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Image Quality and Image Geometry

High-contrast images are reproduced most faithfully.

Abstract: *Known or measurable quantities in glass-plate targets were subjected to a laboratory-controlled photographic system, and then the recorded images were measured. The changes observed by comparing the standard quantities with the imaged quantities revealed that a high-contrast target was reproduced most faithfully, and the low-contrast target the least faithfully.*

Introduction and Concept

The effects of image quality on image measurement in aerial photography is of increasing concern to photogrammetrists. This interest parallels innovations and improvements in measuring equipment and techniques. Quality of photographic image measurements on modern high-precision comparators is now commonly given in the one micrometer range; 10 years ago such claims of exactness were frequently considered overly optimistic if not misrepresentative. Although certain factors which influence the formation or assessment of photographic images have been often described and studied, a rising need remains to relate these factors to mensuration potential of the present and future. In particular, there is a need to provide to the photogrammetrist a means for weighting observations throughout the photo format, especially with the use of micrometer-capable machines. Therein lies the motivation for this investigation.

The basic idea in this work is to subject known or measurable quantities contained in glass-plate targets to a laboratory-controlled photographic system and then to measure these same quantities in the recorded image. In this way the changes observed through comparison of the standard quantities with imaged quantities can reveal information about the capability of the photographic system to reproduce the target faithfully and to permit exacting measurements of the image.

* Summary of the presentation at the International Conference on Image Deformation held at the National Research Council of Canada, Ottawa, Canada, June 1971. This is a part of the doctoral research of the author at the Ohio State University, Department of Geodetic Science.

The Investigations

A laboratory experiment was designed and conducted to investigate the effects of resolution, contrast transfer and edge sharpness (acutance) on image measurement in various locations of the photographic format. Glass-plate targets containing multiple-contrast three-bar patterns and a Military Standard Resolution Target were photographed through a light-source collimator-camera system. The camera used was a Zeiss RMK-AR 15/23 aerial survey camera loaded with Kodak Panatomic-X Aerial Film. The laboratory arrangement permitted tilting and rotation of the camera so that the target images could be placed along a diagonal and semi-axis in the photographic format. The glass-plate targets and images were then scanned in a Micro-Analyzer which digitized discrete density values at one micrometer intervals along the scanning direction. Through a computer plotting program, selected portions of the scanned items were presented at a graphic scale readable to less than one micrometer. The plots were then measured and analyzed to yield information on image quality parameters and effects. The study is still in progress at this time; a brief description of the experiment and initial findings are presented in the following paragraphs.

The target was a glass plate, $4 \times 3\frac{1}{2} \times 1/16$ inch, coated with Kodak "High Resolution" Emulsion. In three quadrants were placed long-line patterns of high, medium and low contrasts; in the fourth quadrant was located a Military Standard Resolution Target of high contrast. In all quadrants, the three-bar elements decrease in width by a factor of $2^{1/6}$. After some experimentation, the production of these targets was accomplished by using precision-made master targets and the method of contact printing (glass plate to glass plate) with variable exposure to obtain the different contrasts.

Illumination of the target was provided by a Xenon light source in a 12-inch integrator ball. After passing through a neutral density filter and the target, the light bundle was collimated in an 80-inch $f/10$ collimator. A fixed primary surface mirror reflected the rays upward into the camera which was housed vertically in a test stand. To assure proper location and to check the quality of the image received by the camera, it was to open the shutter prior to each exposure and visually inspect the image on the register glass. By tilting, rotating and translating the camera, the image was centered over the desired réseau cross. All exposures were taken with the minus-blue filter B over a period of two days. A temperature of 74°F and relative humidity of 42 percent were recorded at the test stand each day.

The film used was Kodak Panatomic-X Aerial Film 3400 (ESTAR thin base) which is a panchromatic $9\frac{1}{2}$-inch negative film that features high contrast, high acutance and very high resolution. It was selected in order to minimize film effects on the image as much as possible. Film processing was done in an HTA-3 continuous processor with Kodak DK-50 chemistry. Sensitometric step tablets were placed on each strip of test film and the characteristic curve plotted each time after processing. A high degree of processing control was evident as a 1.4 gamma was constantly maintained.

The primary measuring device used was the Mann Data Micro-Analyzer which provided precise measurements of linear distances and density differences. These measurements were recorded as an analog on a paper chart and were simultaneously digitized on magnetic tape which was computer compatible. The analog record was used to monitor the scanning while in progress and to assist in selecting portions of the output for processing in the computer. The digitized record contained a discrete density value per micrometer of distance traveled across the platen and served as the principal source of all linear and density measurements. Scanning programs were developed and followed to allow multiple scans across each contrast group and for averaging linear and density measurements.

In order to keep the scanning effort at an acceptable level and to produce a manageable quantity of data, only ten exposures from each of two glass-plate targets (one in the radial, one in the tangential direction) were chosen. Of these exposures, three were on a semi-axis and eight were along a diagonal (each group contained a center exposure).

Through the use of a computer-driven automatic plotter, scans of the 3-bar elements on the glass plates and their images on film were plotted. The former were nearly perfect square-wave curves whereas the latter were closer to sinusoids. It was evident that edge degradation, especially in the images, presented a problem as to where the boundary was between a bar and adjacent space. This problem is comparable to that facing a photogrammetrist in making edge measurements under high magnification and in the micrometer range with high-precision plotters or comparators. Typically in these instances, the measuring mark is placed in the middle of the transition zone separating the background and object because a well defined boundary under such conditions rarely exists. A similar procedure was followed in the measurement of these plots: an average value was determined empirically for the density of the bar on one side of the boundary (edge) and for the density of the space on the other side of the boundary. These two density values were meaned to determine a midpoint on the edge; a coordinate for this midpoint was read from the abscissa scale to the nearest half micrometer. By determining edge coordinates in this manner, bar and space widths were readily computed.

Results of bar and space edge determinations for the glass-plate targets, based upon five scans across the bar/space groups, showed that the standard deviations increased with the contrasts from low to high. This correlated well with noise levels observed in the plots. The overall mean of the standard deviations computed for edge coordinates of glass plate scans was ± 0.72 micrometer.

In the imagery, a loss of contrast in the interior of the three-bar patterns was observed, especially as the bar/space widths decreased. As a result, a resolution limit was reached where the three bars were no longer distinguishable. A further consequence of this phenomenon was the effect on the measured width of bars and spaces. Because the measuring technique relied heavily on the density difference between bars and spaces, edge coordinate errors resulted from degraded image quality. This effect caused the first and third bar widths to be progressively wider than the interior spaces and bar as degradation became more severe. It was incorrect to assume that all measurements of image plots were of the same precision as in the target plots because of increased noise in the image and the quality of the imagery which ranged from severely degraded to good. For the majority of situations, about one micrometer precision was estimated in determining the edge coordinates from images.

After scaling the target to the image plane, it was possible to compute differences between corresponding quantities. The systematic effect mentioned above became quite evident as image widths of the first and third bar were consistently larger than those scaled from the target. Because of this it was difficult to establish a criterion for the resultant image-quality effect on bar/space widths. It was decided to treat a 3-bar group as an entity consisting of five quantities, namely the five bar/space widths determined from six edge coordinate measurements. The magnitude of difference of these five quantities from corresponding standard values were averaged for each 3-bar group. This average then served as an indicator of the image-quality effect on width measurement.

Tables and graphs were made of the magnitudes of bar and space-width differences along the radial direction of the diagonal and semi-axis. All graphs showed a tendency toward symmetry about the format center. The differences ranged from one to seven micrometers. The smallest discrepancies were generally found about 2 to 4 centimeters from the center, the largest ones were consistently observed in the region 8 to 12 centimeters from the center. Comparison of results by the various contrasts showed definite systematic effects which are generally summarized below.

Results

The low-contrast pattern yielded the widest dispersion of error in bar/space width determination. It featured some of the lowest and highest differences of all three contrasts. It had the most pronounced loss of measurement precision in the region 8 to 12 cm from the center.

The medium-contrast pattern behaved much better. It had a narrow dispersion of bar/space width differences but also displayed significant weakness at 8 to 12 cm from the format center. Near the center, this contrast had the best fidelity in preserving the true bar and space widths.

The high-contrast pattern seemed to be least affected in the region 8 to 12 cm from the center. This contrast showed the least dispersion of bar/space width differences but was generally not as faithful as the medium contrast in reproducing the target.

It should be noted that the bar/width measurements were made in a tangential direction. According to the "Inspection Slip" for the camera used, the maximum tangential distortion does not exceed 10 micrometers. As the bar/space width measurements were made by subtracting edge coordinates, it is believed that tangential distortions would correlate closely for narrowly separated opposite edge coordinates and, in the subtraction process, would be essentially removed. Therefore, it can be concluded that the observed results of bar/space width measurements are chiefly influenced by image-quality effects.

Acknowledgments

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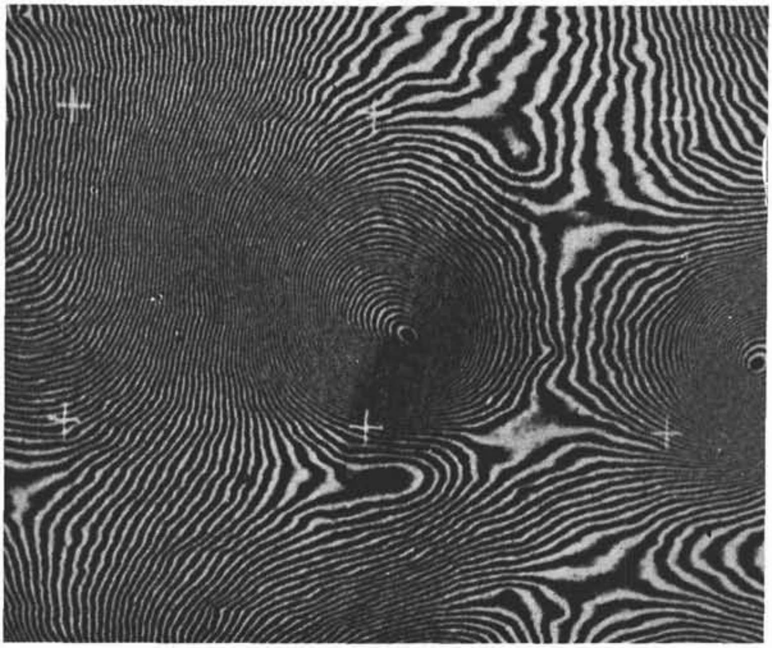

FRONTISPIECE. Interferogram from a smooth-faced pressure pad. The fringes provide a contour map of the variations in separation between the film and glass where the contour interval is about one-fourth of a micrometer.

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Film Flatness in Survey Cameras

The register-glass, pressure-pad system is incapable of rapid flattening due to air trapped between the film and the glass; the use of a roller shows some promise.

(*Abstract on next page*)

THE IMAGE distortion caused by lack of flatness is well known. (Figure 1). A format of 23-cm square is commonly used in conjunction with a 15-cm focal length lens. The image-forming rays at the corner of the format for this combination will be incident at an angle of 45°, and any separation between focal plane and emulsion surface will result in an equal displacement of the image radially outwards. This becomes progressively less for points nearer the center of the format. For the super-wide angle cameras, the effects are even greater.

FOR REGISTER-GLASS cameras, the presence on the glass surface of a calibrated réseau, which is printed onto the negative at the moment of exposure, facilitates the assessment of the image distortion due to the combined effects of lack of flatness and film-base distortion. It has been argued that if the separation between the emulsion surface and focal plane does not vary very rapidly, moderate lack of flatness does not matter as all necessary corrections can be made from observa-

* Presented at the International Conference on Image Deformation, Ottawa, Canada, June 1971 by permission of the Deputy Controller of Aircraft, Ministry of Defence, U.K.

ABSTRACT: *The effectiveness of film flattening systems of certain survey cameras. Most of the results are for cameras with a register glass and pressure pad for flattening the film, but some results are for a vacuum-back plate. The most striking difference found between these two systems was the speed with which they flattened films. The register-glass, pressure-pad system is incapable of rapid flattening due to air trapped between the film and the register glass. An alternative method of flattening the film rapidly and effectively has been developed using a roller, and this shows some promise.*

tions of the réseau distortion. This work has shown, however, that the separation can change rapidly between réseau marks due to dust and other particles propping the film up.

In a register-glass camera the emulsion surface of the film and the back surface of the register glass provide two reflecting surfaces in close proximity between which light interference may be obtained, and observation of the fringes provides a very sensitive method of following the variations of the separation between the two surfaces. A Fizeau interferometer was built to exploit this (Figure 2) consisting of a large condenser lens producing a collimated beam which illuminates the surfaces through the register glass; it is necessary to remove the lens and other parts of the optical system.

Interference occurs between the reflections from the two surfaces, and the light passes back through the lens to form an autocollimated image of the lamp where the interference pattern may be viewed. The 546-nm green line from a medium power mercury street lamp is used, giving enough light either to view the interference pattern projected onto a screen, or to obtain a photograph with a brief exposure (Frontispiece). All points on the format linked by a particular interference fringe will have the same separation between the film and glass surfaces. Movement to an adjacent fringe of the same kind (dark or light) indicates a change in optical path length of one wavelength, or a change in separation of about a quarter micrometer—the fringes provide a contour map of the variations in separation between film and glass.

To establish whether the separation is increasing or decreasing in passing to an adjacent fringe, a white light source is used. Only low-order fringes where the separation is from zero up to a few wavelengths will then show, and the direction of increasing separation can be established (Figures 4 and 5). In practice the incandescent electrodes of the mercury lamp provide a suitable polychromatic red light which may be selected by means of a broad-band red filter. The actual separation is determined by counting the net number of fringes crossed in passing from a point of zero separation to the point being measured.

A CINÉ RECORD of these fringes (Frontispiece) was made. The slow flattening by this method is immediately apparent. Much movement and change in the fringes can be seen during the first five seconds of the flattening process, changes are still taking place at 15 to 30 seconds, and complete stability is not obtained until 2 minutes have passed. There is little doubt that this slow flattening is due to the slow expulsion of air along the narrowing gaps between the film in the middle and the glass and pad surfaces on either side. The force that can be deployed by the pres-

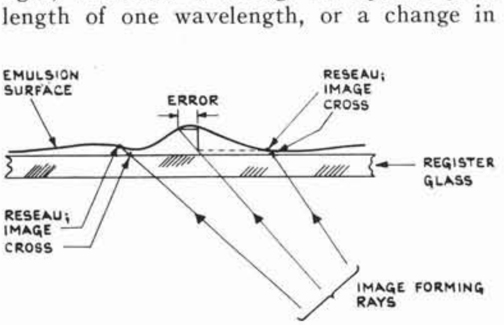

FIG. 1. How image distortion is caused by a lack of film flatness.

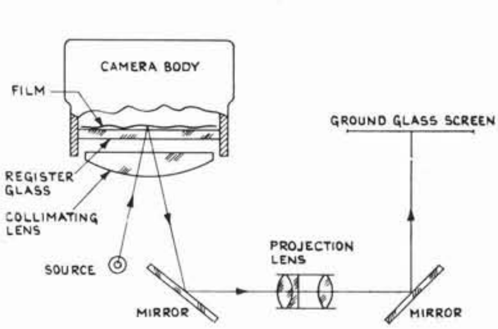

FIG. 2. Diagram of the Fizeau interferometer built to display deviations from film flatness.

sure pad to achieve this explusion is limited by the need to avoid mechanical deformation of the optical unit and other parts of the camera.

The camera for the Frontispiece had an impervious pressure pad surface of cork impregnated with rubber, ground flat and polished. Faster flattening is obtained with a pad having ventilation grooves cut in the otherwise flat surface, which helps the discharge of air trapped against the back of the film. However, the film can be forced into these slots early in the flattening process by the air trapped against the glass (Figure 3). The effect is relieved as the air escapes (Figures 4 and 5).

Measurements made on interferograms obtained after the film had stabilized showed a variety of results. The best was obtained with a pressure pad which had a substantially ribbed back plate to which the flattening force was applied at four distributed points. The pad surface had been recently ground flat, and carried ventilation slots. This gave a maximum separation of 15 micrometers. A similarly designed plate which had warped slightly gave 40 micrometers, and a smooth-faced pad with no slots 29 micrometers.

A CAREFULLY MADE and maintained pressure pad will therefore produce good flatness of the order of 15 to 20 microns provided a short time interval is not being used. For time intervals in the 3 to 10-second range, it is possible that serious image distortion due to lack of flatness could occur.

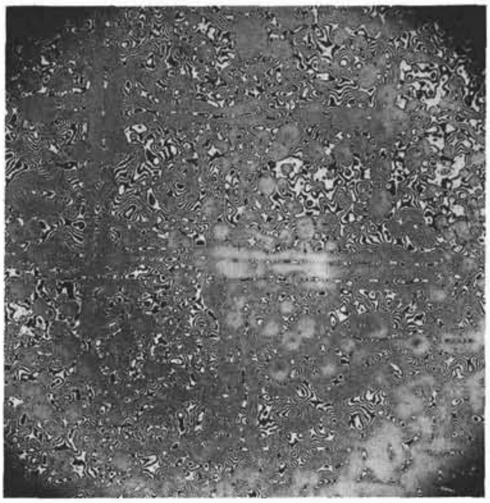

FIG. 4. As for Figure 3 but after 60 secs of flattening showing some areas in optical contact.

With a vacuum-back camera, direct observation of the film surface is possible and, where flattening is accomplished in this way, a film surface has a rather pimpled appearance, most noticeable if the straight edge of a tubular lamp is viewed by reflection in the surface. If the vacuum is released, the film, although no longer flat, has a much smoother appearance. The effect is useful for observing the rapidity of the flattening action.

Interferometric observations were made on one of these vacuum-back cameras using an optical flat in place of the register glass. The

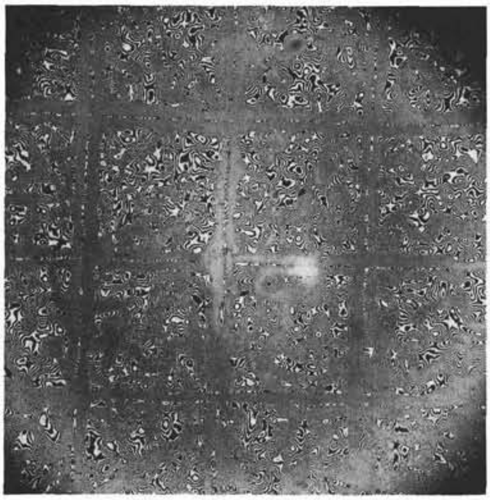

FIG. 3. Interferogram in monochromatic light after 5 seconds of flattening, showing the film forced into ventilation slots in the pressure pad.

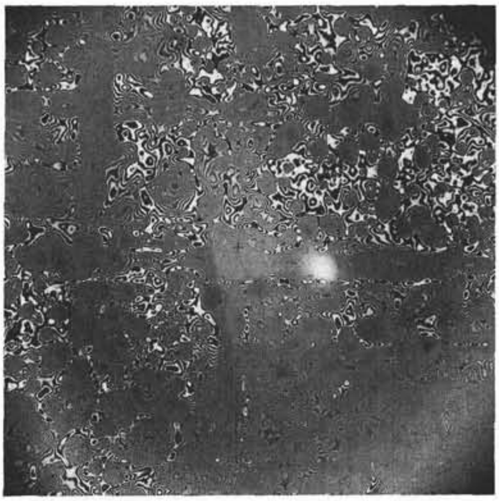

FIG. 5. Taken 5 secs after Figure 4, but in polychromatic light to accentuate the areas of small separation.

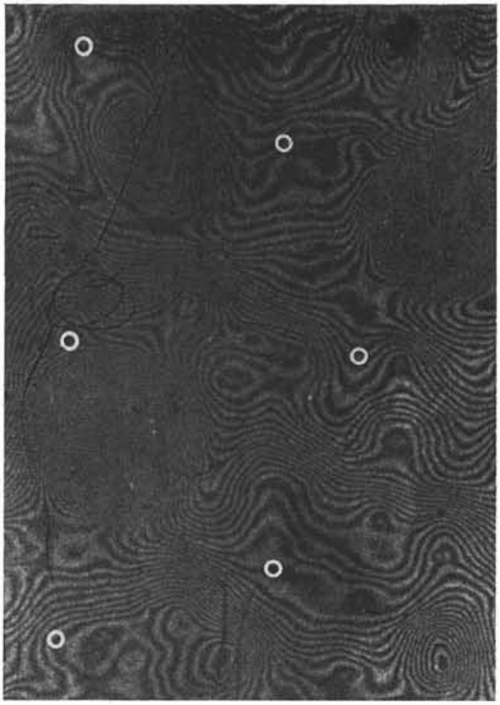

FIG. 6. Interferogram obtained with a vacuum back, showing coincidence of the flattest areas with the holes in the plate.

information of particular interest that came out of these measurements was the repeatability of the pattern of surface unevenness from one exposure to the next. The pattern obtained in the same area of the format for two successive film samples were the same to within two fringes. Thus, with the vacuum-back camera at least, it seems that any lack of flatness may be attributed to the mechanics of the camera and not to varying features and qualities of the film, although variations in film thickness must affect the flatness. It was also shown that in a vacuum back with small holes to apply the vacuum, and no channels in the surface, the areas of film over the holes were of comparative flatness, and the pimples lay on the space between (Figure 6). This implies that some of the pimples occur because the hole evacuating the volume behind the pimple is sealed off by film sucked onto it before evacuation is complete.

ANOTHER METHOD that was employed on the vacuum back was direct measurement of the pimple height with an ultra-short depth of field microscope, equipped with a scale measuring movement along the microscope axis to 0.2 micrometers. The microscope was focussed on the top of a pimple and then on the flatter surrounding surface, and the pimple height found from axial movement of the microscope between these two positions.

The results obtained by the two methods agreed very well showing a maximum departure from flatness of 18 micrometers and a flattening time of about 1 second. By employing the considerable force available in atmospheric pressure, these cameras flatten film quickly and effectively without imposing the unacceptable stresses that would be generated by a pressure pad exerting the same force.

As variations in film thickness will affect the flatness of the emulsion surface in vacuum back cameras, a method of measuring them was developed, using multiple-beam interferometry. Samples of the film were coated on both sides with a reflecting layer of aluminium, and placed in the collimated beam of the interferoscope. Multiple reflection and interference within the film between the two reflecting layers produced high contrast transmission interference fringes which could be viewed directly, or recorded on film placed in contact with the upper surface of the test piece (Figures 7 and 8). Fringe counting with these records gave the variation in optical thickness which, multiplied by the refractive index, gave the variations in mechanical thick-

FIG. 7. Thickness fringes from triacetate film base, showing minute linear features on the emulsion surface.

ness. The refractive index was determined by measuring the optical and mechanical thicknesses of samples with an interference objective attachment to a microscope. The greatest thickness gradient found among the samples of triacetate and polyester bases measured was 1.4 micrometers per centimeter; this can have no significant effect on film flatness.

We have seen that although the register glass with its réseau is of great value in detecting image distortion due to a combination of film base distortion and lack of flatness and in the reduction processes of analytical triangulation, the air trapped between the film and the glass provides a considerable obstacle to the effective and rapid flattening of film where a pressure pad is used. The time interval between successive exposures may be five seconds or less, of which only a second or two may be available for the flattening. Speed is therefore important.

The use of a roller to flatten film onto a register glass can eliminate the problem of trapped air. The film is laid under very light tension on the register glass, and a rubber roller is passed across the back, pressing the emulsion into contact with the glass. Examination with the interferoscope shows that optical contact can be obtained along the line where the roller is in contact with the

FIG. 8. Thickness fringes from polyester film base.

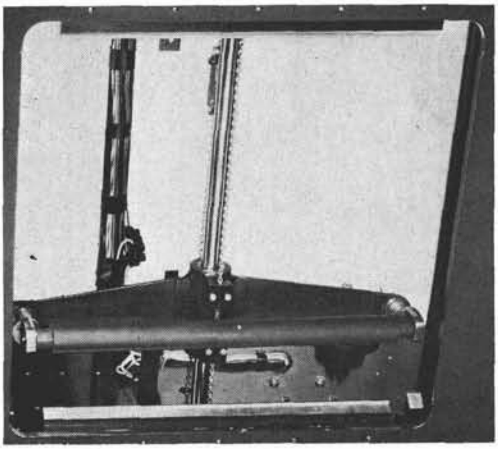

FIG. 9. Flattening roller viewed through the register glass.

film. The applied force needed to achieve this is small, as the area in contact is small. In practice a force of ten pounds has been used with a $\frac{3}{4}$-inch diameter roller covered with 65 BS hardness rubber. As the line of contact passes across the format the trapped air is pushed in front and expelled at the edge of the format (Figures 9 and 10). Any slight excess

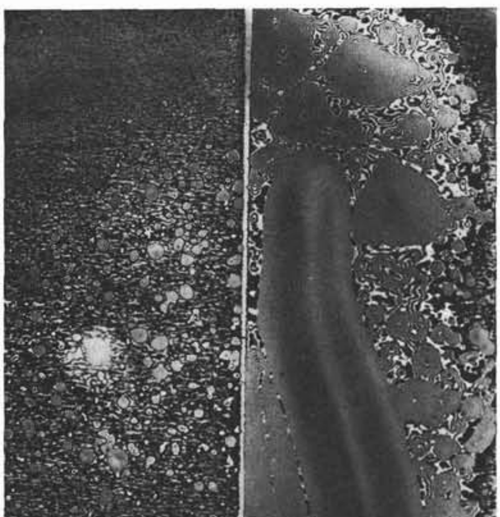

FIG. 10. Flatness interferogram obtained with roller, showing well flattened film on the left, a line of optical contact under the roller, and air and excess film scavenged on the right.

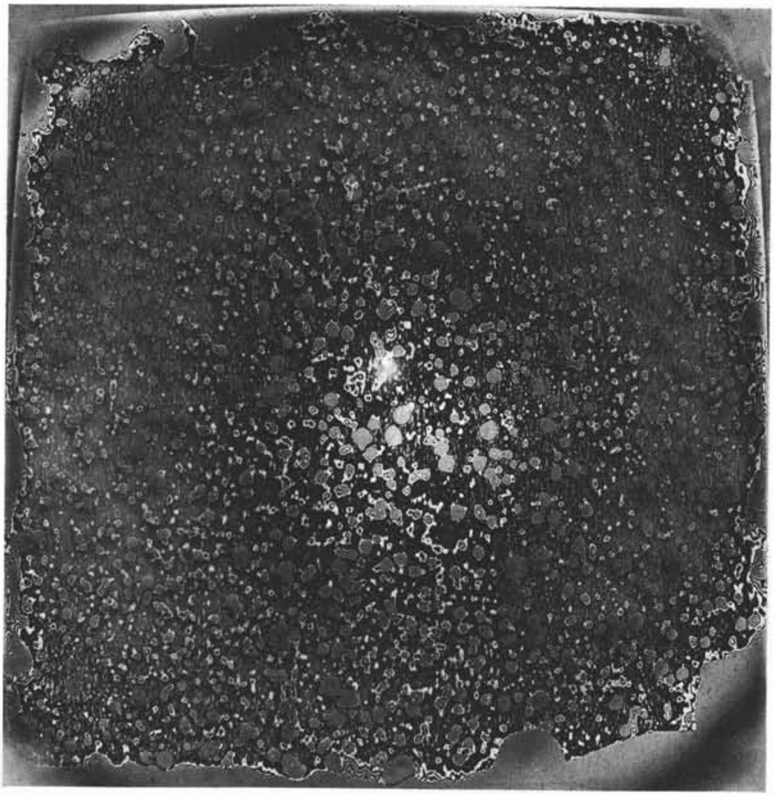

FIG. 11. Edge lift after passage of the roller.

of film is also removed. Any tendency for the film to lift would now result in a pocket of low pressure between the film and the glass, and atmospheric pressure continues to act on the other side. This gives rise to a considerable force tending to keep the film flat: up to 14 pounds per square inch at ground level giving a total maximum flattening force of about ½ ton. This is applied across the film only, and exerts no force on the register glass. It is the same force that is used to flatten film in vacuum back systems.

The flatness achieved by the roller is therefore largely maintained by the ambient pressure, the film rising only one or two fringes except at the edge, where air can leak in between the film and the glass. In this area the film lifts immediately after the passage of the roller (Figure 11). This difficulty is overcome by use of a narrow channel cut in the register glass at the edge of the format (Figure 12). A vacuum is applied to the slot which holds the film down after the passage of the roller. The slot ¾ mm wide and 1¼ mm deep, does more than this, as it slowly removes the residual air left by the roller between the film and the glass. The flatness therefore continues to improve after rolling, and very impressive results can be obtained after a few minutes of this action (Figure 13). This improvement spreads from the outside, where it is of most advantage, inwards; although the process is slow, it is useful.

EVEN IF THE above flattening process has been conducted on clean film on a freshly cleaned register glass, small circular areas still

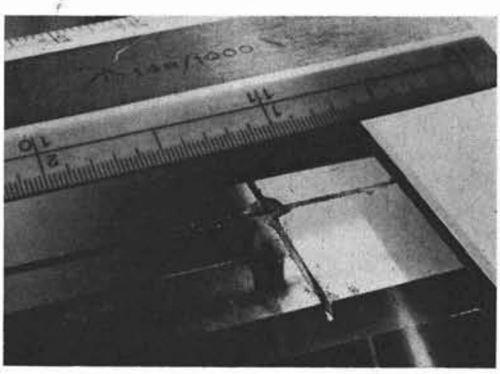

FIG. 12. Vacuum slot for film-edge retention.

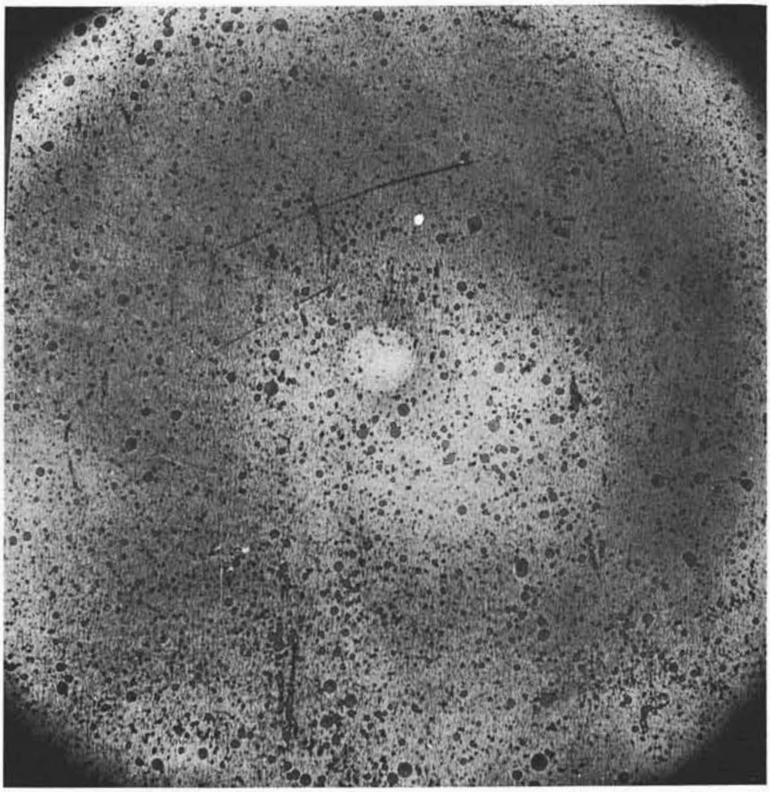

FIG. 13. Improvement in film flatness produced by continuous application of edge vacuum.

remain unflattened, and the film surface has the same pimpled appearance seen with the vacuum back. The interferograms show concentric fringe patterns in these patches. If a slow controlled rise of the film surface is arranged by manipulating the slot vacuum, and the patch fringes are observed directly with a low power microscope, it can be seen that, although the patches spread, the number of fringes they contain remains constant, at least initially. This indicates that the height of the patch is constant, at a value presumably dictated by the size of a particle underneath acting as a prop.

Evidently dust is the final barrier to almost perfect film flatness, and the ultimate can only be achieved in dust-free environments. It is possible that some of the particles are inclusions in the emulsion, but considering the high standards of cleanliness applied to film manufacture the proportion is probably very small. A much more potent source of trouble is the flanged film spool. Friction between the film edge and the spool flange during winding can generate appreciable quantities of film dust which could interfere with the flattening process.

ORIGINALLY the flattening was performed by first applying the slot vacuum, which gathered and held the film, and then making one pass with the roller. This caused some distortion of the film base arising from the firm hold that the vacuum slot kept on the film while the roller was discharging the excess film and trapped air. The slot is now divided into two parts, and the roller is passed over the film twice. During the first roll no vacuum is applied, and the roller scavanges the trapped air and removes any excess in the film length. The vacuum is then applied to the slot surrounding the half of the format that was rolled last, as this has had least time to rise at the edge. The second role is then made, and the vacuum applied. The greatest time-lag between rolling and edge vacuum application occurs at the center line of the format parallel to the roller. Some lift is observed at the ends of this line which is removed by application of the vacuum.

The performance of the various flattening methods are compared in Table 1.

THE POSSIBILITY of stress marking on the film caused by the high localized pressure of

TABLE 1. FLATTENING PERFORMANCE

Flattener	*Comment*	*Maximum Gap Micrometers*	*Flattening Pressure lbs. in*$^{-2}$	*Flattening Time Seconds*
Grooved Cork Pad	Old Warped Ground	78 40 18	0.2 0.14 0.14	45
Smooth Cork/Rubber Pad	Ground Very Rigid	29	0.31	120
Vacuum Back	Holes No Slots	17	0.57 (400 mm H_2O)	<1
Roller		7	<14	1

the roller was investigated, using a film that had an unusually high sensitivity to this trouble. Instead of a double roll, the roller was stopped half way across the format, rested there for 30 seconds, and returned to the start, leaving half the format not rolled. Subsequent exposure and development of the film revealed no variations in the density which could be attributed to the roller.

In cameras flown at high altitudes, the decrease of atmospheric pressure will obviously reduce the force available to keep the film flat. Tests at a simulated altitude of 60,000 feet have been made in a decompression chamber, the equivalent ambient pressure being 1 pound per square inch. The pressure differential that can be produced across the slot is also obviously reduced. It was found that a $\frac{1}{4}$-pound per square inch was sufficient to hold the film edge after the flattening process. In the final results, the localized areas of larger separation caused by dust particles tended to spread at the expense of the areas of good flatness, but maximum separation in these local spots remained the same as the pressure was reduced. Flatness did not improve with time, but it was considered that the system would operate satisfactorily up to these altitudes. The total flattening force available over the whole format is still more than 80 pounds.

A SURVEY camera employing a roller for flattening the film, and a vacuum slot for edge retention has been built. The double pass of the roller takes about one second, but the minimum cycling time is four seconds as a rather old design of film transport was used. A test survey comparison was conducted using this camera in tandem with a standard pressure pad camera. Both had the same alignment and were operated from the same time base, so that they provided two identical sets of photography. These were from 12,000 feet over a single, well surveyed strip. No windows were used. The cycling time was 5 seconds, the minimum at which the pressure-pad camera could be operated, and at this time interval noticeable distortion was expected due to lack of flatness in the pressure pad photography but not for the roller.

The results were disappointingly negative. There was no detectable difference between the survey accuracy obtained from the two cameras. This was, we think, due to pointing errors which arose during analysis. We shall repeat the test in a modified form, with even closer control over the experimental conditions and the subsequent analysis.