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.

are basically counteracting requirements.

The maximum theoretical resolving power (N_m) of a lens, along its optical axis, may be expressed by the equation.

$$N_m = \frac{1426 \text{ lines/mm.}}{f\text{-number}}$$

However, off-axis resolution diminishes for tangential lines as the $\cos^3$ of the angular separation from the optical axis of the point considered. For radial lines, resolution off-axis diminishes only as the cosine of that angle. In practice this means that where wide-angle coverage of a lens is required, the resolution of tangential lines at, for example, 45 degrees off-axis would be down to about 35 per cent of its on-axis maximum; even for radial lines, resolution would be down to about 70 per cent.

Practical considerations make wide angular coverages even less desirable. Various aberrations such as coma, lateral color distortion, field curvature, and astigmatism are all much more difficult to control in lenses with wide angular coverage than in those with narrow coverage. Thus, narrow-field angles are very preferable for high-resolution photography.

An important consideration in discerning small ground detail is the optical system's focal-length. For a given altitude, ground resolution can be increased by the use of longer-focal-length optics, but as the focal-length becomes longer, generation of the wide glass areas required to keep a reasonable low *f*-number becomes increasingly difficult. Since resolution decreases with increasing *f*-number, the use of huge optics is generally unsatisfactory for aerial reconnaissance.

BASIC CAMERA TYPES

There are three basic camera types that may be considered: frame, strip, and panoramic. The ground coverage obtainable with each of these cameras is described below.

Frame cameras

In a frame camera, the lens forms an image of the scene to be recorded over the full area of a single frame of film. If a between-the-lens shutter is used, the entire frame is exposed simultaneously; with a focal-plane shutter, a slitted curtain sweeps across the frame, exposing the film as it travels. When using a frame camera in aerial reconnaissance, exposures are made at regular intervals as the vehicle passes over the terrain. The intervals are so timed that a sufficient overlap is recorded on the consecutive frames to record complete coverage, without gaps, of the area of interest (*A*, Figure 1).

Strip cameras

A strip camera records a continuous strip of terrain as the aircraft flies over it (*B*, Figure 1). In its simplest form, this type of camera consists of a fixed lens mounted in the camera which records on the film that which is directly below. The shutter is kept open during the entire recording period, the exposure being controlled by a slit of variable width.

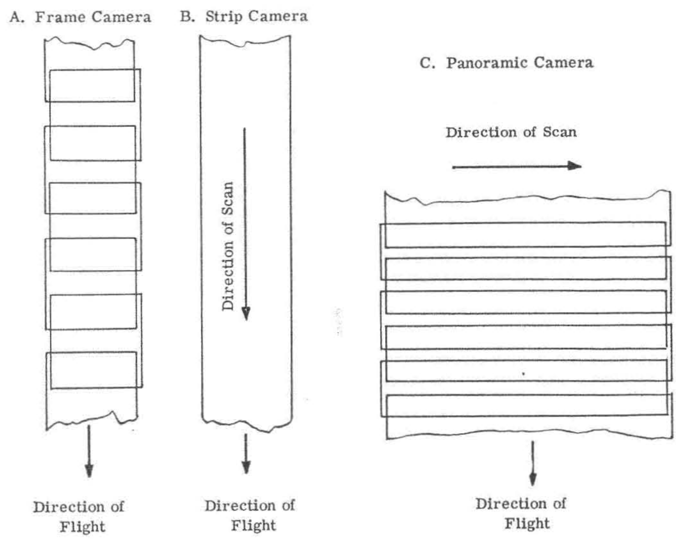

FIG. 1. Ground coverage obtained with frame, strip, and panoramic cameras.

During exposure the film is moved in the direction of flight at a rate equivalent to the rate of image motion.

Panoramic cameras

A panoramic camera is also a scanning type of camera; unlike the strip camera, however, it sweeps the terrain of interest from side to side across the direction of flight (*C*, Figure 1). This permits the panoramic camera to record a much wider swath of ground than either frame or strip cameras. As in the case of the frame cameras, continuous cover is obtained by properly spaced exposures timed to give sufficient overlap between frames. This means of exposure limits the effectiveness of a panoramic camera for photography at low altitudes and high speeds; since the area is covered by relatively narrow camera angles in the direction of flight, a fairly high cycling rate is required when the vehicle is traveling at a low altitude. Moreover, the duration of a complete sweep cycle from side to side is usually longer than the cycle of a frame camera. Panoramic cameras are thus most advantageous for applications requiring the resolution of small ground detail from high altitudes.

If frame cameras with focal-lengths comparable to those employed in panoramic cameras are used for wide-area coverage, either a large array of cameras must be used to cover a reasonable swath (90 degrees or more), or a single camera must be rapidly cycled and indexed from one position to another. Indexing of an entire camera in a vertical configuration requires power and may disturb the uniform motion of the vehicle. Equally difficult, especially from the standpoint of resolution, is the indexing of a mirror for a camera in a horizontal configuration; e.g., if a swath 140 degrees wide is to be covered with a 24-inch lens, an array of seven frame cameras, or a single frame camera indexed into as many positions, would be required. Since the frame camera using a square format would cover the same forward distance on the ground that it covers laterally, it can be seen that a single frame camera would have to take pictures at a high rate. Seven cameras could be used, but this would require an equal number of lenses and the total weight would become excessive.

If strip cameras are considered for wide area coverage and if, for instance, a one-foot lens were used to cover a strip of film $4\frac{1}{2}$ inches wide, it is obvious that the ground coverage for a single camera per pass would be only about 21 degrees. Therefore, a number of such cameras would also be required in this case to cover a reasonable swath. Based on state-of-the-art considerations, a single panoramic camera can not only handle the type of problems outlined here, but it will always weigh less than a group of frame or strip cameras with comparable resolution and coverage capabilities.

It is often thought that panoramic coverage is excessively wasteful at the edges of the frame, i.e., at the limits of the lateral coverage. However, an array of single-frame cameras would cause the same overlapping unless they were cycled non-simultaneously. In panoramic photography, the picture is taken at a known time and in such a manner that all points in the picture can be related directly to the principal point.

The panoramic camera concept has in many cases been selected as the most promising for meeting design goals. Even a one-foot focal-length, coupled with 5-inch film, requires a lens performing to only about 11 degrees off axis. This relatively narrow-field angle makes it possible for the lens designed to achieve an image close to perfection, for the focal-length and aperture required, over the total width.

The Design of Panoramic Cameras

BASIC PANORAMIC CONFIGURATIONS

The numerous mechanical approaches to the design of panoramic cameras may be divided into two general categories: (1) direct-scanning cameras with swinging (or rotating) lenses, and (2) cameras that scan by means of rotating mirrors or prisms.

Direct-scanning camera

A typical direct-scanning camera is the Hyac type shown in Figure 2. The design involves rotating the lens about its rear nodal-point and accurately positioning the film in the proper focal-plane position by means of two small rollers mounted on the end of a scan arm which rotates with the lens.

The scan arm also carries the scanning slit. With the lens sweeping at a given rate, the width of this slit (in the direction of scan) determines the amount of exposure given each picture element; the wider the slit, the longer the exposure. In a typical application this width may be varied from 0.07 to 0.04 inch. The length of the slit across the scan direction must, of course, cover the width of the image strip to be obtained. The maximum scan which can be obtained with a camera of the type shown is necessarily somewhat less than 180 degrees, since at that angle the lens would already be looking back onto the film

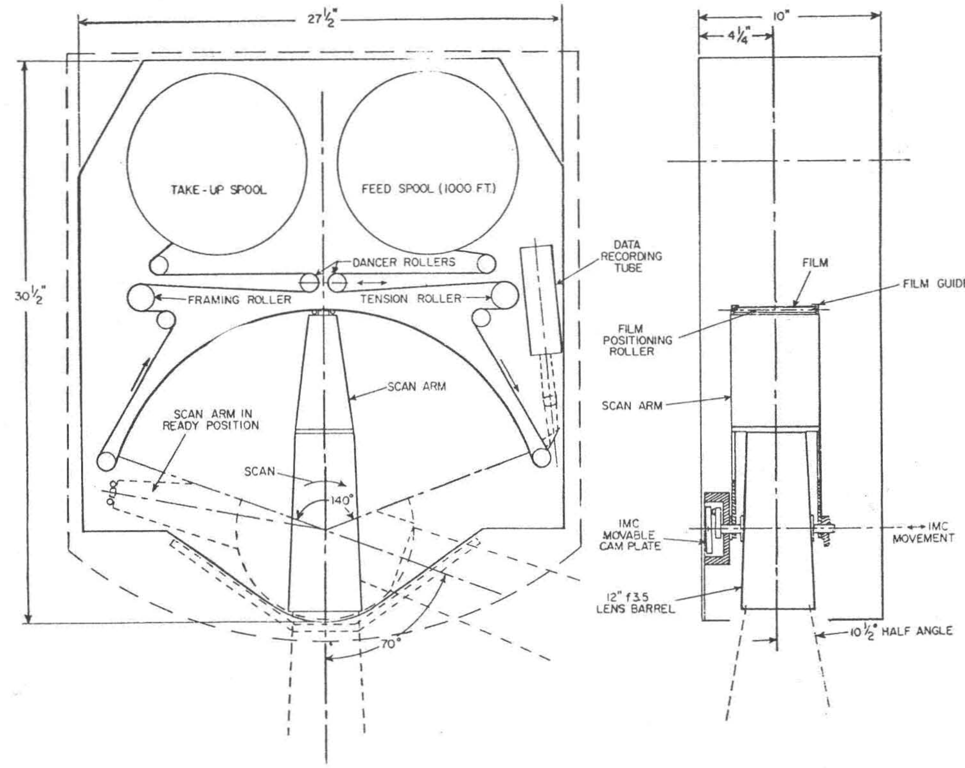

FIG. 2. Hyac 140-degree camera.

platen (the example illustrated here was designed for 140 degrees of angular coverage). However, as can be seen in Figure 3, a full 360-degree coverage can be obtained with a direct scanning system if the optical system is offset by means of two mirrors.

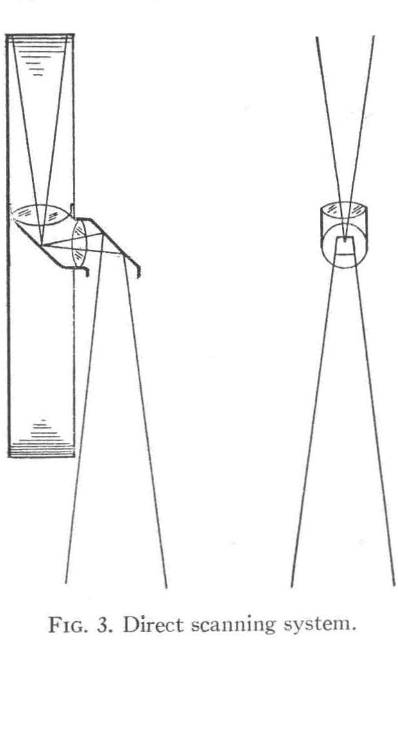

FIG. 3. Direct scanning system.

It should be noted that, in the direction of scan, only the lens and scan arm move while the film remains stationary. Furthermore, since the center of the lens rotates as a unit with the scanning slit, the sharpest possible image is always projected onto the film even if irregularities should develop in the scan rate. In the worst case there could be some variation in the exposure because of these irregularities (resulting in corresponding variations in the film density) but the resolution would remain essentially unaffected.

The first successful high-resolution airborne panoramic camera was designed in 1957. A direct-scanning camera, the Hyac I had a 12-inch f/5 lens and covered a total scan angle of 120 degrees. In-flight performance of the Hyac I resulted consistently in resolutions of 100 lines per millimeter on SO 1213 film.

Rotating prism camera

Figure 4 is a schematic of a rotating-prism scanning camera employing the concept of a continuously rotating lens. A full 180-degree scan, or even more, can be achieved with this configuration. A double-dove prism, the

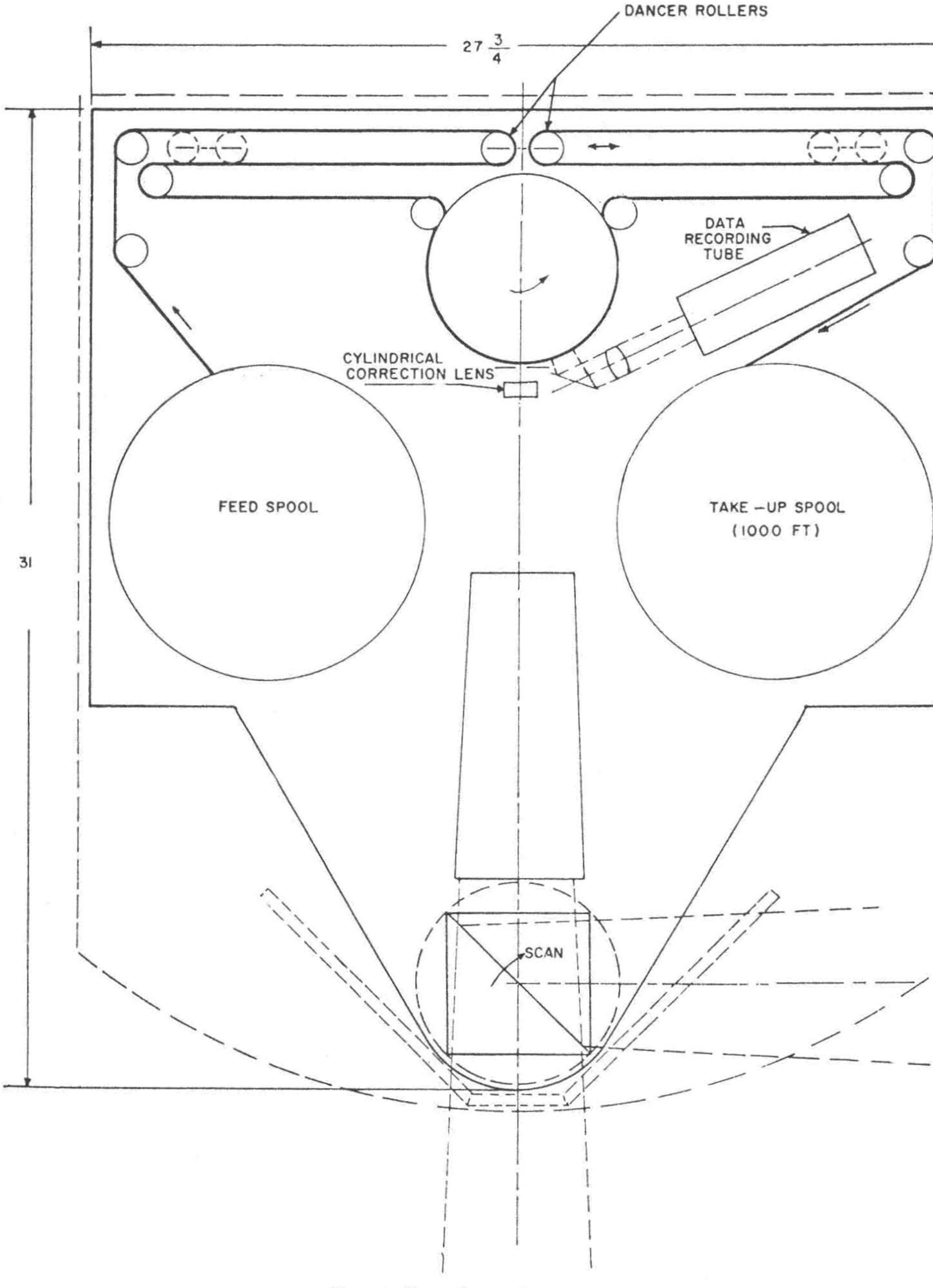

FIG. 4. Rotating prism camera.

diagonal faces of which are aluminized and cemented together, is placed in front of the lens. This prism must rotate 90 degrees for each 180-degree scan. The light path is diverted by a diagonal mirror and imaged on the film which passes around a rotating drum. The rotation of the drum must be accurately coordinated with that of the prism in order to achieve good image quality.

The diameter of the drum as shown on the drawing is such that it must make exactly two revolutions for one 90-degree turn of the prism. The film passes from a supply spool around an idler roller, over a pair of loop-forming or dancer rollers to another idler roller, and then to a roller which guides it around the drum. The path to the take-up spool is similar. Because of the fast motion of the recording drum whenever a picture is being taken, enough space must be allowed so that a full frame can be stored by the dancer rollers.

In the ready position, the prism is turned a few degrees beyond the point which allows it to look 90 degrees out to one side of the vehicle. When the mechanism is released, the prism and drum are both brought up to the desired speed. The prism turns 90 degrees clockwise at a uniform rate and the drum makes two revolutions in order to complete the 180-degree scan. The prism then travels a few degrees beyond for deceleration. When the prism is turned in the counterclockwise direction in preparation for the next photograph, the drum remains stationary. To maintain theoretical resolution, the synchronization must be significantly more precise than the final resolution to be achieved. If resolution on the order of 100 lines per millimeter is desired, relative motion in the image plane cannot exceed approximately 1/200 mm. In addition, systems employing dove prisms cannot be successfully applied where large apertures are required. The large glass mass of the prism is extremely sensitive to temperature changes, and any distortion of the prism produces image degradation. The fact that the reflection comes from a reflecting surface inside the glass adds to the seriousness of this effect. Image doubling from the two prisms takes place at the slightest provocation; even under the best laboratory conditions, the theoretical resolution of the lens is cut in half in one direction by the aperture-splitting action of the double-dove prism.

It should also be noted that the configuration, as shown, will result in positive prints that are mirror images of the scene they represent. If properly oriented photographs are required, an additional mirror must be inserted in the optical path.

Comparison of the two schemes

Comparing direct scan with rotating prism scan, it can be said in general that, where highest possible resolution for a given lens is of paramount importance, the direct scanning camera is to be preferred. This is primarily because of the need for extremely fine coordination of film and prism motions which, in the latter system, must be to a few seconds of arc.

On the other hand, a direct-scanning camera, especially if it is equipped with scan arm, requires more space than does a rotating prism system. This becomes particularly true in systems using very long focal lengths.

REPRESENTATIVE PANORAMIC DESIGNS

The Hyac camera (Type I Figure 5)

The simplest and most reliable of the panoramic types considered here is the Hyac camera. This camera is characterized by rotation of the lens about its nodal-point, by a curved focal-plane which does not move during scanning, by a non-folded optical path, and by the provision of image-motion compensation (IMC) through translating the lens along its axis of rotation with a flat cam surface. This design avoids the complexity of synchronized film motion; the absence of folding mirrors and the structural simplicity of a rigid tie between-the-lens axis of rotation and the platen minimize the degrading effect of vibration.

Modified Hyac camera (Type II in Figure 5)

This is similar to the original Hyac camera in that the film remains stationary in a platen while a lens scans through the required panoramic angle by rotating about its nodal-point. The difference is that the nodal-point of the lens is located at a considerable fraction of the focal-length in front of the lens. This is a telephoto lens long known for its compactness. Thus, the lens translates along an arc concentric with the platen for scan. This is particularly adaptable to reflective optical systems such as a Cassegrainian. (For example, a 240-inch f/20 Cassegrainian mirror system has been designed and constructed in which the front mirror is located only 40 inches from the focal plane.)

The advantages of this type are the lightweight mirror system and the ability to package a long focal-length in a configuration of small volume. The mechanical problem is somewhat more difficult than that of simply rotating a lens, but it is by no means insurmountable. The power requirement will be relatively high because of the large masses that must be moved, with an attendant higher friction bearing than for a rotary Hyac.

Modified Hyac camera (Type III in Figure 5)

This type features a flexible platen and a rigid scanning arm, compared with Hyac's rigid platen and spring-loaded scanning arm. Since the film is not restrained by the platen to lie along the locus of the focal plane, it is necessary to meter the film past the slit. This design is considerably more complex than that of the basic Hyac camera because the film must be kept in precise synchronism with the regular rate of the scanning lens. Such synchronization would probably be more difficult to achieve with this particular

PANORAMIC CAMERA TYPE								
	HYAC CAMERA	MODIFIED HYAC CAMERA	MODIFIED HYAC CAMERA	MODIFIED HYAC CAMERA	MOVING FOCAL PLANE CAMERA	OSCILLATING MIRROR CAMERA	ROTATING OPTIC BAR CAMERA	NODDING LENS CAMERA
RELIABILITY	VERY RELIABLE	RELIABLE	RELIABLE	FAIRLY RELIABLE	RELIABLE	FAIRLY RELIABLE	LOW RELIABILITY	VERY LOW RELIABILITY
INHERENT RESOLUTION CAPABILITIES	EXCELLENT	EXCELLENT	FAIR	FAIR	GOOD	FAIR	GOOD	POOR
WEIGHT & POWER	LOWEST	MODERATE	LOW	MODERATE	MODERATE	HIGH	HIGH	HIGH
FEATURES	FILM STATIONARY. NO SYNCHRONIZATION REQUIRED.	ADAPTABLE TO CASSEGRAIN LENS ROTATES ABOUT NODAL POINT EXTERNAL.	FLOATING PLATEN-RIGID ARM. FILM POSITIONED & METERED AT SLIT.	SCANNING ARM POSITIONS & METERS FILM SYNCHRONOUSLY. NO PLATEN.	FILM FIXED TO PLATEN-PLATEN MOVES IN SYCHRONISM.	SLIT & LENS STATIONARY. FILM MOVES SYNCHRONOUSLY WITH MIRROR.	CONTINUOUS ROTATION. FILM MOTION SYNCHRONIZED. MODIFIED E-2	FILM, LENS, & MIRROR MOVE SYNCHRONOUSLY.
TYPE NUMBER	I	II	III	IV	V	VI	VII	VIII

TECHNIQUE SKETCH

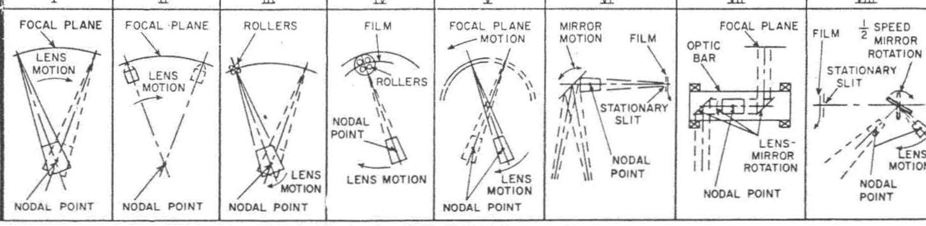

FIG. 5. Representative panoramic configurations.

design than with the moving focal-plane camera since the film rather than the platen would have to be driven, and its much smaller mass would make it more susceptible to vibration. The flexibility of the film and the need for precise synchronization will also affect the inherent performance capability, as will the necessity of driving the film. It should be noted that driving the film by means of sprockets has been rejected in all considered designs since it is not feasible with such a drive to obtain the resolution required.

Modified Hyac camera (Type IV in Figure 5)

In this design, the lens rotates about a point lying between the nodal-point and the focal-plane. The film lies unrestrained in the camera and is positioned and metered by rollers at the slit. In these respects, this modification is similar to that discussed in Type III, the principal difference being the rate at which film is metered. The advantage of smaller volume for a given focal-length must be weighed against the disadvantage of not having the lens rotate about its nodal point.

Moving focal-plane camera (Type V in Figure 5)

In this design, the film is held in a curved focal-plane and both the focal-plane and the lens are rotated about a common center. Such a design is one step removed from the simplicity of the basic Hyac camera in that there are two moving elements which must be kept in synchronization. The reliability of such a device should be reasonably high, but its inherent performance capability is not as high as the basic Hyac system because of image quality lost due to vibration of the film when moving.

The weight of such a camera is slightly more than that of the Hyac because of the necessary platen-moving mechanism; power requirements are somewhat higher for the same reason. The over-all dimensions of the moving focal-plane camera are comparable to those of the basic Hyac. A slight advantage in adaptability is achieved by the ability to rotate about a variety of axes, but this advantage is lost in the present case because of the necessity of enlarging the vehicle cutout as the axis of rotation moves away from the node.

Oscillating-mirror camera (Type VI in Figure 5)

In this design, the lens remains fixed with the optical axis transverse to the direction of flight. A mirror in front of the lens oscillates and the film is moved past a fixed slit at a rate suitable to synchronize with the image movement. This is more complex than the designs discussed previously, although it is still only necessary to synchronize the motions of two elements, the oscillating mirror and the film. Since this must be done with considerable distance between these elements, the inherent performance capability would be low.

The weight would probably be high since an additional element, the scanning mirror, has been added. This mirror will of necessity be quite large and heavy. Power requirements will also be large since this mass will have to be accelerated and decelerated quite rapidly for scanning.

Rotating optic-bar camera (Type VII in Figure 5)

This is a modified Air Force E-2 camera designed and built by the Boston University Physical Research Laboratories and Vectron Inc. This design is more complex in that two mirrors, the lens, and the film must be in constant rotation. A mirror at 45 degrees, the lens, and a second 45-degree mirror are disposed with the optical axis along the longitudinal axis of the vehicle. The entire bar is then rotated at constant speed about the optical axis. If the second mirror is placed at one half the angular speed, IMC is accomplished by shifting the entire bar longitudinally. Obviously, this is a more complex device than those previously discussed; because of the concentric arrangements, however, reliability can be high if care is exercised in fabrication.

The weight is unusually high since two extra mirrors are involved. Power requirements are held to a minimum because of the continual rotation characteristics of the system.

Nodding-Lens camera (Type VIII in Figure 5)

In the nodding-lens design, the lens as a whole is rotated about a point on the surface of a mirror any place between the rear vertex and the focal-plane. The mirror is rotated at half the angular speed of the lens, and the film is driven at a rate equal to the focal-length times the angular rate of the lens. This is the most complex design we have considered, and because synchronization must be maintained among all three elements, its reliability and inherent performance potential are considered to be low.

Mounting and Stabilization

As with other types of aerial photography, the full potential of panoramic photography can only be realized under conditions of proper stabilization and image motion compensation (IMC).

Because of the wide angular coverage of the panoramic camera, the relative effects of pitch, roll, and yaw very considerably over the picture area. For instance, near the horizon the effects of roll and of yaw are maximized while effects of pitch are relatively less. When scanning directly below the vehicle, on the other hand, effects of roll and pitch are much more important than are effects of yaw. Thus, for maximum information acquisition, a mount that will stabilize the camera in all three axes is important.

Of equal importance is IMC. With the use of faster vehicles and requirements for finer ground resolution, the camera will move over several times the resolution width even during short exposure times (1/400 to 1/2,000 second). To compensate, the lens must be moved back, opposite the direction of flight (i.e., at right-angles to the direction of scan). A certain amount of error is unavoidable since the height and ground speed of the vehicle are usually known only imperfectly. This IMC error can be further compounded if the vehicle, because of weather conditions, is doing more than a negligible amount of "crabbing." If it is, the vehicle is not actually traveling in the direction of its heading, and IMC, operating along the vehicle's longitudinal axis, will compensate in the wrong direction. Thus, azimuth correction in the mount is also important for maximum resolution.

A third requirement for all types of photography is exposure control. In a panoramic camera with a fixed scanning speed this is most readily accomplished by varying the slit width. Required exposure is a factor which usually changes rather slowly and therefore presents a relatively minor problem. Standard techniques are available for measuring available light and setting the required exposure automatically.

(*To be continued and completed in March 1962 issue*)