same four directions; the mean standard deviation $\bar{s}$; and the overall standard deviation s_o. The physical meaning of these numerical parameters can be described best by consideration of a moiré pattern produced by a distorted frame of photographic film. Such a moiré pattern is given in Figure 7 and was obtained as outlined in Figure 4. The ten numerical values describing the moiré pattern are listed in Table II. The types of film and processing conditions which show this behavior will be described later in this paper.

Visual examination of Figure 7 shows a high

TABLE II

EVALUATION OF THE MOIRÉ PATTERN OF A BADLY DISTORTED AERIAL FILM NEGATIVE

Direction	*Size Change of Film Negative, %*			
	Average	s	$\bar{s}$	s_o
Length	−.031	.034	.021	.028
Width	−.063	.010		
Diagonal 1	−.023	.020		
Diagonal 2	−.063	.020		

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* A more exact method of evaluating this "overall distortion" would be the use of the "Analysis of Variance" technique to obtain the appropriate components of variance. However, the shorter method of computing s_o from all 72 measurements is satisfactory for this study since both the Estar polyester and cellulose acetate butyrate values are obtained from the same type and number of measurements. A more basic problem involving these estimates is the fact that the measurements are somewhat interrelated. Further study is being conducted to reduce this complication. However, the relative results of the comparison between the two film bases should not be affected seriously and the s_o terms should serve as a reasonable method of comparison.

degree of nonuniformity in dimensional change, particularly when Figure 7 is compared to the uniformity inherent in this method, as illustrated in Figure 6. This nonuniformity is numerically expressed by the relatively high values shown in Table II. Of particular concern is not the magnitude of the size change values themselves, but the fact that they are not uniform even within a given direction. This is shown by the four standard deviation values which range from 0.010 to 0.034%. The mean standard deviation in this example is more than tenfold greater than that found in glass plates.

The differences in the different directions are taken into consideration in the overall standard deviation of 0.028%. This can be interpreted to mean that about 60 per cent of the time a given point in this film will show a displacement from its correct position of less than 0.028% of its distance from any other point. Relative to the center of a 9-inch frame, a significant percentage of the points can show a displacement greater than 0.00028 ×4.5 inches, or 32 microns. For a 20,000:1 reduction, this would amount to an error in horizontal ground measurement of two feet. This may be of concern to the photogrammetrist in some applications. It should be pointed out that this value refers to the *nonuniformity* in size change which cannot be corrected by simple magnification of the film negative.

A pictorial representation of the nonuniformity in size change is shown by the illustration in Figure 8. This shows a drawing of two moiré patterns, for two films, superimposed one on the other. The broken lines and open dots represent a film with uniform dimensional change, and the solid lines and solid dots represent the film shown in Figure 7 which has a nonuniform dimensional change. The relative amount of displacement and direction of displacement in the area of the moiré dots is shown by the dotted lines. This nonuniform size change is relative to the center of the film which is in register at points *A* and *B*. This represents the area of both films which have been adjusted by printing to the same average size change.

RESULTS

COMPARISON OF CELLULOSE ACETATE BUTYRATE AND ESTAR BASE FILMS

The relative performance of cellulose acetate butyrate and Estar polyester base aerial films was studied using 75-foot by 9½-inch rolls. The films were first exposed to the master halftone plate at a controlled condition of 70°F., 50% R.H. The film in the can is at a moisture equilibrium close to this humidity. Eight exposures were made at equal

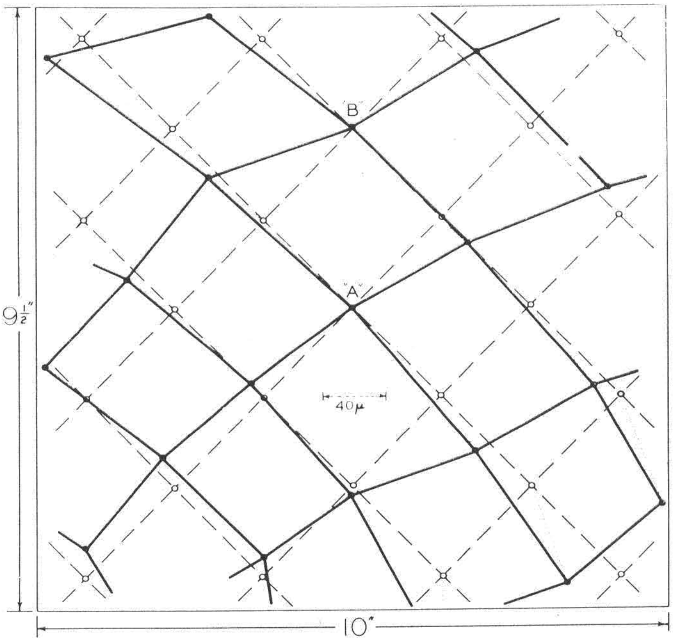

FIG. 8. Drawing of two superimposed moiré patterns, one showing uniform (broken lines) and the second showing nonuniform (solid lines) dimensional changes.

TABLE III

NONUNIFORM PROCESSING SIZE CHANGE OF AERIAL FILM NEGATIVES

Film	*Processing Size Change of Film Negative,*** %									
	Average				*Standard Deviation*				*Mean Std. Dev.* $\bar{s}$	*Overall Std. Dev.* s_o
	Length	*Width*	*Diagonal 1*	*Diagonal 2*	*Length*	*Width*	*Diagonal 1*	*Diagonal 2*		
Kodak Plus-X Aerographic Film, Type 5401*	+.015	−.027	+.006	+.004	.010	.007	.012	.010	.010	.017
Kodak Super-XX Aerographic Film, Type 5425*	+.008	−.080	−.016	−.015	.003	.010	.007	.007	.007	.027
Kodak Special Plus-X Aerial Film (Estar Base), Type SO-135	−.015	−.022	−.016	−.017	.002	.002	.003	.003	.003	.004

* Cellulose acetate butyrate base.
** Measured at 70°F., 50% R.H. before and after processing.

intervals throughout the 75-foot rolls. The films were then processed in a Morse Rewind Processor, Type B-5, and dried on a Smith Automatic Electric Dryer, Type A-5. To eliminate film dimensional changes due to a change in the equilibrium relative humidity, the film rolls were conditioned after processing to 50% R.H. prior to registration with the master halftone plate. The dimensional changes due to processing and the standard deviation values, as calculated from the moiré pattern, were averaged for the eight frames of a given roll. These average values, as listed in Table III, are considered typical of the three films studied.

The nonuniformity in dimensional change of the cellulose acetate butyrate base products is appreciable. It should be pointed out that the length-width difference in dimensional change is not surprising. Similar unbalance in aerial films when in roll form and machine processed was reported by Calhoun (4) over fifteen years ago. What is surprising is the variation in dimensional change within a given direction. This is shown by the standard deviation values as high as 0.01%. As illustrated by the example shown in Figure 8, this nonuniformity is not confined to a local area, but is a general departure from uniformity over the complete film frame.

The overall standard deviation, s_o, which takes into consideration the differences in size change in the different directions, was 0.017% for the Type 5401 Plus-X and 0.027% for the Type 5425 Super-XX Aerographic films. As discussed in the previous section, this might account for an error in linear displacement in the film of 30 microns. However, as noted in Figure 8 both smaller and larger values are obtainable.

A consideration of the size changes in the Kodak Special Plus-X Aerial Film (Estar Base), Type SO-135, shows a striking difference in behavior. The nonuniformity in size change both within a given direction ($\bar{s}$) and between directions (s_o) is very low. In fact the values of the standard deviations are barely greater than the errors inherent in the method of analysis. This would amount to a random linear displacement of less than 5 microns between two points which are 4½ inches apart. These data illustrate a very marked improvement in dimensional uniformity of polyester base film compared to cellulose acetate butyrate base film.

Several repeat tests were made of the experiment described in the previous section, and the same relative behavior was found. Differences were found in the magnitude of the nonuniformity of the cellulose acetate butyrate base films, but this nonuniformity was always considerably greater than that observed with the Estar base films. In all cases the uniformity of size change of the polyester base films was excellent.

VARIATION IN SIZE CHANGE THROUGHOUT A ROLL

The behavior of the cellulose acetate butyrate base films also showed some variation within a given roll of film. This is illustrated in Figures 9 through 12. Generally the overall distortion became worse from the outside to the core end of the roll although this pattern was not always observed. However, the Estar base films showed no significant variation throughout the roll

It is noted that the Type 5425 Super-XX film on the cellulose acetate butyrate support showed a greater nonuniformity of size change than the Type 5401 Plus-X film on the same base. As will be discussed subsequently, this is caused by the thicker emulsion layer of the Super-XX film compared to the Plus-X film.

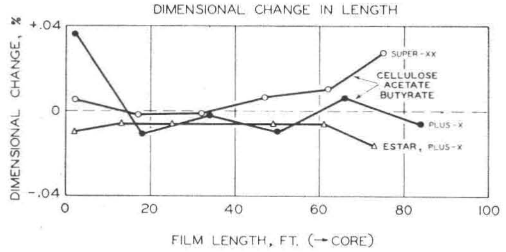

FIG. 9. Processing dimensional change in length direction of aerial film as a result of processing. Film processed in Morse Rewind Processor and dried in Smith Automatic Electric Dryer. After drying, film was conditioned to 70°F.-50% R.H. All films tested as 9½″×75′ rolls. The first and last exposure on the cellulose acetate butyrate base Plus-X film was made on the integral leader and trailer.

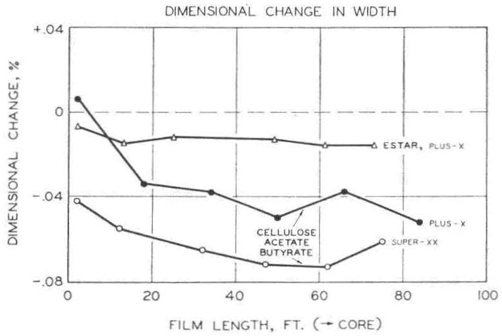

FIG. 10. Processing dimensional change in width direction. (Same experimental conditions as in Figure 9.)

EFFECT OF PROCESSING TYPE

All results reported previously were obtained on aerial rolls processed using the Morse Rewind Processor, Type B-5 and the Smith Automatic Electric Dryer, Type A-5. This represents a practical method of film processing which is widely used in the trade. In addition, films were also developed in a continuous type processor in which the processing and the drying were accomplished in one pass through the machine. For comparison purposes, individual frames of film were cut from a single roll and were given tray processing. Following processing, they were allowed to dry by hanging freely in the air.

The uniformity of dimensional change is shown in Table IV for films processed by the three methods described. These results are the averages obtained on eight different frames throughout one roll for each processing method. As with the previous data, both the exposure and the registration with the master halftone plate were made at 70°F., 50% R.H.

The same pattern observed previously is again evident. Regardless of the method of processing, the cellulose acetate butyrate base films show appreciably higher average "unidirectional distortion" ($\bar{s}$) and much higher "overall distortion" (s_o) than the Estar base films. Similar behavior was observed for all three methods of processing. It is of interest to note that even when the films were tray processed and were not subjected to external tensions, the nonuniformity in size change was appreciable.

PRACTICAL FILM DRYING

All the measurements so far reported were obtained from film that was completely conditioned to 50% R.H. after having attained sensible dryness in the processing or drying

TABLE IV

EFFECT OF PROCESSING METHOD ON THE NONUNIFORM PROCESSING SIZE CHANGE OF AERIAL FILM NEGATIVE

Processing	*Film*	*Type No.*	*Processing Size Change of Film Negative, %***			
			Average		*Mean Std. Dev.* $\bar{s}$	*Overall Std. Dev.* s_o
			Length	*Width*		
Tray Processing	* Kodak Plus-X Aerographic Film	5401	−.030	−.075	.005	.010
	* Kodak Super-XX Aerographic Film	5425	−.050	−.060	.009	.018
	Kodak Special Plus-X Aerial Film (Estar Base)	SO-135	−.015	−.012	.003	.003
Morse Rewind Processor Type B-5 and Smith Automatic Electric Dryer, Type A-5	* Kodak Plus-X Aerographic Film	5401	+.015	−.027	.010	.017
	* Kodak Super-XX Aerographic Film	5425	+.008	−.080	.007	.027
	Kodak Special Plus-X Aerial Film (Estar Base)	SO-135	−.015	−.022	.003	.004
Continuous Type	* Kodak Plus-X Aerographic Film	5401	+.032	−.029	.007	.024
	* Kodak Super-XX Aerographic Film	5425	+.072	−.012	.009	.033
	Kodak Special Plus-X Aerial Film (Estar Base)	SO-135	+.016	+.012	.004	.005

* Cellulose acetate butyrate base.
** Measured before and after processing at 70°F., 50% R.H.

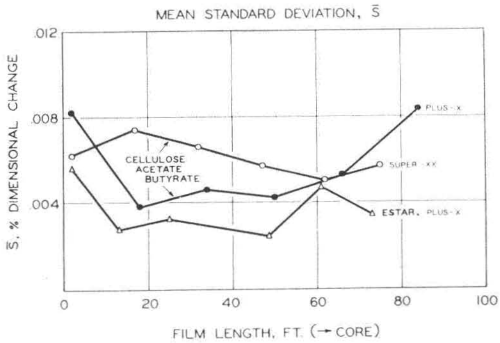

FIG. 11. Mean standard deviation, $\bar{s}$. (Same experimental conditions as in Figure 9.)

equipment. It is recognized that this is an idealized procedure and does not represent a very common method of operation. Size change measurements were therefore made on film that reached sensible dryness, both in the Morse Rewind-Smith Dryer System and in the continuous type processor. The bar graphs in Figure 13 represent the average size change values. Also shown are the average size changes after conditioning the film to 70°F., 50% R.H.

In the rewind system the two cellulose acetate butyrate base films had a very large swell immediately after processing. Although these films appeared dry to the touch, the film base still contained a relatively large amount of moisture. After complete conditioning, these films showed the small shrinkage characteristic of these products. The Estar base film showed only a very small swell after processing. This is due to the low water pickup of this base (14). When the emulsion was dry to the touch, the film contained very little excess moisture; in fact it was very nearly in equilibrium with the ambient conditions.

It should be recognized that the values reported here are very dependent upon the drying conditions used in the A-5 Dryer, such as film speed, temperature and moisture content of the drying air, and the type of baffle system employed. These values point out that under reasonable operating conditions, film may appear to be dry and still contain a large quantity of water. The lower water take-up of Estar base is clearly an advantage.

Under the conditions used in the continuous type processor, the films were better dried than in the rewind system. The two Plus-X films were actually somewhat overdried, whereas the Super-XX film with its thicker emulsion layer was slightly underdried.

The need for complete conditioning of the film for topographic work can not be over-

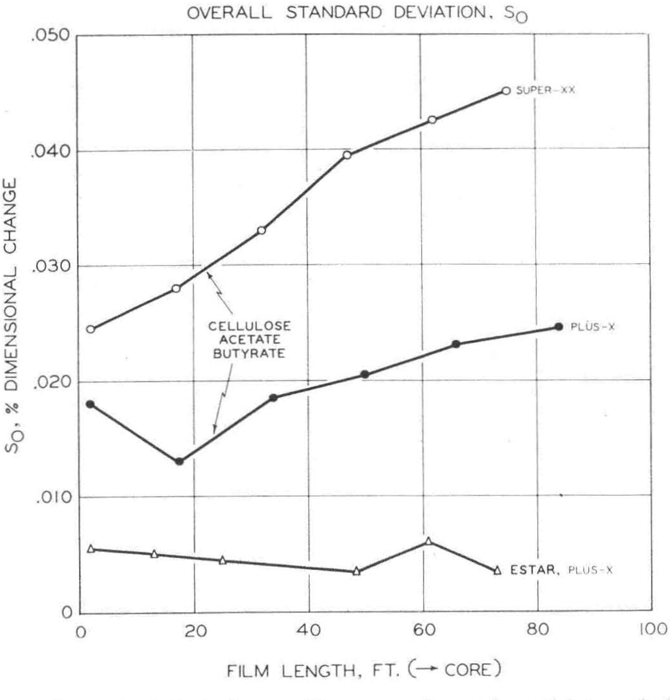

FIG. 12. Overall standard deviation, s_o. (Same experimental conditions as in Figure 9.)

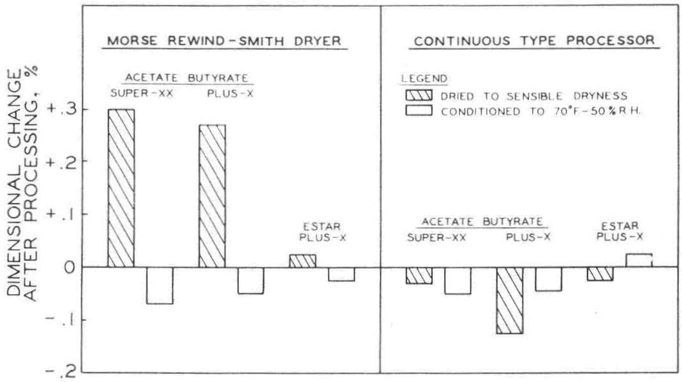

FIG. 13. Dimensional change after processing of $9\frac{1}{2}'' \times 75'$ rolls of aerial films showing effect of drying efficiency. The Smith Dryer was operated at 70°F.-50% R.H. while drying in the continuous machine was at 110°F.-40% R.H. Measurements made using moiré pattern method.

emphasized. Figure 13 illustrates how the overall size may be in considerable error, even when the film is sensibly dry. In addition to the overall size, incomplete drying can result in tremendous errors due to nonuniformity in size change. Figure 14 shows a moiré pattern obtained on Kodak Plus-X Aerographic Film, Type 5401 (cellulose acetate butyrate base) which was underdried. This film remained wound in this condition for about a month, and during this time the edges began to dry out. The moiré pattern shows the short edges and the long center of this roll. This severe nonuniformity can not be completely corrected by subsequent conditioning of the film. During the month of storage, some plastic flow of the film base took place which caused permanent nonuniformity in the film dimensions.

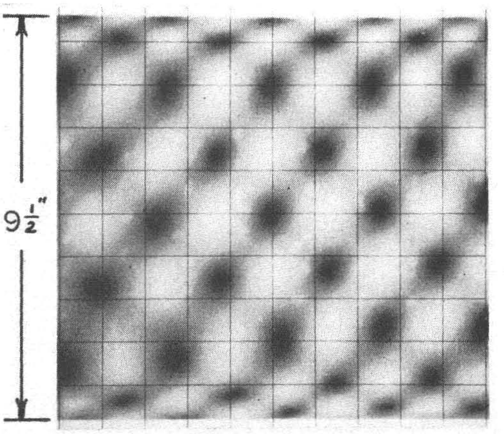

FIG. 14. Moiré pattern of cellulose acetate butyrate base Plus-X Aerographic film illustrating the distortion resulting from nonuniform moisture conditioning during storage of the processed film on a roll. The smaller spacing of the dots along the edge of the film indicates a more thorough conditioning of the edges to the ambient air.

For the ultimate in topographic precision, processed film at the time of printing the diapositives should be in equilibrium with air at the 50% relative humidity which is the condition in the film package. This would require a conditioning time of about an hour for an unwound length of film, but more than half the necessary moisture equilibrium would be reached in ten minutes (17). Where air conditioned space is not available, an improvement in precision is realized if the entire negative is at the uniform humidity of the printing room air.

DISCUSSION

This study has demonstrated that nonuniformity of size change in carefully handled cellulose acetate butyrate base aerial films may be greater than the maximum levels tolerable to the photogrammetrist for some applications. This nonuniformity can occur as the well known length-width unbalance or "differential distortion," and also as a "unidirectional distortion" within a given film direction. The possibility of "local distortions" in areas less than one inch in size was not investigated in the present work.

One of the causes of film nonuniformity is believed to be due to the compressive forces exerted by the emulsion on the base. These result from contraction of the wet emulsion during the drying operation. However, the emulsion does not dry at the same rate over its complete area. (This is evident by the buckling of film which occurs during the course of drying.) Therefore, nonuniform compressive forces of the emulsion result and cause nonuniform dimensional changes in the film due to plastic flow of the base. The better uniformity for the Plus-X film, Type 5401 compared to the Super-XX Film, Type 5425 is due to the thinner emulsion layer of the former. This thinner emulsion causes reduced emulsion compressive forces on the base and consequently less base flow.

The better dimensional uniformity of the Estar base films compared to the cellulose acetate butyrate base films is due to the superior mechanical properties of the Estar support. When plastic base is subjected to a compressive force, it will show (a) an instantaneous elastic compression followed by (b) a time dependent creep or cold flow. Previous studies (14) have shown that the Estar base is considerably stiffer than the cellulose acetate butyrate base. Therefore, it is more resistant to the instantaneous elastic compression and its magnitude of dimensional change is very much less. This elastic compression is believed to be "frozen in" once the emulsion is dry. The earlier investigation (14) also indicated that the creep of Estar base is significantly less than that of cellulose acetate butyrate base. The higher stiffness and lower creep of the Estar support compared to the cellulose acetate butyrate base is greatly accentuated when the supports are wet. This is the practical situation in the drying of film.

Another factor should be noted in a comparison of the cellulose acetate butyrate and Estar base films. The latter films have an emulsion on one surface and a gelatin backing on the opposite side. However, the cellulose acetate butyrate base films have a gelatin layer on only one side. Therefore, during the drying operation, the cellulose acetate butyrate base is subjected to a greater unbalance of forces than the Estar base. This is evident from the film curl and buckle, and helps contribute to the higher nonuniformity in dimensional changes for these products.

The mechanism of base flow due to compressive forces caused by the drying emulsion can be looked upon as due to internal forces in the film. It is also well recognized that external forces, such as machine tensions, can contribute to nonuniformity of size change. This is believed to be another important factor in this particular study, as indicated by the dimensional increase in the lengthwise direction of the cellulose acetate butyrate base films after processing in the Morse Rewind-Smith Dryer and the continuous type processor (Table IV). The tensions used in this study were not considered greater than would occur in practical operations. Estar base films again have an advantage in such instances because of their high stiffness and low flow. It is therefore believed that the excellent mechanical properties of Estar base allow the films to better resist both the compressive forces of the emulsion and the tensile forces of the processing equipment.

It should be emphasized that all the values reported in this paper were obtained from laboratory studies. While the relative behavior of the different film types is well established, the numerical values should not be used to quantitatively predict the random linear displacements found in every practical operation.

CONCLUSIONS

A moiré pattern method can be used to quantitatively measure the dimensional change nonuniformity of aerial films. The precision of this method is such that repeat dimensional change measurements will show a standard deviation of less than 0.002% size change.

Using the moiré method, cellulosic base aerial films may show random linear displacements of the order of 30 microns after processing. This is believed to be due to the flow of the base under stress during the processing and drying operations. Comparable errors with Estar polyester base films amount to less than 5 microns. This general behavior occurs regardless of whether the films are processed by a rewind system, by a continuous machine, or when they are given tray processing. The use of aerial films on polyester base will give marked improvements in photogrammetric accuracy.

Appreciable errors in dimensions result when processed films are not conditioned to a standard moisture content prior to use. Drying film to sensible surface dryness does not mean that it is adequately dried with respect to moisture equilibrium. Use of inadequately dried film can cause very large errors in photogrammetric work because of both the overall film size and because of distortions due to subsequent nonuniform drying in the roll.

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*Calibration of a Precision Coordinate Comparator**

GEORGE H. ROSENFIELD
Photogrammetric Analyst
Mathematical Services, RCA Data Processing

(*Abstract is on next page*)

SECTION I:—INTRODUCTION

THE comparator is a precision coordinate measuring instrument which has been manufactured and adjusted to meet a particular level of accuracy when used in accordance with the manufacturer's specifications. However, by proper calibration it is possible to achieve additional accuracy in the measurements. The calibration procedure consists of determining an appropriate error model to describe the systematic errors of the comparator. The correction is then performed by operating on the observations with the correction equations obtained from the computed error model. Since calibration is not entirely a stable condition, it is necessary that recalibration be performed at periodic intervals. In the meantime a comparator evaluation will determine whether significant changes in accuracy have taken place.

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