OPTICAL RADAR AND PASSIVE OPTO-ELECTRONIC RANGING[1]

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ABSTRACT

The purpose of this paper is to present the fundamental technical arrangement involved for optical radar, its resolution, and requirements concerning the light source for use with it. Some basic optical radar problems are explained and pertinent equations are derived.

The paper shows that 10^{17} quanta per pulse at a repetition rate of 77 per second are sufficient to achieve optical radar. For this a minimum volume of only 1 mm^3 is required for a luminescent semiconductor to produce this quanta flux. The light source does not necessarily have to be a laser, since the narrow bandwidth of the lasers cannot, by the present state of the art, be fully utilized with the overall optical bandwidth of such a system. If a source can produce the necessary quanta flux with a bandwidth of not more than about 20 Å, the job will be as well performed by this source as by a laser. Very promising luminescent semiconductors for such an endeavor, using the visible spectrum, seem to be the II–VI compounds. An automatic passive optical range-finder system using a special pick-up transducer (conceived by the author) which automatically suppresses any background structure (clouds, etc.) is explained.

INTRODUCTION

The growing number of radar installations, not only those used for military purposes but also in civilian aviation and the ever increasing air traffic, constantly increase the probability of interference between radar stations. It is obvious that, in the future, with more and more stations operating in overlapping frequencies, serious interference difficulties may be encountered. Therefore, the use of new frequency bands and new methods are vital. An optical radar system, with which either light in the visible range or frequencies corresponding to the infrared windows through the atmosphere are utilized, may be of considerable value. Range-finding by passive opto-electronic means is also possible, reducing further the possibility of interference between different radar stations. The purpose of this paper is to present the fundamental technical arrangement involved for optical radar, its resolution, and requirements concerning the light source for use with it; further, a passive opto-electronic range-finding arrangement, and the available resolution and sensitivity, is presented. The parameters investigated permit determination of the minimum number of quanta of light necessary to accomplish such tasks.

OPTICAL RADAR

As is the case with conventional radar, three objectives must be accomplished by the optical radar system: image display, image recording, and distance measurement. However, the operation mode of optical radar is usually different from that of conventional radar. Beams of visible or near-infrared radiation, especially those generated by lasers, can usually be focused to a much smaller angular diameter than radiation in the microwave region, which makes modes of scanning possible with optical radar that would be impractical or even impossible for the conventional radar. An optical radar system consists of a light source which, by employing appropriate mechanical and optical means, scans the scene with a narrow beam of light; a photodetector (or photodetectors) which receives and transduces into an electrical signal the light that was furnished by the source, reflected by the objects composing the scene, and then collected by an optical system; and the appropriate electronic circuitry for image display and distance

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measurement, including equipment for obtaining a photographic recording and for a magnetic tape recording, etc., of the video signal.

Figure 1 shows, for illustrative purposes, an airborne optical radar system which scans the ground, line by line, with constant angular velocity, perpendicular to the line of flight, whereby the effective ground velocity of the aircraft determines the ground progression of each line of scan. If it is desirable to have a continuous immediate observation of the scene as yielded by the electrical signal, two storage reproducer tubes, where the images are superimposed by optical means, could be used alternately. During the time that one is displaying, the other can store line by line from the bottom to the top of the screen until the full number of lines necessary for display of a whole image is stored. As an alternative, a storage tube with a moving, endless, bandlike storage screen is conceivable for continuous display.

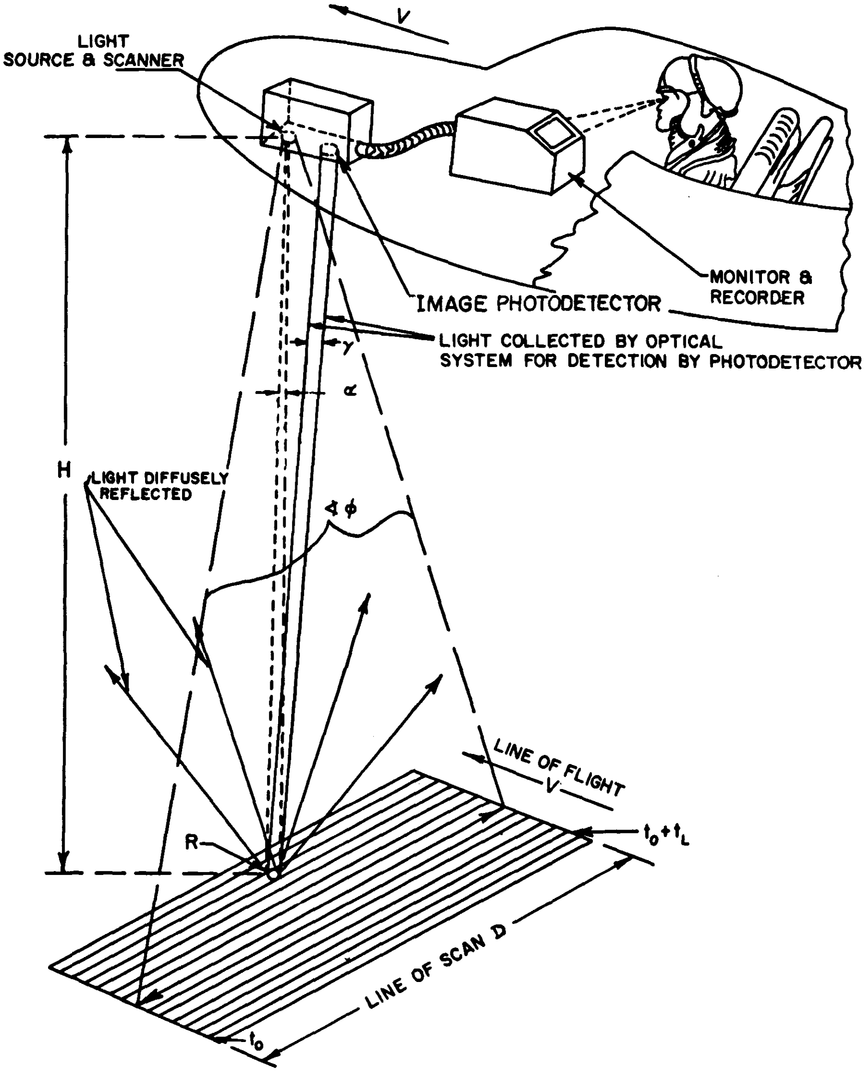

FIGURE 1. Geometry Involved in Optical Radar Scanning.

The photodetector of the optical radar may detect not only the light from its own source, but also that from natural illumination (light coming from the area, determined by the angle of view of the receiving optical system, other than that from the spot under analysis by the scanning light beam), which would obviously cause unwanted photocurrent in the detector and, hence, reduce the signal-to-noise ratio. For this reason, the wavelength selected for the light source should be in a spectral region where there is as little natural illumination as possible, and the spectral response of the photodetector should be restricted to that wavelength as much as possible by choosing an appropriate photodetector response and suitable filters. This will assure an optimum signal-to-noise ratio.

The beam of the light source which is used to scan the scene can be pulsed for each resolution spot so that, during the pulse, a higher quanta flux and improved resolution are obtained than would be possible if the beam were furnishing quanta during the time it is moving from one resolution element to the next. Further, suitable pulsing of the video signal generated by the photodetector may assure a better cathode ray tube (CRT) presentation of the scene, since no noise or background signal is fed to the following amplifier and CRT between the signal pulses. For the least complicated system, the angle of view of the photodetector must correspond in its angular dimensions to the length of one line of scan and to its effective width, $k^*\gamma$, when k^* is a tolerance factor. In more complex systems, for the achievement of the optimum signal-to-noise ratio in the presence of background, one may use a photodetector to scan the scene in synchronization with the light source. Then, however, when relatively high-speed scanning is used, the distance the reflected light must travel may have to be known in order to maintain the proper angle between the scanning source and the photodetector. Here the minimum permissible angle of view of the photodetector will be determined by the width of the beam of the light source, the speed of the aircraft, the distance involved, and the accuracy with which the necessary angular difference between source and detector can be determined from this data.

For use with radiation in the visible and the near-infrared, a photomultiplier tube with an appropriately small-diameter photocathode, or a narrow-slit photocathode, is most suitable. However, the size of the photocathode must be such that the returning light can be positioned on the photocathode in spite of unavoidable deviations, as caused by vibrations, etc. Photodetecting devices which have photocathodes with an unnecessarily large area will decrease the signal-to-noise ratio, since the photocathode size determines the amount of dark current and the light imaged from areas other than those illuminated by the optical radar source causes unwanted photoelectron emission. Use of an aperture in the focal plane, when using an unnecessarily large photocathode, will reduce this unwanted emission but not the dark current. Obviously, in a system in which a scanning beam of light is used to illuminate the ground, the use of an image-forming photodetector, similar to that used in simultaneous or sequential light amplifier systems, will not yield a better signal-to-noise ratio than will a well-designed photomultiplier.

Obviously, the practical limit of the resolution of an optical radar system is determined by the achievable effective beam width. The number of lines, L, in second^{-1}, scanned, as shown by figure 1, should be adapted to the aircraft velocity, V, in meters second^{-1}; the aircraft altitude, H, in meters; and the effective cone angle, α, in radians, in which the light source radiates so that each line of illumination on the ground will be adjacent to the next one. The following equations are derived for vertical reconnaissance. The number of lines per second is

$$L \approx \frac{V}{\alpha H} \approx \frac{V}{R}, \tag{1}$$

where the perimeter of the base of the cone subtended by α has an intensity of

≈ 0.37 of the peak intensity inside the base, and R is the width in meters of one line of scan on the ground and also the diameter of one resolution element.

When rapid scanning systems are used, the time required for the light to travel from the source to the scene and then to the detector may be long enough so that the detector cannot be focused onto exactly the same spot on the ground as the source; the detector must follow the source by the angle δ.

If t_L is the time in seconds necessary to sweep the angle, ϕ, in radians, which corresponds to one line of scan, t_R is the time in seconds for the light to reach the scene and to return to the detector, and δ is the angle in radians between the axis of the beam of the source and the axis of the cone of light detected by the photodetector (see fig. 1), then

$$\delta = \frac{t_R}{t_L}\phi \approx \frac{2H\phi}{ct_L}, \tag{2}$$

where c is the velocity of light in meters per second.

Since α is a given value, the value chosen for ϕ determines the effective number of horizontal resolution elements, n_R, per line. Thus,

$$n_R \approx \frac{D}{R} \approx \frac{\phi}{\alpha}, \tag{3}$$

where D is the length in meters of one line of scan on the ground.

Example 1: An optical radar system is used in an aircraft (fig. 1) flying at 750 meters per second; $\alpha = 10^{-2}$ radians, $H = 1000$ meters, $\phi = 1$ radian. Eq (1) yields $R \approx 10$ meters, $L \approx 75$, and, using Eq (3), the number of resolution elements for each line is $n_R \approx 100$. Assuming continuous scanning, that is $t_L = 1/L$ from Eq (2), $\delta \approx 5 \times 10^{-4}$ radians. This value is neglibile here and a photodetector which is made to scan the target area may be in the same angular position as the transmitting beam of light.

The light from the source transmitted into a circular cone with an angle, α, is diffusely reflected at the target and only a very small fraction of this light (cone with angle γ) can be collected by the optical system and detected by the photodetector. An approximation for the ratio, K, of the number of quanta, Q_E, emitted by the source to the number of quanta, Q_R, incident on the photodetector, may be calculated. For simplicity, any conceivable angular preference in the reflection from the ground will not be considered and, hence, it is assumed that the portions of the received quanta which are reflected by the ground are distributed equally into a half sphere with the area $2\pi H^2$. Then,

$$K = \frac{Q_E}{Q_R} \approx \frac{2\pi H^2}{\pi d_a^2/4}\eta_A^2\,\eta_G\,\eta_O \approx 8\left(\frac{H}{d_a}\right)^2 \eta_A^2\,\eta_G\,\eta_O, \tag{4}$$

where d_a is the diameter in meters of the aperture in the optical system used for collecting the reflected light, η_A is the transmission efficiency of the media between the source and the scene, η_O is the efficiency of the optical system, and η_G is the ratio of the number of quanta reflected from the ground to the number received there. Obviously, the changes in η_G between the different ground resolution elements are the principal reason that optical radar works. Additional modulation of the returning light can be caused by a change in the angular preference of the reflected light from one resolution element to another. If η_Q is the quantum conversion yield of the photodetector, the factor, K'_{eff}, expressing the ratio of the number of quanta, Q_E, emitted by the source to the number of primary electrons, E_P, produced by the photodetector becomes

$$K'_{eff} = \frac{Q_E}{E_P} \approx \frac{K}{\eta_Q}. \tag{5}$$

The theoretical signal-to-noise ratio, S, attainable under ideal conditions (no noise other than conversion noise, for which a Poisson distribution is assumed) is

$$S = E_P^{1/2} = \left(\frac{Q_E}{K'_{eff}}\right)^{1/2}. \tag{6}$$

If the light source is also used to measure the distance, it has to be pulsed. The pulse repetition rate, P_R, cannot be greater than the reciprocal of the sum of the pulse duration, t_p, and the time required for the light to travel from the source to the scene and then to return to the photodetector. Then, for P_R and the greatest distance, L_{max}, in meters, which is to be measured, we find

$$P_R \leq \frac{1}{\left(t_p + \frac{2\,L_{max}}{c}\right)}. \tag{7}$$

Obviously, to obtain the optimum signal-to-noise ratio, the pulse duration, t_p, should be as short as possible in order to get the highest peak power with a given average power of the source. Further, t_p should also be shorter than the time required for the light to travel twice the least distance to be measured, L_{min}, in meters. Thus,

$$t_p < \frac{2\,L_{min}}{c}. \tag{8}$$

For most practical purposes, t_p should be in the microsecond range. For an image-display system, the minimum number of pulses, P_L, for each line and, therefore, the number of resolution elements necessary to sufficiently cover the area of one line of scan on the ground should be

$$P_L \approx \frac{D}{R} \approx \frac{\phi}{\alpha} \approx \frac{t_L}{t_p + t_i}, \tag{9}$$

where t_i is the time interval during which the beam is blanked and $t_i/t_p \geqq 4$ for most practical purposes in order to approach optimum resolution. The minimum number of pulses, P, in second^{-1} becomes

$$P = L\,P_L. \tag{10}$$

Example 2: Some commercially available lasers emit a cone of light (wavelength—6943Å) with $\alpha = 10^{-2}$ radians, deliver a nominal energy, E_L, of 3×10^8 ergs for each pulse, and can produce up to 6 pulses per minute. The pulse duration, t_p, is about 1 millisecond. The number of quanta, Q_E^*, produced during each laser pulse, is

$$Q_E^* = \frac{E_L}{h\,\frac{c}{\lambda}} = 5 \times 10^{17} E_L \lambda, \tag{11}$$

where h is Planck's constant and λ is the wavelength of the light in meters. In this case, for each pulse,

$$Q_E^* \approx 5 \times 10^{17} \times 3 \times 10^8 \times 6.943 \times 10^{-7} \approx 10^{20} \text{ quanta}.$$

Then, using the data of Example 1, utilizing an optical system of 8-inch diameter, assuming $\eta_G = 0.1$, $\eta_O = 0.5$, $\eta_Q = 0.1$, $\eta_A = 0.9$, and using Eqs (4) and (5),

$$K'_{\mathrm{eff}} \approx \frac{8\left(\dfrac{1000}{0.2}\right)^2}{0.1\times 0.5\times 0.1\times(0.9)^2} \approx 5\times 10^{10} \text{ quanta/electron.}$$

By using the output of one laser pulse, Q_E^*, for one line of scan, the number of electrons, E'_P, obtained during the effective time one resolution element is illuminated, is

$$E'_P \approx \frac{Q_E^*}{K'_{\mathrm{eff}}\ P_L} = \frac{Q_E^*\alpha}{K'_{\mathrm{eff}}\phi}. \tag{12}$$

Then, for the data of example 2,

$$E'_P = \frac{10^{20}\times 10^{-2}}{5\times 10^{10}\times 1} = 2.0\times 10^7 \text{ electrons.}$$

For the above, by using Eq (6) analogously, the theoretical signal-to-noise ratio is $S=(E'_P)^{1/2}=4.5\times 10^3{:}1$.

This value is more than sufficient for a good signal-to-noise ratio in practice, especially if suitable filters are used with the photodetector to eliminate stray light. Since the laser of this example produces a pulse of radiation with a duration of only one millisecond, the scanning of one line has to be performed during this one millisecond. In Example 1, 75 lines per second were scanned, which would result in a line time of ≈13 milliseconds; then, if the same conditions as in Example 1 are to be assumed, the unit would have to be blanked during the next 12 milliseconds until the aircraft had progressed far enough to prevent overlapping of adjacent lines. Achieving the scan in one millisecond by mechanical means may present some difficulties. In addition, not only should all the laser pulses be congruent, but each laser pulse can have only a negligible amount of unsteadiness in its amplitude over the used portion, since any fluctuation would show up as false information in the signal. Further, as quoted in this example, because this type of laser can produce only 1 pulse every 10 seconds, a prohibitively large number of lasers of this kind working sequentially would be necessary. Therefore, a laser with the same average power output as the above, but which produces one light pulse of approximately 10^{17} quanta about every 13 milliseconds instead of one pulse with 10^{20} quanta every 10 seconds, would be a practical solution in this example, since only one laser would be needed instead of an impossibly large number, as previously indicated. Most semiconductors have about 10^{22} excitable electrons per cm^3, of which one may assume the use of about 10^{20}, for emission of light; hence, a minimum volume of only 1 mm^3 is required to produce this quanta flux when assuming that repeated excitation of the semiconductor is possible within the quoted repetition rate.

The narrow spectral interval of the light from a laser can only be used to its full advantage if the opto-electronic system employed has a nearly identical spectral sensitivity characteristic, which cannot be achieved by the present state of the art. The use of interference photocathodes may be advantageous (Deutscher, 1958). The use of sources other than the present ruby lasers should be strongly considered for the above purposes; light-emitting semiconductors, for example, especially those capable of producing a single pulse of extremely short duration with precisely controlled timing. Due to the state of the art in optical detection systems, luminescent semiconductors used as light-emitting diodes with a bandwidth of not more than 20Å should do the job as well as a laser source, if the same power can be produced. In contrast to the ruby laser, these luminescent semiconductors should provide shorter pulse times, a constant quanta flux over the duration of the pulse, the capability of producing one single pulse at an arbitrary, precisely determined time, and conversion from low-energy quanta or excitation by direct-current pulses. The Solid State Physics Research Laboratory of the Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio, has grown crystals, some of which fulfill parts of the above-mentioned requirements and may be suitable for such purposes (Litton and Reynolds, 1962). It is believed that the most promising compounds for such an endeavor are the II–VI compounds, because their bandgap is in the visible or in the ultraviolet. These compounds are all direct bandgap materials which means that their transition occurs at a wave vector $k=0$. A green narrow bandwidth light-emitting diode is very desirable for its use in an optical radar system which works from the air to detect underwater objects.

In any case, for the above purpose, one should attempt to find light sources that can be excited by means of a form of energy which is abundant and readily available. Since, by the present state of the art, the conversion efficiency of most lasers is only a few per cent and the achievement of significantly higher efficiencies cannot be definitely foreseen in the future, powerful sources which can be excited by an arrangement that uses direct current pulses may be the best solution. For example, gallium arsenide diode light sources (near infrared) which are energized by a dc source (Ainslie et al., 1964; Engeler and Garfinkel, 1964) may also offer a suitable solution, if they can be built to produce the necesary quanta flux as shown by the calculations in this paper.

PASSIVE OPTO-ELECTRONIC RANGE FINDER

Passive opto-electronic range finding can be achieved by an arrangement using a special pick-up transducer tube (U. S. Patent, 2969477), which was conceived by the author and is illustrated in Fig. 2. The photocathode of this transducer is alternately exposed to the light from each of two lens systems by means of a mirror, which locks into the appropriate positions for step 1 or 2 during the exposure times. For high-speed operation, two Kerr Cell shutter arrangements may be used, or two pulsed image converter tubes, if the latter are sufficiently well matched. The rotatable mirror must then be replaced by an appropriate optical arrangement which focuses the images onto the same photocathode area and displays them alternately by pulsing the Kerr Cells or the image converters alternately.

Figure 3 shows the results from the different positions of the switching arrangement, MS, in figure 2. During step 1, the stream of electrons produced by the photocathode, which corresponds to the optical image focused onto it, is sufficiently accelerated to produce a secondary emission yield greater than 1 on the target plate. The removal of electrons from the target plate results in a positive charge pattern on it. When the mirror is switched to step 2, the operational mode of the tube is changed in such a manner that the secondary emission yield effective on the target plate is less than 1, depositing electrons on the target plate. The positive-charge pattern formed during step 1 is neutralized where sufficient electrons from step 2 are superimposed. The image section of this transducer obviously has to be designed in such a manner that the two different electron images focused onto the target plate have the same dimensions. When this is done, effective neutralization of the positive charge pattern can be accomplished by the deposition of the electrons in step 2 and by choosing the proper settings of the apertures 1 and 2. If, by proper optical alignment of the two lenses, both with an angle of view α', identical electron images are obtained for a background (clouds, stars, etc.) at an essentially infinite distance, objects in the foreground will not be completely compensated, resulting in some charge remaining on the target plate. By utilizing a scanning beam (step 3), this charge is transformed into a time sequential signal, as shown in figure 3. From this time sequential signal, the distance of

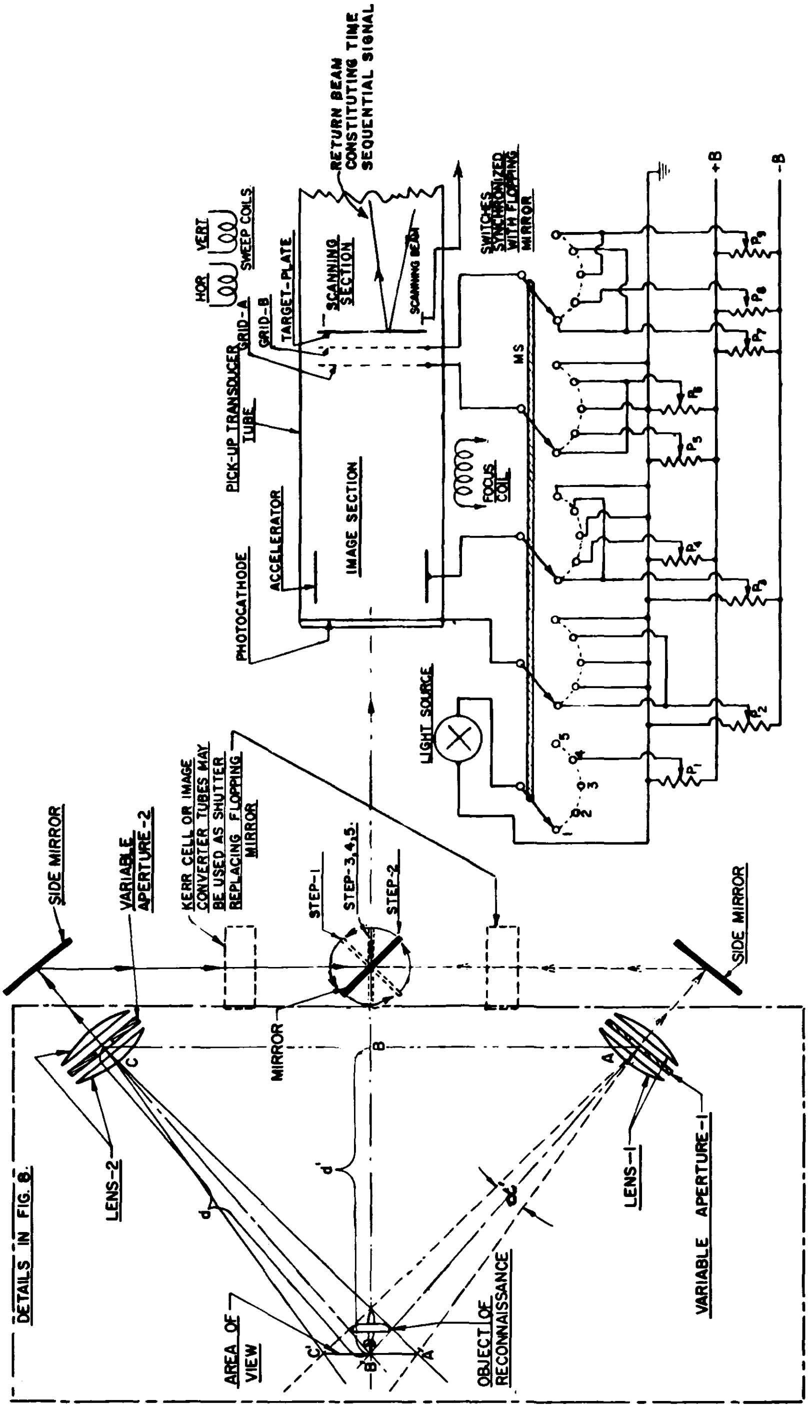

FIGURE 2. Pick-up Section of a Passive Optical Range Finder.

the object as well as the values of the x and y coordinates of the object in the field of view can be obtained by utilizing appropriate electronic circuitry. During step 4 (fig. 3), the photocathode is homogeneously flooded by the light source shown in figure 2 and the resulting photoelectrons raise the target plate potential as indicated. This is necessary to be able to erase the remaining negative portion of the signal as seen in step 2b. The scanning during step 5 results in a signal output from the transducer as shown and causes complete neutralization of the target plate.

For the following calculation, it is assumed that any image disparity between either the sizes or the positions of the positive and negative image charges on the

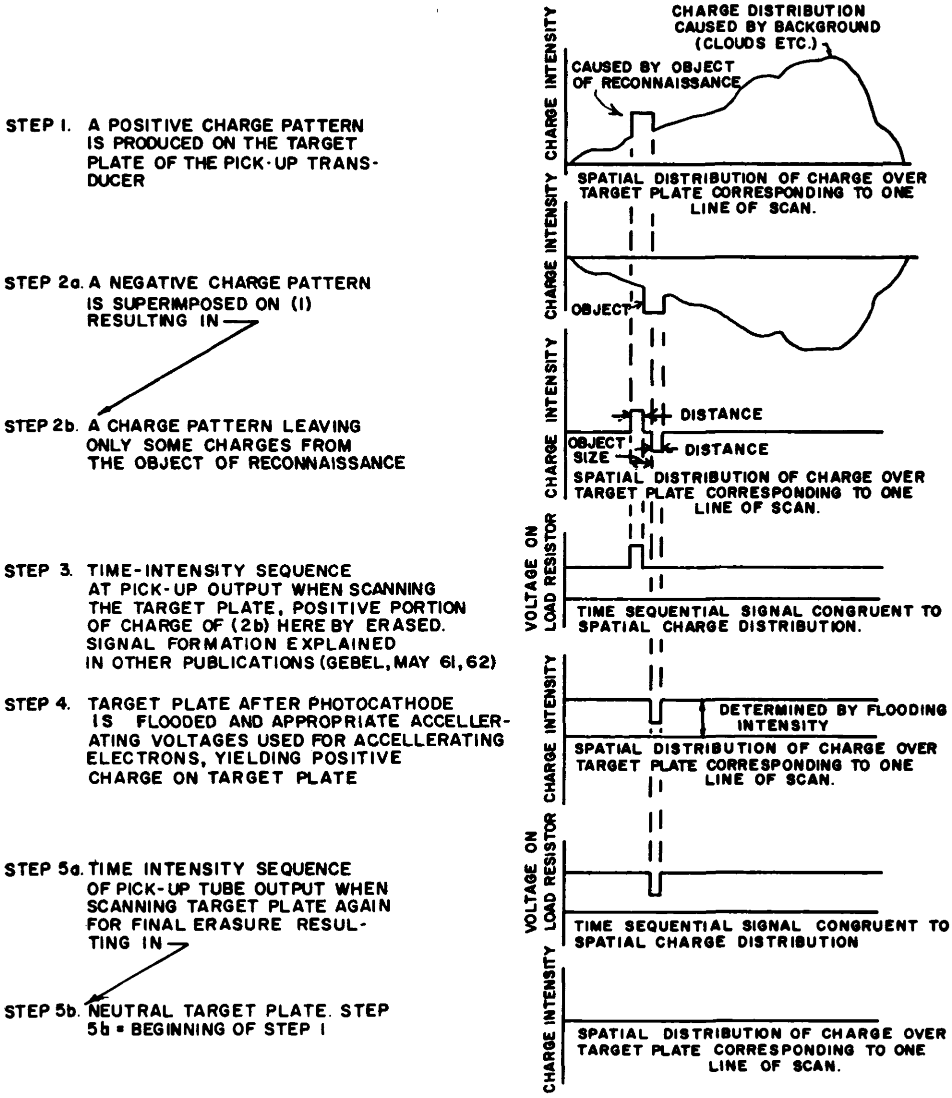

FIGURE 3. Spatial Information Distribution Corresponding to One Line of Scan in Passive Rangefinding Arrangement.

target plate, because of optical or geometrical inaccuracies, is sufficiently smaller than the width of one line of resolution so that it may be neglected. For simplification, it is further assumed that the imaging area is square.

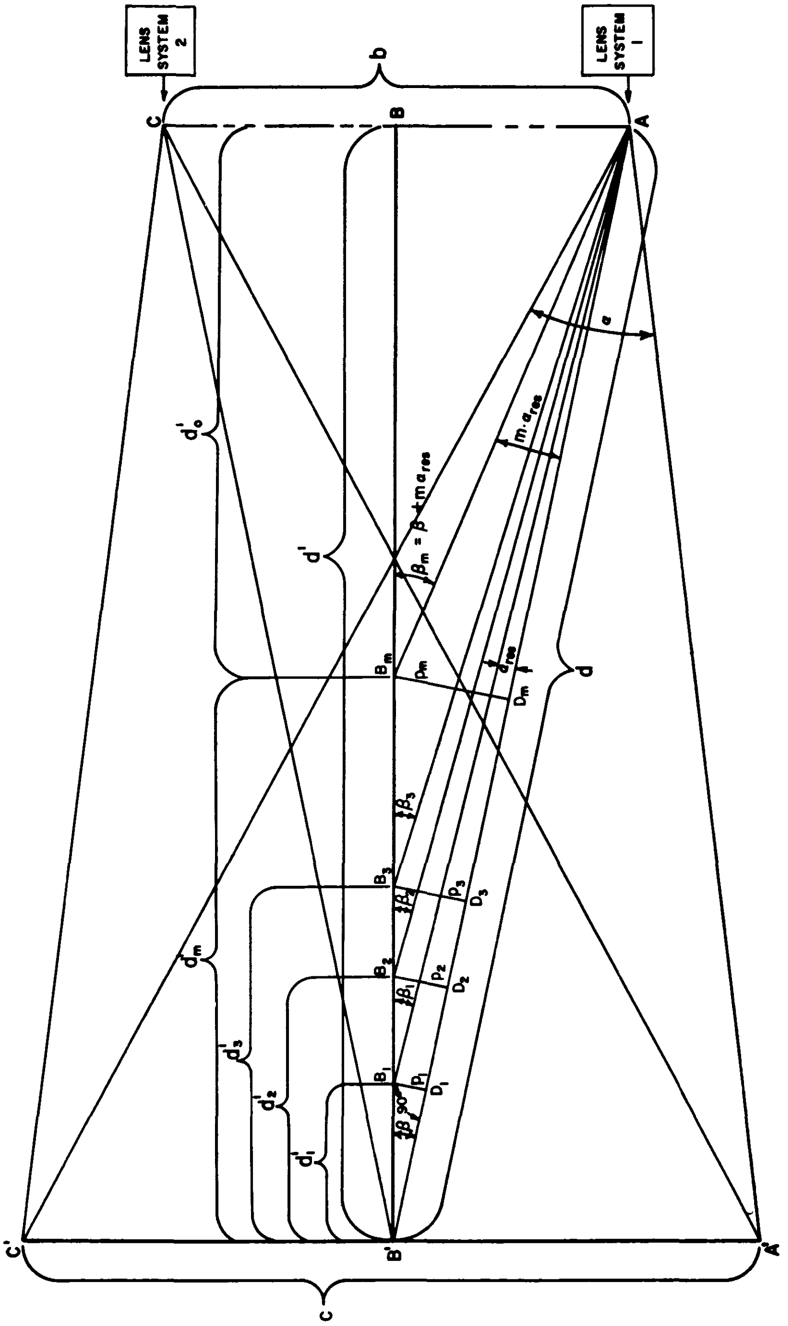

FIGURE 4. Diagram for Accuracy Determination in Passive Optical Range Finding.

The smallest resolvable angle, α_{res}, in radians (fig. 4), which corresponds to one line of resolution when focusing for infinity, is

$$\alpha_{res}=\frac{L_{res}}{f}=\frac{W}{n_pf}, \tag{13}$$

where n_p is the number of effective television resolution lines of width L_{res} in mm for a transducer photocathode with effective width, W in mm, and f is the focal length in mm of the optical system. Horizontal and vertical resolution are usually made equal by design for scanning systems. Then, if α_{res} is given, the number of resolution elements, n_O, in the horizontal direction which the object will cover on the reproducer screen is

$$n_O=\frac{L}{d\ \alpha_{res}}, \tag{14}$$

where d is the distance of the object from the optical system and L is its apparent horizontal dimension. However, even though an object may have a size corresponding to less than one resolution element, it will be reproduced with the size of one resolution element, if its contrast and brightness are sufficient for detection.

The limiting accuracy of such systems can be calculated by using the following reasoning: The system is assumed to be aligned so that the length and position of line c of Fig. 4 appears the same to the two optical systems at A and C. Movement of the object from B′ to B_1 along d′ can be observed by lens system 1 only if the distance p_1 is of sufficient length to correspond to one element of resolution on the sensor. The shortest distance between point B_m and line d, which corresponds to m elements of resolution, shall be called p_m. Then,

$$\tan\beta=\frac{0.5b}{d'}. \tag{15}$$

Also

$$\beta_m=\beta+m\ \alpha_{res}, \tag{16}$$

$$d'_o=\frac{0.5b}{\tan\beta_m}, \tag{17}$$

and the distance, d'_m, the object has moved for m resolution elements is

$$d'_m=d'-\frac{0.5b}{\tan(\beta+m\ \alpha_{res})}, \tag{18}$$

where d′ is the distance from the range finder to the original position of the object, β is the angle to the perpendicular from which the object was observed, when at its original position, and b is the base of the range finder.

Example 3: In a range-finder system, as shown by Fig. 2, let the base be 4 meters, the optical system be 500 mm focal length, the effective photocathode width be 25 mm, and the resolution be 1000 TV lines. The projected horizontal object dimension to be detected is assumed to be 2 meters. The smallest resolvable angle is, using Eq (13),

$$\alpha_{res}=\frac{25}{1000\times 500}=5\times10^{-5}\text{ radians}\approx 10\text{ sec of arc.}$$

The number of horizontal resolution elements for the object, if at a distance of 10 km, is, using Eq (14),

$$n_O = \frac{2}{10^4 \times 5 \times 10^{-5}} = 4.$$

Assuming that the background alignment was made in such a manner that all objects at a distance greater than 10 km cancel, the distance which an object (located at 10 km) has to move toward the range finder so that p_m corresponds to $m = 1$, using Eqs (15) and (18) and $b = 4$ meters, is

$$d_m' \approx 10^4 - \frac{0.5 \times 4}{20 \times 10^{-5} + 1 \times 5 \times 10^{-5}} = 2000 \text{ meters;}$$

therefore, the distance, d_o', of the object from the range finder is 8 km. For a p_m which corresponds to $m = 6$, the above equation yields 6,000 meters ($d_o' = 4{,}000$ meters). A distance, d_o', of 2,000 meters from the range finder then corresponds to an m of 16 and 200 meters to an m of 196. Thus the accuracy of the instrument is determined at a given value of m by the distance difference for adjacent values of m, which gives, for the above example, a maximum uncertainty of ±2.5% at 2,000 meters and ±0.5% at 200 meters, if no interpolation between m values is used for further improvement of the accuracy.

The limiting sensitivity achievable by such a system is basically determined by the degree of background compensation at the transducer target plate and by the fundamental statistical fluctuations in the charge pattern of the target plate. If total compensation of the background is assumed, the statistical fluctuations in the background will remain and will add geometrically. I have treated extensively the limiting sensitivity for any light detection situation extensively, as determined by statistical considerations, in another paper (Gebel, 1961). In order to prevent overlooking the statistical limitations when calculating the limiting sensitivity in low-light-level work, it is convenient to convert the conventional photometric units into terms which express the involved number of quanta per unit of area per unit of time. I have published conversion tables and equations for different blackbody temperatures and spectral regions in a book (Gebel, 1964). The above two publications may be used and should suffice for analyzing the limiting sensitivity achievable by passive optical range finding under different situations.

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