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Memorandum of Project MICHIGAN

OPTICAL-MECHANICAL SCANNING TECHNIQUES

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Robert L. Hess
Technical Director
Project MICHIGAN

OPTICAL-MECHANICAL SCANNING TECHNIQUES

ABSTRACT

A general discussion of optical-mechanical scanning techniques and a detailed analysis of a representative type of device (an air-to-ground reconnaissance mapping device) are given. The interactions of altitude, vehicle speed, total scan angle, resolution, and detector time constant are explored to reveal the constraints on the operation of such a device, and the changes necessary to obtain higher performance are formulated. In addition, certain geometrical features of the operation of such a device are discussed insofar as they relate to the display of information from the device.

1

INTRODUCTION

The description of the characteristics of reflecting and refracting optical systems for collecting and focusing infrared radiation does not complete the characterization of infrared equipment in military and industrial applications. These telescopes usually have relatively small fields of view because of their optical limitations; thus, for many applications (e.g., reconnaissance, mapping, thermal photography, tracking, and missile guidance) some method is needed to make this small field of view cover a much larger one. This is often accomplished by a programmed space-scan or scanning, which can be done in a number of ways. In this memorandum, each of these ways is defined and described briefly, and the conceptual constraints on a scanner used for air-to-ground mapping are derived to demonstrate the methods by which engineering compromises are made.

An equipment which employs electronic scanning is in principle identical with standard television systems: an image is focused on a photosensitive surface which is in turn scanned by an electron beam. The major constraints in this system are the properties of the surface. If a satisfactory material is available, the properties of the electron optics and scanning techniques well known in the television industry are applicable. This type of system is very satisfactory in many respects, but a useful sensitive surface is not readily available.

An alternative technique is to cause a single detector, or a one- or two-dimensional detector array (mosaic), to "see" a series of small parts of the field of view. This type of sampling is generally called optical-mechanical scanning or simply "scanning," as opposed to electron-beam scanning, the process described above. There are, in principle, two types of scanning—image plane and object plane. The first of these is so termed because an image of the total object field is formed by a collecting telescope; this image is then sampled point by point by a second optical system containing the transducer (the infrared detector). It is clear that the scanning device, the optical element that changes the instantaneous field of view of the detector, can be simple, small, and easily designed. On the other hand, a high-quality image of the entire field must be formed by the collecting optics. The problems involved in obtaining such an image over fields larger than some 10^{o} or 20^{o} are quite difficult to overcome; it is mainly for this reason that image-plane scanning systems are difficult to design and construct.

Object-plane scanning, of course, also has its advantages and disadvantages; however, the problem is not to improve the optical system but to design the proper scanning device. For this reason, object-plane scanning has been quite successful to date and will be discussed further.

Many types of scan patterns and scan methods can be visualized. They all fit into several general classes, however: circular or spiral, cycloidal, and rectilinear or raster. Each of the scan patterns has certain characteristics that make it more suitable for some applications than for others. For instance, one should probably use a regular, repetitive raster or simple circular scan to construct an image, the particular geometry depending upon the shape of the object field. A search system or tracking system does not require the construction of an image; therefore, a scanning system that searches more critical areas more frequently may be desired.

To illustrate the versatility of the scanning systems, several types will be described. First, a hypocycloidal pattern can be generated simply by superimposing one circular scan upon another. If an offset mirror is rotated about a shaft, and the shaft in turn has a locus which is a circle, then the scan pattern shown in Figure 1(a) is obtained. A more interesting and versatile scanning system is composed of a pair of prisms or wedges. If these are counterrotated at the appropriate rates, a rosette pattern somewhat similar to the hypocycloid is generated (see Figure 1b). But if the wedges are rotated in the same direction at different rates, a spiral (Figure 1c) is developed. Other patterns are possible, the most interesting of which is probably the simple sinusoid (Figure 1d). If this pattern is appropriately set up, one can obtain a scan very similar to that of a television raster (with no flyback or interlace, however) and thus obtain an image. The possibilities for other types of scan—servo-corrected pseudo-sine waves, circular scan (Figure 1f), Palmer scan (Figure 1e), and others—are virtually limitless. The particular application dictates the form of the scan; the values of detector time constant, required frequency of coverage, total field of view, resolution, and physical limits on moving parts, among other things, generally limit the system.

2

ANALYSIS OF AN AIR-TO-GROUND RECONNAISSANCE MAPPING DEVICE

As an example, since not all scanning applications can be considered, an air-to-ground reconnaissance mapping device will be briefly considered here. Its features and constraints illustrate most of the design problems of object-plane scanning. The scan pattern is illustrated in Figure 2.

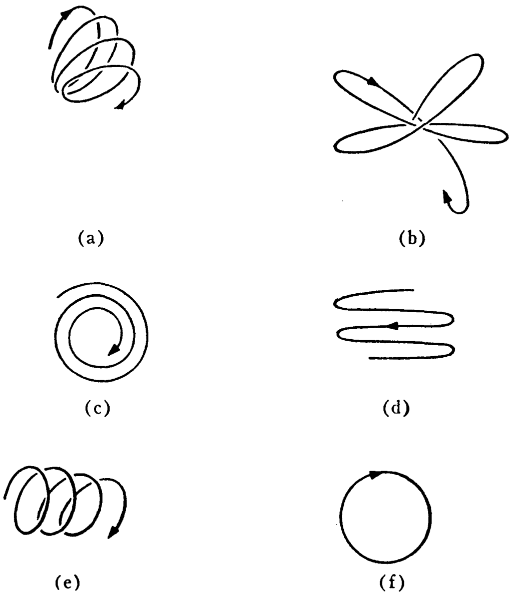

FIGURE 1. EXAMPLES OF REPRESENTATIVE SCAN PATTERNS: (a) Hypocycloid; (b) rosette; (c) spiral; (d) sinusoid; (e) Palmer; (f) circular.

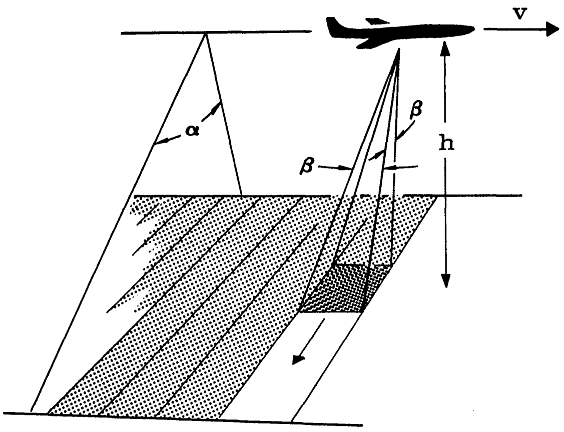

FIGURE 2. REPRESENTATION OF THE SCAN PATTERN FOR A TYPICAL PRISM SCANNER

An airborne vehicle traveling with speed v at altitude h carries a scanner having an instantaneous field of view (resolution element) of angular size β in both dimensions. To provide a good image, β (Figure 2) is typically made quite small, on the order of milliradians. This instantaneous field of view is scanned through an angle (α) at right angles to the aircraft path by a rotating element in the scanner. The motion of the vehicle carries the scanner forward so that successive scans cover different strips of the ground. The portion of ground swept over during a single scan through angle α is called a "line." If successive lines are not contiguous (if parts of the ground between the lines are not scanned), the condition is termed "underlap." This can occur if the vehicle speed is too high or if the rotating elements revolve too slowly. If successive lines scan partly over the same terrain the condition is called "overlap." Underlap is clearly undesirable, since information is not obtained between successive lines. Contiguous scanning is desirable in that no ground remains unscanned, and there is a certain economy in not scanning more than once over any part of the ground. Under certain circumstances overlap is useful since the redundancies can be used to increase the signal-to-noise ratio.

A typical device for obtaining such a scan pattern is illustrated in Figure 3. A mirror in the form of a prism with n faces rotates at a rate r about an axis which is parallel to the flight path of the aircraft. Hence n lines are scanned per revolution when a single-element detector is used. Each face of the prism is inclined 45° to the axis of rotation. Normally, the detector acts as the field stop of the system, determining the angular dimensions of the instantaneous field of view. If the detector, instead of being a single element, consists of l identical elements arranged in a closely spaced linear array, then l contiguous lines will be swept out simultaneously by each face of the prism. Thus n × l lines will be scanned per revolution.

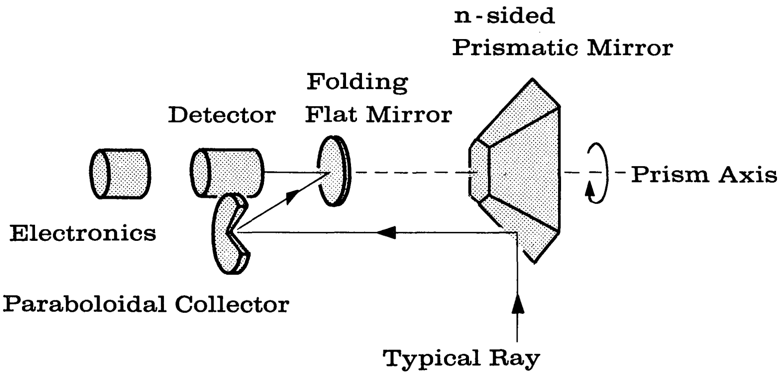

FIGURE 3. SCHEMATIC ILLUSTRATION OF A TYPICAL PRISM SCANNER

The principal detector characteristic of significance here is the time constant τ. It will be assumed that the scanner must dwell on each resolution element for a time not less than $k \times \tau$, where k is a positive dimensionless number representing the dwell time in terms of the detector time constant.

The operation of such a scanner must meet two conditions: (1) The scanner must dwell on each resolution element for a time not less than $k\tau$. The number of resolution elements scanned per second is $2\pi r/\beta$, so the dwell time is $\beta/2\pi r$. Hence, $(\beta/2\pi r) \geq k\tau$. (2) The scanner must be operated at such a rate that no underlap occurs (overlap may be permitted). In the direction of aircraft travel, the width of the strip scanned by each face of the prism is βhl; the width of the strip scanned each second is $\beta hlnr$. If no underlap is to occur, this expression must be greater than or equal to the vehicle speed ($\beta hlnr \geq v$). These two expressions can be rearranged to obtain

$$r \leq \frac{\beta}{2\pi k\tau} \quad \text{and} \quad r \geq \frac{v}{hln\beta}$$

in which all quantities are positive.

Thus r has an upper limit set basically by the detector time constant and a lower limit set by the zero-underlap requirement (i. e., by v/h). A third constraint upon r is also important: the maximum rotation rate permitted by mechanical considerations such as strength of materials, vibrations, and allowable distortions.

When r is eliminated from the above inequalities a constraint upon β is obtained:

$$\beta \geq \sqrt{\frac{2\pi k}{nl} \cdot \frac{v}{h} \cdot \tau}$$

Unlike r, β is constrained by a lower limit only. This constraint is imposed by the joint action of v/h and τ.

Under the limiting condition that the lines be contiguous, the inequalities become equalities and the relations become

$$r = \sqrt{\frac{1}{2\pi knl} \cdot \frac{v}{h} \cdot \frac{1}{\tau}}$$

$$\beta = \sqrt{\frac{2\pi k}{nl} \cdot \frac{v}{h} \cdot \tau}$$

The individual terms in these expressions warrant some discussion. The designer usually will have little or no control over v, h, τ, and k. The first two are usually set by the requirements for vehicle operation. The properties of the detector materials determine τ, and these are not subject to change though there is some small choice available in the selection of different detector materials. The amount of information degradation which is tolerable determines k, which is usually not less than 2. Thus, the only free variables are n, l, and to a lesser extent β in that it is constrained by a minimum value but not by a maximum value, except as the picture quality is degraded. As noted above, r is constrained by both greatest and least values as well as by mechanical considerations.

The value selected for n determines α, the total angular width of the scan, since $\alpha = 360^\circ/n$. Note that, since $n = 1, 2, 3, \cdots$, then $\alpha = 360^\circ, 180^\circ, 120^\circ, \cdots$.

In the reconnaissance of large areas it is desirable to spend as little time as possible flying over the area. Therefore, α should be as large as possible, so n should be as small as possible, e.g., $n = 2$, so $\alpha = 180^\circ$.

Inasmuch as the maximum detail is usually desired, β should be as small as possible. Also, for mechanical reasons it is desirable to minimize r. Since both β and r must be minimized, the designer has at his complete disposal only the factor l. Thus, in a sense, this factor lies at the heart of the scanner-design process.

Two types of reconnaissance missions appear to be reasonably safe for the aircraft: very low, very fast flight, or very high, very fast flight. The first, a low-altitude, high-speed reconnaissance system, is represented by the following parameters: $k = 2$, $n = 2$, $v = 1000$ fps, $h = 1000$ feet and $\tau = 10^{-5}$ second; then

$$r = 63\frac{1}{\sqrt{l}}\ \text{rps} \quad \text{and} \quad \beta = 7.8 \times 10^{-3}\frac{1}{\sqrt{l}}\ \text{rad}$$

If $l = 1$, the simplest configuration to implement, then $r = 3780$ rpm and $\beta = 7.8$ mrad.

An r of 3780 is reasonable since apertures commonly used in such devices are about 6 inches in diameter and since such mirrors can be rotated at rates up to 6000 rpm without undue difficulty in holding distortion within optical limits (about 25 μ).

A β_{min} of 7.8 mrad is larger than is desirable since optical components can be made with resolution better than 1 mrad. If, in an attempt to reduce β without increasing l, the fastest detector readily available is selected (i.e., $\tau = 10^{-6}$ second), then $r = 12,000$ rpm and $\beta = 2.5$ mrad. This still falls short of the desired instantaneous field of 1 mrad, and the rotation rate becomes a serious problem. Thus, decreasing the detector time constant cannot greatly improve the performance of single-element-detector scanners operating with large α.

If, on the other hand, 1 is increased to achieve a β no greater than 1 mrad, it must be at least 9, and in this case r = 4000 rpm and $\beta = 0.8$ mrad for $\tau = 10^{-6}$ second. Both of these are achievable values. Note again that further decreasing τ would result in unrealistic values for r.

The second example concerns itself with very high-altitude reconnaissance. At present it is not unreasonable to think of flight altitudes of 100, 000 feet, an increase by a factor of 100 over the 1000-foot altitude considered in the above example. An increase in v by the same factor does not seem possible at present because propulsion-unit and aerodynamic considerations seem to restrict v between 3000 and 5000 fps. In addition, if these limitations are neglected there is an upper limit on v of 25, 000 to 30, 000 fps, a speed quite close to escape velocity. Thus, very high and very fast operation must result in a reduction of the ratio v/h. But because of the manner in which v/h enters the expressions for r and β, this reduced ratio results in values for these quantities which are relatively easy to obtain. Thus, the low and fast operation considered in the example is the most difficult to achieve in terms of scanner use. Therefore, any other method of operation is bound to make scanner implementation easier.

There is one exception to the last statement. If it is desired to maintain, at very high altitudes, the same linear ground resolution that is obtainable at low altitudes, a difficulty arises. At an altitude of 1000 feet an angular resolution of 1 mrad implies a linear ground resolution of 1 foot at an altitude of 100, 000 feet; a ground resolution of 1 foot implies an angular resolution of 10^{-2} mrad. But the Rayleigh criterion states that, for a circular aperture of diameter d, the best obtainable resolution at a wavelength λ is given by $\beta = 1.22\lambda/d$. At a wavelength of $10\,\mu$, a desired β of 10^{-2} mrad requires a circular aperture with a diameter of 120 cm, or about 40 inches. This aperture is very near the maximum diameter which can be employed in airborne vehicles. However, the Rayleigh criterion is an idealized limit for a perfect optical system. In practice such performance cannot be realized. Thus at very high altitudes linear ground resolution may have to be sacrificed because of fundamental physical limitations.

3

GEOMETRICAL FACTORS

There are two features of the operation of the scanner described above which must be considered in the display of the information. First, although the angular resolution is constant, the linear resolution on the ground is not; it becomes progressively larger as the optical axis of the scanner is inclined at larger angles from the vertical, and it does not change isotropically. Second, when a linear detector array is employed, the projection on the ground of the instantaneous field of view of the array rotates as the scan angle increases. These features are discussed below; the mechanism of resolution change in direction of aircraft travel as a function of the angle of view away from the vertical is sketched in Figure 4.

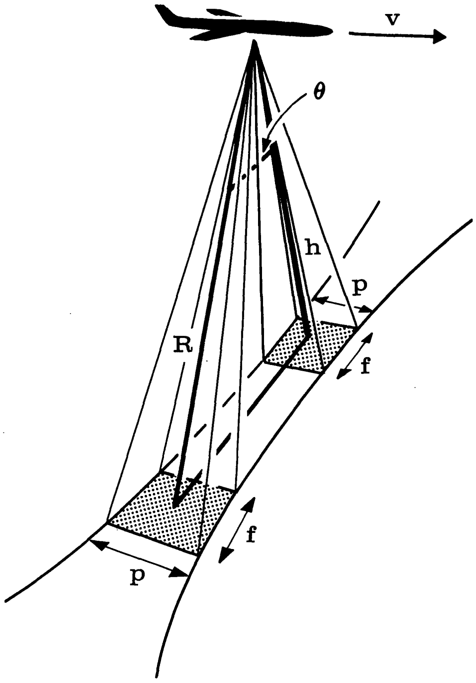

FIGURE 4. GEOMETRY FOR THE DETERMINATION OF RESOLUTION CHANGE IN THE DIRECTION PERPENDICULAR TO THE FLIGHT DIRECTION

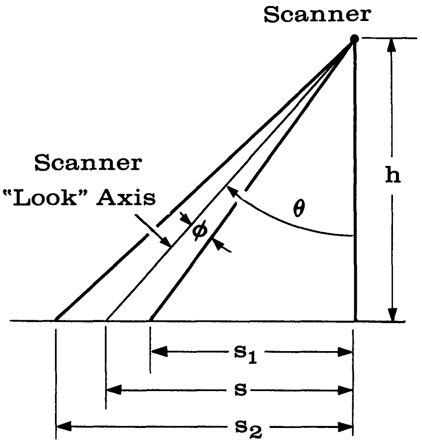

FIGURE 5. GEOMETRY FOR THE DETERMINATION OF RESOLUTION CHANGE IN THE DIRECTION PARALLEL TO THE FLIGHT DIRECTION

In Figure 4, and in the following text, a flat earth approximation is assumed. The angle away from vertical is designated by θ, the range from the scanner to the earth at any instant is designated r, and p is the length of the instantaneous field of view in the direction of aircraft travel. It can be seen from the figure that $p = \beta r$ and $r = h \sec \theta$ so that $p = \beta h \sec \theta$.

To obtain an expression for the change in the other dimension of the instantaneous field of view as a function of θ, see Figure 5. From this figure,

$$s_2 = h \tan(\theta + \phi) = h \frac{\tan \phi + \tan \theta}{1 - \tan \phi \tan \theta}$$

and

$$s_1 = h \tan(\theta - \phi) = h \frac{\tan\theta - \tan\phi}{1 + \tan\theta \tan\phi}$$

But $\tan \phi \approx \phi$ for small ϕ; therefore,

$$s_2 \approx h \frac{\phi + \tan\theta}{1 - \phi \tan\theta}$$

$$s_1 \approx h \frac{\tan\theta - \phi}{1 + \phi \tan\theta}$$

$$f = s_2 - s_1 \approx 2h\phi \frac{1 + \tan^2\theta}{1 - \phi^2 \tan^2\theta}$$

For values of θ not more than 85°, $\tan\theta$ is not much larger than 10. Since ϕ is about 10^{-3} rad, $\phi^2 \tan^2 \theta$ can be ignored.

Thus,

$$f \approx h\beta(1 + \tan^2\theta) = h\beta \sec^2\theta$$

Therefore, the field of view changes as $\beta h \sec\theta$ in one direction and $\beta h \sec^2\theta$ in the other.

It is also true that, when a linear detector array is used with a rotating-prism scanner of the type discussed here (i.e., with prism faces inclined at 45° to the axis of prism rotation), the projection of the elements of the linear array upon a flat earth rotates as the projection moves laterally to the aircraft flight path. The angle of rotation of the projected array elements is just equal to the angle θ away from the vertical through which the element prism face has rotated.

4
SUMMARY AND CONCLUSIONS

In summary: the example has shown that the parameter l is of central importance in the design of scanners of the rotating-prism type. By the use of linear detector arrays with small numbers of elements (about 10), any reasonable resolution, β, can be obtained at reasonable rotation rates, r. There seems to be no immediate need in this type of scanner for detectors having much shorter time constants than those now used. The design of this equipment involves several unusual geometrical factors which should be corrected if undistorted presentation of information from a scanner operating over wide ($\alpha \geq 120°$) total fields of view is to be obtained.

The example given here does not include an assessment of all the variables involved in the design of optical-mechanical scanning equipment because these devices in general are used not only for air-to-ground reconnaissance, but also for air-to-air guidance and warning, ground-to-ground search and detection, and a variety of different military and civilian problems. Many factors must be considered in their design. Thus, although the example given here encompasses only a small part of the great variety of problems facing the infrared instrumentation engineer, it illustrates several of the basic design processes and yields practical results for a specific application.

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(Memorandum no. 2900-154-R)
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