$$+ .035(25) + .12(35) + .015(45)$$
$$+ .015(45)$$
$$= 19.26 \text{ minutes}$$

Thus a quantitative comparison of the previous cost per photograph processed of \$4.425 and through-put time of 21.025 minutes can be made by decision making personnel in order to determine the desirability of such an addition to Rectifier magnification. *In this manner it is possible to quantitatively evaluate equipment design in terms of system performance.*

Conclusion

This paper has presented a specific example of the utilization of operations research in the design of a specific photogrammetric support system. By the use of similar techniques, the expected performance of any system can be determined provided the distributions of input variables, possible system states and the specified output quality requirements are known or can be reasonably estimated. In this manner, not only may the initially expected system performance be determined, but also the effect of changes in equipment design on the system performance may be *quantitatively* evaluated. Thus, more precise measures of worth can be introduced into both system and equipment design decisions.

Acknowledgments

The most helpful comments and suggestions of Mr. Arthur Faulds and Mr. Robert Brandt concerning the photogrammetric aspects of this paper are gratefully acknowledged.

*A Slit-Scan Electro Optical Rectifier**

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ABSTRACT: *A unique machine is described which has the capability of rectifying practically all types of oblique aerial photography. The rectifier takes advantage of optical projection for transforming the photographic information, and electronic computer controlled distortion for achieving dimensional restitution. By combining these two techniques a machine results which produces rectified photographs having very high resolution, excellent dimensional characteristics, high speed of operation, and flexibility in regard to the types of oblique photography which can be processed.*

Oblique frame, vertical panoramic, and oblique slit scan photography can be rectified. Oblique panoramic can be rectified by special adaptation. A large range of focal-lengths and oblique angles can be accommodated by the rectifier. A resolution figure of 80 lines-per-millimeter should be achieved in the rectified photograph with speed of operation being less than 15 minutes for 100 square inches of copy.

Introduction

The requirement for improvements in equipment for rectifying oblique aerial photography has become of increasing importance in the past few years. This has come about because of the increased use of a variety of types of aerial photography and of the high resolution being obtained. In addition the requirement for reconnaissance and mapping has increased substantially.

Historically, rectification equipment has been limited to the optical projection type. With a few exceptions only oblique-frame type aerial photography can be processed by

* Presented at the Society's 27th Annual Meeting, The Shoreham Hotel, Washington, D. C., March 19–22, 1961.

the optical rectifier. Even with this restriction the optical rectifier is limited in resolution and in range of focal-length and degree of tilt that can be accommodated by a single instrument.

Several panoramic optical rectifiers have been built or are now being designed, but in each case they are limited in resolution, in maximum scan angle, to a single focal-length, and to vertical photography.

In order to produce a rectifier that is more versatile and does have the required high resolution, advanced electronic techniques have been applied to the problem. This includes digital computer techniques as well as video electronics for photographic image transformation.

Hycon Manufacturing Corp. has demonstrated a universal type electronic rectifier which can rectify all types of photography. Electronic scanning as well as recording is used. Dimensional rectification is accomplished by servo-drives operated from prepunched tapes. A digital computer prepares the punched tape by solving the transformation equation.

Fairchild Camera and Instrument Corporation has delivered to Rome Air Development Center (RADC) a spot scanning electro-optical rectifier which accepts oblique frame photography and produces positive prints on paper up to 36 inches by 48 inches in size. This machine can rectify frame photography from one and one-half inches up to one hundred inches focal-length and tilt angles up to eighty-five degrees from the vertical. Scanning is accomplished by an oscillating mirror and the video processed photographic information is recorded with an ultrasonic light modulator. A built-in electronic analog computer plus a mechanical computer transforms the dimensions required for rectification.

Both the Fairchild and Hycon electronic rectifiers have limitations in resolution and speed of operation. In each case the copy is scanned by a spot of finite size. The photographic information within the spot is integrated by a photomultiplier tube into a video electronic signal having an average value representative of the information in the spot. The limiting resolution is, then, the size of the scanning spot. If attempts are made to decrease the spot size for increased resolution, there arise problems of signal to noise and speed of recording.

These problems are overcome in the design of an electro-optical rectifier now being designed for RADC. In this design photographic information is transposed from oblique copy to rectified print by optical projection. Transformation of both dimensions of the copy is accomplished using servo drives and punched paper tape derived from a digital computer.

Rectifier-System Operation

A schematic of the slit-scan electro-optical rectifier is indicated in Figure 1. Oblique copy is placed on a flat, glass platen that may be rotated to the correct swing angle. The copy is scanned by a very thin line of light projected from an illuminated slit. A high-pressure mercury-vapor tube is used as the light source and an elliptical mirror images the slit in the plane of the copy. Exposure control is obtained by moving a variable density filter between the light source and slit.

The copy is moved past the projected slit and as this is done the scanned information is

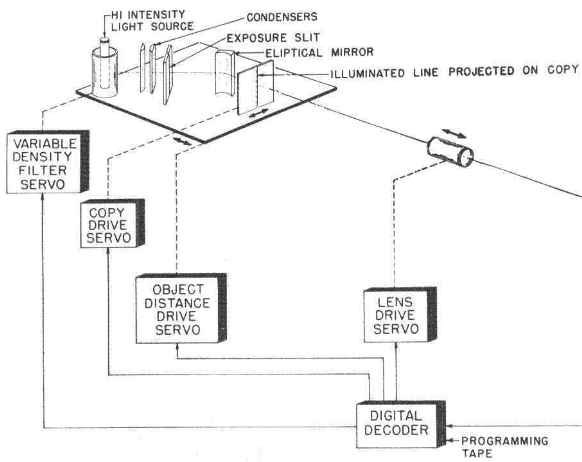

FIG. 1. Schematic of slit scan electro optical rectifier.

SAMUEL W. LEVINE

projected to a recording cylinder by a high-resolution imaging lens. Rotation of the recording cylinder is preprogrammed to correlate with the rate of scan of the copy by the illuminated slit. In this manner the photographic content of the oblique copy is transferred to the rectified recording.

Rectification in each dimension of the photograph is accomplished by utilizing two different optical techniques. In the direction along the slit the required change of dimension is obtained by correctly positioning the lens and copy. In the direction perpendicular to the slit, the required change of dimension is obtained by relative motion between copy and recording.

By these means the photographic information is transformed in an optical projection system where the limiting factors on resolution are the resolving power of the projection lens and recording film. Dimensional rectification is obtained by programmed motion of the lens and copy position, and of the relative motion between copy and recording.

An artist's rendition of the rectifier is given in Figure 2. As may be noted, the scanning-slit is set in a vertical direction. This is done to reduce the load on the servo system driving the copy holder. Copy in the form of roll film may be loaded on the copy holder so that it will not be necessary to cut out separate frames for rectifying. The recording cylinder loading is accomplished in a darkened room, but the lights may be turned on when loading has been completed. The electronics are located in the lower part of the machine and in an auxiliary rack located nearby.

GEOMETRICAL BASIS FOR RECTIFIER DESIGN

Application of this technique to rectification may best be understood by considering the analytical geometric aspects of rectification. In all oblique aerial photography, with a few exceptions, there is a so-called principal-line or its equivalent. Lines perpendicular to it are linear in dimension within themselves.

Single-frame oblique photographs have a principal-line along which the scale from copy to rectified print constantly changes. Perpendicular to this principal-line are lines which are linear. That is, equal unit length along these lines repesent equal increments of length on the ground. The scale from line to line does change.

In vertical panoramic photography the line along the direction of panoramic scan is comparable to the principal-line in the single-frame photograph. All lines perpendicular to this line are linear within themselves. Tipped

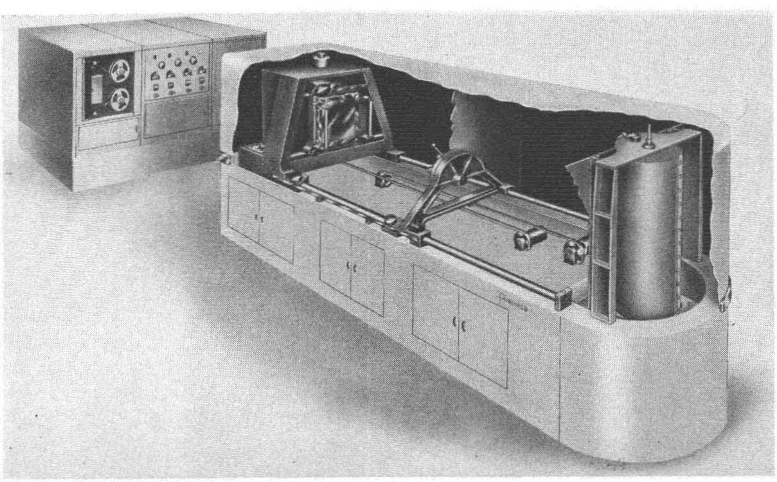

FIG. 2. Electro optical rectifier.

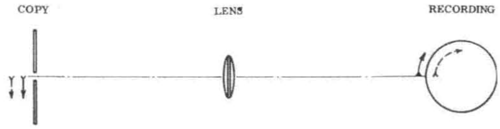

FIG. 3. Schematic of slit scan.

panoramic photography has no such comparison and rectification here requires a separate treatment.

Oblique slit photography has the principal-line analogy although it is not singularly defined. Lines perpendicular to the analogous principal-line direction are linear within themselves as is determined from the fact that the speed of the vehicle is constant.

The common factor in all three types of photography is that perpendicular to a principal-line are lines which are linear. This fact is used in the design of the rectifier in that distance along the scanning-slit is linear and non-variable. In order to rectify, the copy is mounted on the platen so that the principal-line is perpendicular to the slit and therefore lines perpendicular to the principal-line are along the slit length direction and will be linear.

Dimensional Change Perpendicular to Slit

In order to transform the dimension from copy to recording along the principal-line, relative motion between copy platen and recording cylinder is utilized. In Figure 3 is incated the slit scanning the copy, the projection lens, and recording surface. The object to lens distance and lens to image distance is shown such that the magnification factor is unity. It can be seen that if the rate of copy scan is equal to the rate of movement of the recording surface, then no change in size from copy to recording is realized.

If the recording surface rate of movement is two times the rate of the copy scan, then an enlargement of two to one is realized in the direction of scan—that is, perpendicular to the length of the slit. It is to be noted that in the direction along the slit—perpendicular to the scan direction—there is not change of size.

When the object to lens and lens to image position are arranged so that a two to one magnification is obtained, and the rate of copy scan is equal to the rate of movement of the recording surface, then in the direction of scan only a one-to-one magnification is obtained as previously. At a two-to-one ratio of speed of the recording surface to copy scanning a two-to-one enlargement is obtained.

It can thus be seen that change of dimension in the scan direction is independent of the optical magnification characteristic of the projection lens.

When the ratio of recording to copy speed is different than the optical magnification ratio, there is a small image smear effect in the recording that has a degrading effect on resolution in this dimension. By using a very narrow scanning slit this is minimized and in the machine being designed the slit width is 10 microns. Reference to Figure 4 demonstrates graphically the effect on image smear of using a very small slit. On the left is represented a resolution pattern having bars and spaces equivalent to resolution lines, and having the same width as the scanning aperture. The letters above each pattern represent the successive positions of the resolution pattern in time. The projection lens is set for a magnification ratio of one-to-one and the resulting recording is shown at the right. For this example a recording speed of 1.5 is used compared to the scan-speed of unity. As each successive position of scan and record is

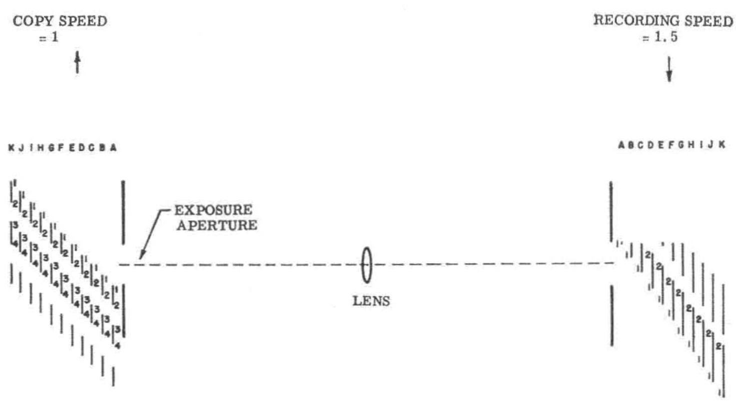

FIG. 4. Image smear effect.

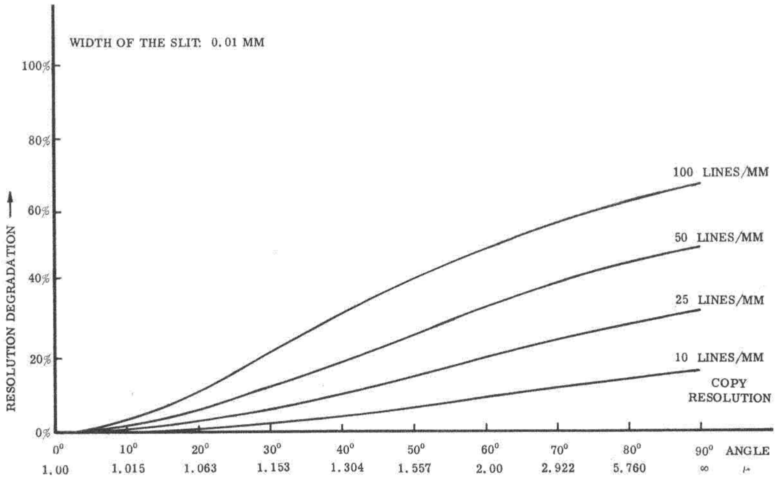

FIG. 5. Resolution of rectifier in scan direction.

analyzed it is seen that an enlargement of 1.5 to 1.0 is realized, but no longer is there a one-to-one relationship between bar and space width. This change of relationship from copy to recording is due to smear. The pattern of density contour of the bar is such that almost zero density exists at the ends with a flat maximum density in the middle.

A mathematical analysis of the effect will show that the smear value which is defined as the ratio of the recorded bar width to the ideal recorded bar width is as follows:

$$s_m = 1 + \frac{h}{b}\left(1 - m\frac{V_a}{V_F}\right)$$

where

h = aperture width
V_a = vel. of copy
b = resolution bar width
V_F = vel. of recording

The effect that image motion will have on resolution is given in Figure 5. Along the abscissa is noted the obliquity angle. This angle refers to the angle of scan in a panoramic camera. Also noted is a magnification factor which is used as a comparable figure in the single-frame and slit-type cameras. Along the ordinate is plotted resolution degradation due to image-motion.

There are several interesting facts that are apparent in this plot. It may be seen that the percentage resolution degradation is a function of the resolution in the original oblique copy—the lower the resolution the less degradation of resolution. For example, in a panoramic rectification at 30° scan-angle, if the original resolution is 25 lines/mm., the reproduction will have a resolution of 23.5 lines/mm., or a degradation of 6%. At the same scan-angle 100 lines/mm. copy will reproduce at 78 lines/mm., or 22% degradation.

It is to be noted that this is resolution degradation in one dimension only. The resultant resolution degradation in the rectified print will be appreciably less than the values indicated in Figure 5. Once the machine has been completed it will be interesting to determine the effect of resolution degradation in one dimension on the resultant resolution.

At the nadir of the panoramic or isoline of the oblique photograph, there is no degradation due to image motion and the degradation increases slowly with the obliquity angle.

Dimensional Change Along the Slit

Change of dimension along the slit is shown schematically in Figure 6. The image recording position remains fixed. The object to lens and lens to image positions are changed to obtain the required magnification and focus.

As previously noted the change in dimen-

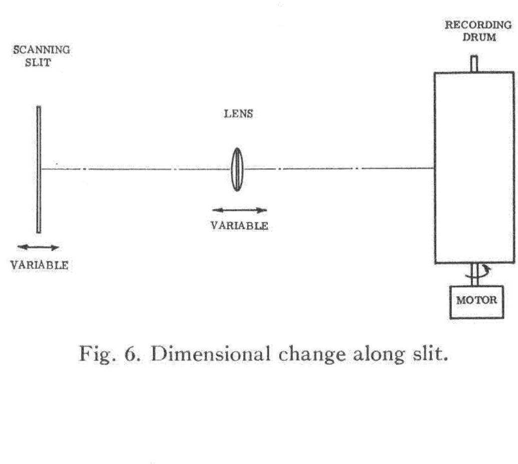

Fig. 6. Dimensional change along slit.

sion along the slit is independent of the change of dimension perpendicular to the slit. Consideration of these two techniques for independent change of dimension in two mutually perpendicular directions makes it apparent that this scheme can be used for rectification. This applies to all cases where one of the dimensions is linear for all line elements. Types of oblique photography falling into this category are single frame, vertical panoramic, and strip photography. Other cases can be accommodated by special adaptations.

Programmed Servo Controls

As indicated in Figure 1, operation of the rectifier is controlled by servomechanism drives programmed through a digital decoder reading punched tape. The recording cylinder is rotated at constant speed by a very precise puck drive and synchronous motor. A tachometer produces a timing signal for synchronizing the operation of the servos. The tachometer timing signal controls the rate at which the punched paper tape is read. This arrangement eliminates the possible error due to variation in electrical frequency of the power to the recording drum synchronous motor.

Punched tape is produced by a digital computer which solves the transformation equations required for rectification. At many locations where the rectifier may be used, a digital computer facility is available, and the tapes can be produced at any convenient time. It is almost always possible to rent computer time for preparing the tape if one is not available at the facility. Should there be no possibility of producing punched tape on a digital computer it is a relatively straightforward problem to design a built-in analog computer to solve the transformation equations. For the machine now being fabricated, the prepunched tape approach was taken because of the availability of a digital computer, improved dimensional accuracy gained by using a digital computer, and economy.

A digital decoder accepts seven level binary code from the punched tape at the rate of six blocks-per-second and produces analog signals for operating the four servos. These drive the lens, the copy to lens distance, the copy platen past the projected scanning slit, and the variable density filter. This optical filter controls the light exposure level so that a uniform density reproduction may be obtained.

The digital decoder and servomechanism control has the capability of giving a high order of accuracy in positioning the various elements during rectification. It is expected that copy-distance positioning, lens-distance positioning, and copy-scan positioning will be accurate to ± 0.0005 inch of the theoretically required positions. This will insure excellent dimensional accuracy in the rectification as well as the exact optical focusing requred for high resolution reproduction.

Scanning Optics and Light Source

In order to maintain the high resolution required in present day rectification a very thin slit of the order of 10 microns width must be used for scanning. This slit is fabricated by stretching a uniform thin wire of 10 microns diameter across and in contract with a glass plate. The assembly is placed in a vacuum evaporator where a metal film is deposited on the plate and the wire acts as a mask. An excellent slit is obtained when the wire is removed.

This slit is illuminated by a high-pressure mercury-vapor tube and a set of cylindrical condensers. An elliptical-cylindrical mirror in an off-axis position projects the illuminated slit-image in the plane of the copy being scanned.

In this machine the copy is mounted on a flat disk of glass which may be rotated about the optical axis of the machine. Such rotation is required for swing-angle adjustment where the principal line of the oblique photography is not parallel to the edge of the format. Facilities are available on the copy carriage to carry roll film so that the copy need not be cut for mounting on the copy platen. The slit-length is 13 inches and the diameter of the copy platen is 15 inches, making it possible to scan a 9 inch by 9 inch photo rotated in one pass. Sections of panoramic photography up to 13 inches in length can be scanned in one pass where the format widths are up to 5 inches. When it is required to rectify panoramic formats longer than 13 inches, the rectification can be performed in sections up to 13 inches in length, and then assembling the resulting rectified sections.

In order to keep the exposure time to a minimum a high-intensity mercury lamp is used. High resolution recording requires a fine grain relatively slow photosensitive emulsion. By using fine-grain film and the mercury tube, it is expected that 13 inches of copy can be scanned in less than fifteen minutes. Where high recording resolution is not required and faster film may be used, the machine can be operated at three times the speed and 13 inches of copy can be rectified in 5 minutes.

Change of Size Capability

Because of the basic machine design it is possible to obtain a change of size of the reproductions during rectification. This enlargement or reduction refers to the isoscale size change, and is in addition to the change of size inherent in rectification. It was found desirable to include in the machine the capability of obtaining an enlargement range of one-half to three. In order to cover this range it is necessary to use two lenses for projection purposes. It is never required that a lens change be made during any single rectification.

Single Frame Photography

The mathematics for single frame photographic rectification has been given in a previous paper by Ross and Levine (1958 Vol. XXIV, No. 5, pp. 789–793). Information that is required for producing the punched tape includes tilt-angle, swing-angle, altitude, camera focal-length, and desired scale-factor.

Copy is mounted on the glass platen with the edge of the format parallel to a reference line, and the principal point coincident with a reference on the platen. The swing-angle is adjusted by rotating the platen the required amount. Scanning takes place with the principal-line traveling perpendicular to the slit. A positive rectified recording up to 36 inches by 36 inches on film or paper may be obtained.

As presently designed the machine will rectify copy from 5 inches to 100 inches focal-length and resultant tilt-angles to 60 degrees with provision for increasing these parameters if required. Corrections for earth curvature, atmospheric refraction, and film shrinkage may be made during the computation of the program tape. It is expected that a resolution of 80 lines/mm. will be obtained at the isoline in single frame oblique and at the nadir in panoramic photography.

Panoramic Photography

The panoramic photography rectification problem may be separated into cases—vertical type where the plane described by the optical axis during scan is perpendicular to the earth's surface, and the tipped panoramic where this plane is at an angle to the earth's surface.

Rectification of vertical photography is the simpler case and can be accomplished by scanning up to 13 inch lengths of copy in one operation. If the copy format is longer than 13 inches then the photography is rectified in successive stages.

Corrections for earth curvature, atmospheric refraction, and film shrinkage are made during the computation stage. Correction for the typical "S" curve of the principal line equivalent of the panoramic picture can be made by moving the copy platen, the imaging lens, or the recording cylinder in a direction parallel to the scanning slit length. This correction would also be computed and programmed in to the machine on punch tape.

In order to correct for the change of exposure that may occur at high angles in the panoramic photograph, a variable density mask is programmed to change exposure

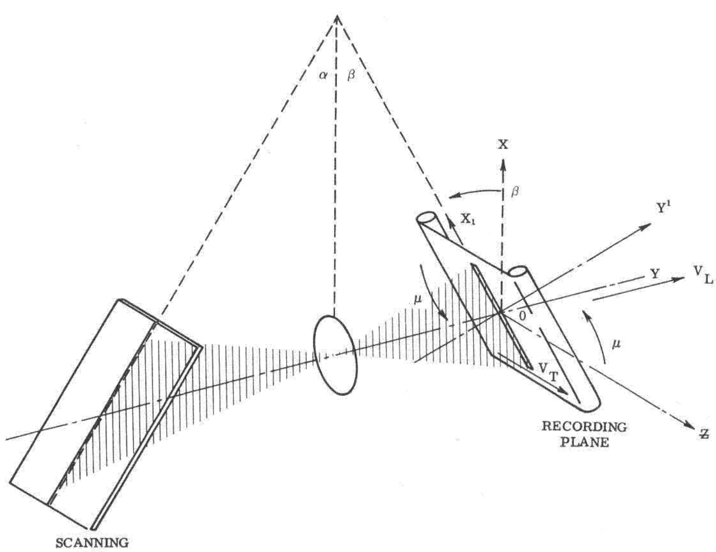

FIG. 7. Tipped panoramic adaptation.

light level during scanning. The exposure could not be corrected by an iris adjustment at the lens because the resolution would then become diffraction limited.

Tipped panoramic photography produces geometry in the photograph in which there is no set of lines that are linear and perpendicular to a principal line. As previously explained this was a requirement for rectification by this machine. However, there are special adaptations for handling this type of photography. An analysis of the transformation equations indicates that one method of rectification which may be used is a two-stage process. The copy is first rectified as though it were a vertical panoramic photograph. The result of this transformation is an oblique single-frame photographic equivalent having a tilt-angle equal to the tip-angle of the panoramic photograph. The single-frame oblique equivalent photo which results is then rectified in the machine as previously described. If the size of the rectified photograph in the first stage is too large, it must be reduced in size during the first rectification and then enlarged in the second stage to the required size.

By modification of the machine it is possible to rectify the tipped panoramic photograph in one step. This is indicated in Figure 7. The scanning slit and copy, the lens, and the recording plane are angled with respect to each other so that the Scheimpflug condition is satisfied. That is, lines through the scan-slit, the plane of the lens, and a line through the plane of recording intersect at a common point. In addition the recording plane is rotated through the angle μ during rectification. These additional motions would all be obtained by servos programmed from punched tape. A mathematical development and proof of this method of operation has been accomplished but is much too lengthy to present here.

Oblique Slit Photography

Oblique slit photography rectification is essentially a simplification of the oblique single-frame case. Obviously the scale remains constant for all lines in the photograph parallel to the line of flight. It is only necessary to rectify in the direction perpendicular to the flight vector. This is accomplished by having a fixed lens to copy and lens to recording distance for the required scale change and obtaining the transformation in the perpendicular direction by relative motion between scanning speed and recording speed.

Conclusion

As may be seen the machine as described in this paper can be used to rectify the various types of oblique photography discussed. By using optical projection, high-resolution and relatively high operating speed is obtained. By using high-precision servomechanism drives driven by digital computer derived punched tape, high-precision in metric transformation will be obtained. For special requirements of rectification, the machine may be modified for optimum operation at the cost of introducing additional complexity.

Panoramic Progress–Part I

ITEK LABORATORIES,
Lexington 73, Mass.

The Advantages of Panoramic Photography

GENERAL

The development and increasing use of panoramic photography in the field of aerial reconnaissance has resulted primarily from the need to cover in greater detail more and more areas of our world and—soon, perhaps—of other worlds as well. In order to cover the large areas involved, and to resolve the desired ground detail, present-day reconnaissance systems must operate at extremely high-resolution levels. Unfortunately, high-resolution levels and wide angular coverage

EDITOR'S NOTE: This paper which is to be supplemented by Part 2 in the March 1962 issue includes the contents of a brochure by Itek Laboratories entitled "Panoramic Progress." A reading was convincing that the contents were so valuable and helpful to photogrammetry and photogrammetrists that repeating in this JOURNAL was highly advisable. For permission to take this action, thanks are given to Itek Laboratories.