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COMPILATION OF DATA FROM RELATED TECHNOLOGIES IN THE DEVELOPMENT OF AN OPTICAL PILOT WARNING INDICATOR SYSTEM

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ABSTRACT

The results of analytical efforts on some of the major scientific and engineering aspects of a proposed optical pilot warning indicator (PWI) are reported. No fundamental obstacles, including projections for its ultimate economic acceptance, appear to stand in the way of early synthesis of prototype xenon lamp silicon detector systems for field tests. Certain system variations look promising for future growth.

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SUMMARY

The primary goal of the optical PWI system described in this report is to provide both a warning signal and position information to aid a pilot in visually acquiring an intruding aircraft in time to determine what, if any, avoidance procedure is required. A minimum cost of the cooperative element of the system (a xenon lamp) is clearly a requirement. The desirability of having a visual flash for conspicuity enhancement makes the xenon lamp a very desirable choice as the cooperative element. The background radiation and transmission characteristics of the atmosphere, for conditions corresponding to visual flight rules, places the requirement of wide dynamic range on the detection system. With appropriate temporal and spectral filtering, it appears to be very possible of assuring detection ranges in the order of 3 to 5 miles under all background conditions, except direct viewing into the sun.

The selection of a silicon detector, based on its spectral response characteristics, its lack of requirement for cooling, its relatively high sensitivity, and its availability, has been borne out by a relatively extensive survey of other possible detector materials. Considerations of the response time required by the pilot to acquire an aircraft visually, using the output information available from the PWI system, make it extremely desirable to use a heads-up, peripheral vision display rather than a more conventional display requiring central vision within the cockpit. Audio displays appear attractive also for low cost warning and rough direction indication.

A simulation facility for testing PWI system performance, which includes multiple target and variable background illumination, is necessary to develop a PWI system. The extension of the most rudimentary optical PWI to include greater performance should encompass methods of discriminating against non-collision threat aircraft signals which do not require a pilot decision to determine an avoidance maneuver. The synthesis of new optical systems using other than a pulsed xenon beacon as the cooperative source may provide the desired higher performance PWI capability.

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*Commonly referred to as PWI

I. INTRODUCTION

A task force was formed within the Optics Laboratory of NASA's Electronics Research Center early in the Spring of 1968 to broaden the research effort already underway on the development of an optically-derived pilot warning indicator (PWI) system. The authors of this paper constituted that group, contributing within their specialties mostly on a less-than-full-time basis. The efforts of other contributors to this work, both within and outside of NASA, is documented at appropriate points in the report.

The self-assigned role of the task force in developing the optical PWI was organized with four major areas: First, and most basic, was the collection and assessment of general scientific and/or engineering data bearing on any optical pilot warning indicator system. This included material on the optical environment, like sky background intensities, cloud-reflected intensities, lightning, and so forth, since an understanding of the magnitude of atmospherically-induced signal amplitude fluctuations was needed to design more effectively a PWI system.

A second general area of interest concerned the analysis, understanding, and expected improvement of the optical PWI system of contemporary choice. Inasmuch as the system under present consideration is the xenon lamp-silicon* detector one-way (not acknowledged and not synchronized) transmission scheme, pertinent work included spectral studies of the xenon lamp and a search for potential improvements therein, an understanding of the behavior of the silicon-derived detector in solar and/or bright sky environments, and the relationships between eyesight and detector ultimate detection ranges, as examples.

The third role was to generate a receptive atmosphere to new approaches in the development of optical PWI systems. It was found that as the catalog of discretely-identified PWI systems grew, the number of hybrid or combination system possibilities grew even faster, for example, by so much so that a deliberate effort at sorting them out in some orderly fashion would eventually be necessary.

Finally, definite consideration would necessarily be given to the service of others interested in PWI progress, for example, by building an optical PWI simulator, the cost of which could not be justified by any single private company, but which could be made available to interested parties. It would include

*Throughout this report, the xenon-lamp-silicon detector PWI system will be conventionally referred to as the Xe-Si system.

examination of industry proposals submitted to either the FAA or NASA and funding of certain proposed efforts. It would also involve being informed; to serve as an unbiased technical focal point for PWI matters on a national scale, in a capacity suited to the qualifications of a government agency.

The essentials in the development of the Xe-Si one-way optical PWI system should be carefully considered. Clearly a cooperative arrangement, the system would require for its operational effectiveness the installation of two (at least) flashing xenon beacons on each and every powered civil aircraft in the United States airspace. The power drain for these would not have to be large, say, 100 watts maximum, and the installed cost per pair for FAA-approved units could be projected at less than $200. (for the typical light aircraft). More sophisticated or higher speed aircraft would be able to bear the advanced costs of special low-drag xenon beacons.

The peak radiated optical power from a pair of these beacons would be in the order of 20 kw, with the preponderance of the spectral energy favorably developed in the visible (∿4000-7000 Å), and the near infrared (IR) (7000-11,000 Å) bands. It is the combination of the high peak power, the fortuitous near-optimum spectral partitioning, and the regular or periodic known nature of the flash, when compared with the lower power, poor spectral position, and indifferent or haphazard radiative pattern of natural IR radiation from aircraft engine(s) (as might be used in a non-cooperative PWI scheme) which dictates the ultimate technical feasibility of this cooperative PWI system.

The detector for a xenon lamp PWI operating in the visible and near IR bands could hardly be anything else than some form of a silicon-derived device. The match between the Si detector sensitivity curve (roughly 6500-10,500 Å) and the spectral energy distribution of a pulsed, high-intensity xenon lamp is excellent. Silicon detectors are also relatively inexpensive, relatively immune to direct solar radiation damage, can be made into arrays, and leave little to be desired in their D* numbers.

Along with possibly some optics and spectral filtering, the remainder of the system would consist of signal processing circuits (for false alarm minimization, and the like), a display, and certain auxiliary functionals, such as a self-check circuit, a control panel, appropriate alarms, and the like. These subsystems will be covered later in this report.

The ideal framework of an optical PWI - what would be demanded of it in terms of operational features, cost, acceptance, and so forth, will be discussed at this point. Any new or proposed PWI must fit reasonably well within these constraints to be considered further. The Xe-Si system described in this report appears to meet these basic characteristics. A breakdown of the essential functions of the PWI system is listed below:

1. To be a cooperative system, a maximum estimated "cooperation" cost of $200/aircraft has been set. This may be for xenon lamps as discussed earlier, for retroreflectors, or for anything else that is equally effective.

2. To bear a total installed cost of $1200.

3. To be effective in both daylight and at night in all VFR flying conditions.

4. To be effective in the multiple intruder situation up to a maximum of seven (ref. 1) targets.

5. To possess characteristics particularly suited for terminal and low- to mid-altitude enroute situations, i. e., to supplement the CAS in other words.

6. To provide a maximum range capability in 3-mile visibility weather of not more than 5 miles nor less than 2 miles.

7. To provide an operational field of view for the detectors of not less than 240 degrees in azimuth and not less than ±20 degrees in elevation. This, for many cockpits, approximates the pilot's immediately available viewspace.

8. To provide as a minimum, an intrusion alarm and a position vector to the intruder. The position vector resolution in azimuth shall be 45 degrees or better.

9. To meet successfully the diversity of installation problems incident to retrofitting some 105,000 aircraft with part of all of a PWI system.

10. To operate with a false alarm and missed target rate adequate to promote rapid acceptance of it within the flying community.

Although these ten factors represent the essentials of an <u>optical</u> PWI, a radio frequency system might also be feasible. However, the task force felt strongly that an optical

PWI had many demonstrably favorable attributes (as compared with rf, microwave, x-ray, and the like), once the initial performance demonstration under IFR conditions had been fully demonstrated. For example, optical systems cope with the intruder bearing problem quite effectively. This condition, in turn, leads to rapid visual acquisition of the intruder and consequent maneuver selection from a two-dimensional escape trajectory manifold, rather than being restricted to only the up-down maneuvers postulated in some range and range-rate collision-avoidance systems. The terminal or congested-area airspace anti-collision problem obviously benefits most from the additional degree of maneuver freedom. Most formats of optical PWI are also inherently adapted to handle the multiple intruder situation, characteristic of terminal areas, in an unambiguous fashion.

One condition for collision of two aircraft flying constant headings (straight flight paths) is that the threat aircraft maintains a constant bearing with respect to the reference aircraft. Thus, a PWI should provide a warning signal for all aircraft which maintain a constant bearing. Bearing measurements can be made with a sectored optical system and all aircraft which do not present a continuing signal in a given sector can be rejected by the system. For relatively near misses, the bearing change is relatively small and, for the low pulse rates of the proposed xenon-silicon system, may require a stabilized reference for adequate resolution within the range and warning time restraints of the single PWI system. Further work on this concept is required.

An alternative to this constant bearing measurement for determining the degree of collision threat is to use some form of range, range-rate measurement. An optical radar using optical corner reflectors on all aircraft is an alternative to the more sophisticated time-frequency or doppler microwave system.

It has been suggested that a PWI that depends on visual acquisition for the collision-avoidance maneuver selection should rationally behave much like the eye does. If that is so, it could promote user acceptance as the one-to-one relationship between PWI and eye-detected targets became more understandable. An optical PWI, then, would meet--or could be made to meet--this criterion, whether or not this criterion is ultimately defendable.

Two other optical PWI features should be briefly mentioned. One is that fixed obstacles (towers, buildings, runways, too), can cheaply and effectively be "illuminated"; and, second, highly prized radio spectrum space is conserved.

On the negative side, nature sets a pair of important boundary conditions to the success of an optical PWI. First, the extreme ratios of radiative background flux to received lamp flux, a number which can be as high as 10^7, even when direct viewing of the sun is excluded, becomes a factor. Not only is the ratio high but its variation (fortunately, very slow) is of about the same magnitude. Nothing comparable to this anomaly exists at radio frequencies.

Second, nature also places a severe limit on one's ability to alter the frequency properties of the PWI radiative source. One quickly learns that the fixed-energy level structures of a very few elements will, to all intents and purposes, govern "frequency freedom," both in absolute radiative frequency as well as in the radiative bandwidth. Again this is in sharp contrast to radio frequency practice.

II. THE PWI SYSTEM

The effort at ERC is presently being concentrated on six more-or-less well defined technical areas relevant to the optical PWI program. These disciplines are shown in block form in Figure 1, arranged to correspond basically to the information flow of an optical PWI. The simulation work, as presently conceived, encompasses only the first three blocks. Subsequent developments may allow inclusion of the display function.

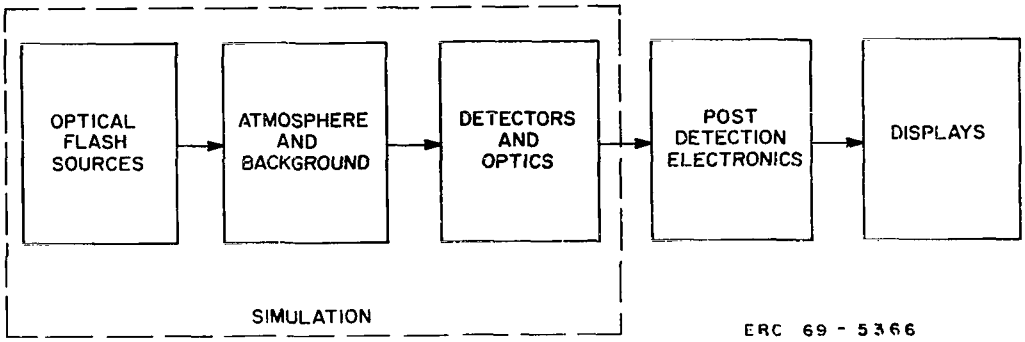


Figure 1. - Defined work areas

The "blocking out" or firm establishment of work areas like this too early in a program presents a distinct hazard to overall innovation later; however, some sense of organization can scarcely be avoided. The individual blocks and their arrangement do not restrict the study effort merely to the Xe-Si PWI system discussed earlier. For the most part, they obviously also correspond to well-worked disciplines from which pertinent scientific data as well as a knowledgeable project staff could be drawn. In a very real sense, the Xe-Si optical PWI system, for example, could be synthesized immediately from existing knowledge; it is almost certain, however, that significant advancement in both detail and overall concept could be expected from appropriate subsystem analysis.

Three of the four task force goals, as described in the Introduction, can be (at least, partly) identified within Figure 1. New approaches to optical PWI system development were not included in this figure. These are covered briefly in a subsequent section on PWI system synthesis.

Several system considerations which will be useful in making a final design and extensions of the xenon-silicon optical PWI system were not included in this analysis of the problem. Examples of such studies are the following:

1. Air Traffic Studies: Collisional angles or trajectories; densities to be expected; analysis of the velocity mix; and future projections.

2. Subsystem Field Testing: Manufacturer consultation on fit and suitability of light/detector placement; ground scanning experiments to determine Xe-competitive radiance; and cloud-edge effect testing.

3. Human Factors: Maximum number of intruders to pilot saturation; reacting time in the single- and multiple-intruder situation; and effects of lamp-induced "tunnel effect" or vertigo.

Sections III through VIII present information pertinent to each of the subtasks of Figure 1.

III. THE LIGHT SOURCE

The PWI work being done at NASA-ERC requires that the light source provide a signal both in the visible region (4000 to 7000 Å) for the pilot's acuity and in the infrared region for the response of the silicon detector. There are many other requirements for the light source; some of them are known at present and some other requirements will undoubtedly emerge in the course of development work.

However, when the dual requirements of low cost and high reliability are added, then the low-current density (J less than 1000 Å/cm^2) xenon flash lamp emerges the most likely candidate as the light source subsystem for the PWI program.

The light source is comprised of the following components: the charging power supply, the discharge circuit, the gas discharge flash lamp, and the trigger with its associated timing circuit. These components will be looked at individually, albeit in the context of the light source system of the PWI program. Tentative additional system limitations imposed upon the light source are: power consumption--about 100 watts; stored electrical energy--less than 25 joules; operating voltage--in the vicinity of, or less than, 500 volts; flash pulse duration--from 0.1 to 1.0 msec; and pulse repetition rate--from 1 to 2 Hz.

The light source system, as an airborne device, must be light weight, of small volume, and suitable for at least the general aviation air space environment.

The most important constraint upon the light source system is the price tag. For quantity production--10,000 units or more --the system, with two flash lamps, is not to exceed $200.

Background and Existing Airborne Light Source Systems

Xenon (atomic number 54 and an ionization potential of 12.08 volts) as an arc lamp filler for daylight equivalent sources in photography work (ref. 2) has been found to be the most efficient radiator.

A far greater impetus has been given to xenon-filled arc lamps for use in laser pumping. However, the latter are driven at high current densities and/or high electrical energies and as such are not really relevant to the PWI program. Yet, they have been studied extensively in the area of radiative efficiencies as relates to the absorbing bands of the various laser materials. A literature survey conducted by Papayonanow and Buser cites as many as 24 sources (ref. 3).

By contrast, the projected PWI-type sources commercially available today are offered as working black boxes with very few technical data to accompany them. One exception is the low profile anti-collision light recently developed by Varian Associates (ref. 4). Though it may not be applicable to the low-cost PWI program, it is a promising candidate for high-speed aircraft, as it can be flush-mounted with only a 6-mm protrusion. So far, three specifically aircraft-mounted light sources have been purchased for NASA-ERC use of the dozen or more available commercially. These are:

1. The aircraft recognition light system (ARLS) by Honeywell;

2. The Sky Strobe by Delta Corporation; and

3. The Instant Visual Identification (I.V.I.) by In Flight Devices Corporation.

The latter two are quite similar and indeed are geared for general aviation use. At present, no information on actual practice with these units is available. The Honeywell light system has been installed in commercial aircraft by American Airlines on the Boeing 727 and BAC111, and by North Central Airlines on the Convair 340-440 and the Convair 580. The operation of this ARLS has been described in a brochure made available by the company (ref. 5) as follows:

"The penetration of blue-white xenon strobes is many times greater than that of conventional incandescent lamps..." Of significance in the Honeywell system is the following: "...The ARLS divides the azimuth angle about an aircraft into four sections as shown in Figure 1. Thus an observer sees 160 flashes per minute (fast) in the forward quadrant, 80 flashes per minute (medium) in either side quadrant, and 40 flashes per minute (slow) in the aft quadrant." To continue: "The wing tip location of the lights provides aircraft attitude (bank angle) information to an observer viewing the forward and aft sector. Also, the size and the rate of increase of the space between the lights of intruding aircraft provides an indication of relative range and rate of closure.... The system is also provided with a servo driven red filter on each light assembly enabling the pilot to select either red or white lighting."*

These commercial sources have been described to suggest that the implementation of xenon beacons on <u>all</u> powered aircraft has already received a head start.

**Figure 2 of this report.*

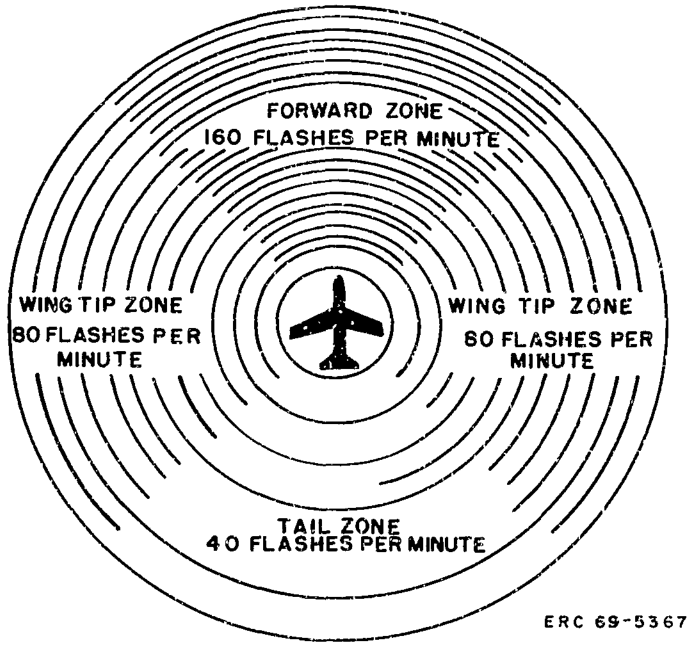


Figure 2. - Flashing pattern of the Honeywell aircraft recognition light system

Light Source Components

The light source components are described individually below.

The charging supply. - The charging power supply will receive raw power from one of the following sources: 12-volt battery; 28-volt battery; or 115-volts 400 Hz. The projected output power will be about 100 watts at the 400- to 500-volt level. A single power supply will handle at least two discharge circuits. For the light source system, the power supply can be located in almost any dead space in the aircraft, provided that it is accessible for maintenance and checkup. Reliability and cost are the dominant factors in the design and fabrication of the power supply.

The discharge circuit. - The light source discharge circuit is an RLC series network. In a general way, all three of these parameters are variable. The capacitance is variable only to the extent that electrolytic capacitors, the present commercial variety, are strongly dependent on temperature. The circuit inductance is only variable within the length of the flash lamp, and even there, only at the beginning and the tail end of the pulse (refs. 6, 7). The PWI light source will have a pulse length greater than 100 microseconds and therefore the flash lamp inductance variations can be neglected.

The circuit output function is to convert an electrical discharge into an optical radiation through the flash lamp.

Therefore it is clear that the best circuit would have only the flash lamp as the resistive component. Here again, electrolytic capacitors have a higher resistance than non-polar capacitors and that resistance is again a function of temperature. A projected capacitance value for the light source would be 200 microfarads operating at about 400 volts. Industry sources advise that such units would have about 0.5 ohm series linear resistance at room temperature. At 0°C the resistance would rise to about 2 ohms. As an alternative to the electrolytic capacitors, monolithic ceramic layer-type capacitors might be considered.

Assuming that the dominant resistance is offered by the flash lamp, then it can be taken as the circuit resistance. It turns out that flash lamp resistivity is indeed a variable and a function of current density (ref. 8):

$$\rho = 1.13\ J^{-\frac{1}{2}}$$

where ρ is the plasma resistivity in ohm-cm and J is the current density in amperes/cm^2.

An interesting question in this connection is the effect of the flashlamp R in the expression $P = Ri^2$ as it might reflect the pulse shape of the radiated power, for the purpose of coding information content of the circuit parameters in the detector system. From the above expressions, $P = k\ i^{3/2}$. For the infra-red spectrum, the relationship is not valid at the tail end of the pulse. For the ultraviolet, whatever there is of it, it is not valid at the beginning of the pulse. These remarks would suggest that only the pass band spectrum utilized by the detector should be looked at in terms of time history and the chances are that it would have to be an experimental curve. With this exploratory description of the circuit components in mind, the circuit as a whole should be investigated. The non-linear differential equation for this circuit (ref. 7) is:

$$L\frac{di}{dt} \pm K_o|i|^{1/2} + \frac{1}{C}\int_o^t i\ d\tau = V_o\ .$$

The cited work (ref. 7) gives computer solutions to this equation as a function of a parameter which characterizes the flash lamp in the circuit. These solutions need not be valid in the PWI case since, in the latter, there will be a linear resistive loss caused by the likely selection of electrolytic capacitors.

Whatever the solution of such circuits may be, it is of interest to discuss these circuits in terms of current pulse shape and, consequently, the shape of the radiation pulse as some function of current of the form i^n.

Current pulse shapes are determined by the relationship between circuit resistance R and circuit impedance

$$Z = \left[\frac{L}{C}\right]^{1/2} .$$

Case 1: The free oscillatory circuit. This type of discharge excludes the use of electrolytic capacitors because of current polarity reversals. It also requires the use of inductors or a significant reduction of flash lamp resistance. The flash lamp life would be reduced and the power and energy transfer would be rather inefficient. It is unlikely that this type of circuit would be adapted for PWI use.

Case 2: The overdamped current pulse shape. This is the pulse mode of the presently available light sources for aircraft use. Figure 3 is a radiation vs. time pulse display recorded with an S-1 detector surface. The light source used had 160 microfarads and was charged at 400 volts. In this type of circuit, the requirements of low voltage operation and long pulse duration almost compel the use of electrolytic capacitors with the lowest price and the lowest stored electrical energy density.

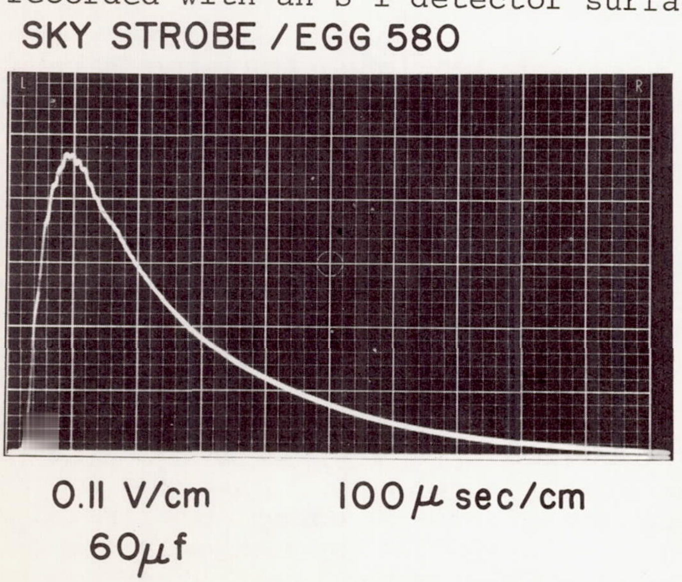


Figure 3. - Time history of the radiation pulse from a conventional aircraft flash lamp

Case 3: The critically damped circuit. This is the most efficient circuit from the point of view of power transfer to the flash lamp as the only dissipative component. Since there are no current reversals, electrolytic capacitors can be used in these circuits.

Case 4: The pulse-forming network. Another technique which may be quite useful for the PWI light source is the lumped circuit with a square wave current pulse. The advantage would be the sharp rise of the radiation pulse and the constancy of the pulse duration. One serious drawback is the effect such sharp rise current pulses have on tube life in that the associated acoustic shock causes the glass envelope to break (ref. 9).

The trigger and associated timing circuit. - The most economical and simple trigger for use in the PWI light source involves a metallized thin strip on the flash lamp which is pulsed to a few kilovolts to initiate the breakdown of the gas in the flash lamp. In this case the flash lamp is the discharge circuit switch. One disadvantage of this technique is the noise the trigger pulse may cause for other aircraft equipment. A series trigger to the flash lamp or a series switch with zero noise would require very close static voltage breakdown to the operating voltage in the region of 500 volts.

The time lag between the trigger pulse and the beginning of the flash is expected to be stable for this application. Marshak et al (ref. 10) quoted a jitter time of 0.1 μsec, for a system close to the one projected here. On the basis of the above remarks and the requirement of 1 to 2 pps, the pulse repetition rate control is quite feasible.

The flash lamp. - It has been mentioned that the PWI-type flash lamps have not been studied extensively by comparison with laser flash lamps. In reference 2, flash lamp spectra are studied for current densities in excess of 1700 A/cm^2. In addition, the line structure spectra displayed in their graphs was taken at 100-Å intervals and as a consequence, the xenon 8231-Å line is shown to be nearly 400 Å wide at the base. Yet, recent work conducted in the ERC laboratory shows a line width of less than 12 Å.

For visual conspicuity, the PWI light source must be of short duration, pulsed no more than a few times per second and be very bright in the spectral region from 4000 to 7000 Å. As a PWI, the infrared region of the spectrum could be optimized on some narrow bandwidth to enhance the signal-to-noise (S/N) ratio of the detector. Also, the logic circuitry may use only the pulse rise time instead of the time-integrated pulse. Study of the line structure of the infrared region should be investigated further. From a spectral point of view, the ideal PWI light source would have the following characteristics:

1. No radiation below 4000 Å,

2. About one-half the radiation in the visible region (4000 to 7000 Å),

3. All radiation in the infrared contained in a narrow band somewhere below 10,500 Å.

The closest thing to this idealized light source is the xenon flash lamp driven at current densities of about 1000 A/cm^2. Of course, system analysis may dictate emphasis on either the visible region of the spectrum to aid the pilot's acuity of vision, or the near infrared region to aid the silicon detector performance. In the latter case, it may become justified to adapt a rich, near infrared source, such as Hg-CsI, with some signal reduction in the visible and the penalty of manufacturing a more difficult light source. The selection of a narrow band of the spectrum from the light source may be dictated also by atmospheric transmission windows in conjunction with the detector response.

Visible radiation increases can be obtained by increasing the current density which would eventually suppress the efficient line spectra of the near infrared and incur risks to the flash lamp life. The dominant system requirements for the PWI light source are cost and reliability. Therefore, the low current density xenon light source should be used as a reference model when considering other light sources for the PWI program. It must be remembered also that this model reaches total radiant efficiencies of up to 65 percent (ref. 2) of which some 40 percent or more is useful radiation for the PWI system. Within the family of rare gases, which allow simple lamp fabrication, krypton and argon could be considered. Here again (refs. 10, 11) it is shown that both these and any other gases have a lower radiation efficiency in the PWI spectra. Upon selecting the bandwidth in the near infrared response of the silicon detector, it might be possible to make use of a mixture of gases with characteristic line spectra falling within the bandwidth selected. Krypton and xenon may be used for their adjacent strong line spectra, 8100 Å for krypton and 8231 Å for xenon. The gain in detector signal, if present, may offset the likely reduction in visible radiation. An area of exploration free from system consideration would be to collect the up to 10 percent radiation below 4000 Å and convert it to the visible region by means of a fluorescent material surrounding the quartz tube.

If dictated by system considerations, another interesting use of fluorescent dyes would be to color-code the flash lamp radiation into two visible colors which could quickly tell the pilot whether the intruding aircraft is moving toware or away from him. Numbers of organic compounds are specified as having a fluorescent yield of 50 percent (ref. 12) and they need not be cost-wise prohibitive when the information gain and the ease of application are considered. A cursory test conducted in the ERC laboratory using rhodamine 6G doped plastic shows no loss on the near infrared region of the spectrum. For the near infrared region of the spectrum it is possible to use DTTC in DMSO (ref. 13) which has an absorption peak at 7600 Å (useless region) and a fluorescence peak at 8100 Å. The strong xenon lines are beyond the absorption limit of the material. In this case, however, there is some loss in the visible. The absorption cutoff of the material is at 5000 Å with a slow slope up to 7000 Å and thereafter with a fast slope to the absorption peak.

Other than spectra considerations are involved in the design of the flash lamp for the PWI program. The geometry of the lamp is dictated by the discharge circuit parameters and the required radiation pattern when installed on the aircraft. An azimuthally omnidirectional radiation pattern will be adopted for the PWI program, with limited (±25 percent) elevation coverage. Such a pattern would require only two flash lamps per aircraft. Matching this pattern, the geometry of the flash lamp could be helical, "U" shape, or a spiral.

The most likely flash lamp location in the aircraft seems to be on the wingtips. This choice would give signal reinforcement along the line of flight. In a crude way and for short distances, wingtip spacing of the lights gives the pilot an estimate of range and closure rate. Also, wing tip location of the flash lamps would be remote from other rf receiving and transmitting equipment in the aircraft. The dimensions of the flash lamp can be confined to a few cubic inches with a weight of a few ounces. Thus wingtip installation should be feasible for essentially all aircraft. The PWI system will impose a severe life test for the light source and the flash lamp in particular.

A total flash lamp failure, such as tube leak, tube break, or tube short, is not only rare in the PWI load range but it is also easy to detect on landing. Flash lamp degradation is the most serious failure to be contained and checked by rigid quality controls during fabrication. The empirically established formulas for the load limits of the flash lamp are useless for this purpose. Inert gas fill selection becomes almost imperative in order to avoid flash lamp life-degradation. It is very likely that rigorous flash-lamp specifications enforced by rigid quality control will tend to raise the price of the flash lamps to as much as $20. to $25. Very pure gas fill, consummate outgassing processes, and electrode selection in design and material as well as sealing techniques, will have to be specified for the flash lamp fabrication.

Also, precise inspection techniques will have to be established as they are evolved through life-testing studies.

IV. THE ATMOSPHERE AND THE RADIATIVE BACKGROUND

A maximum effective operating altitude of 10,000 feet has been chosen arbitrarily for the optical PWI under consideration at ERC. Among the factors entering into this choice were: (1) The FAA rule structure designating this altitude as a boundary between higher and lower speed traffic; (2) a recognition that this is an approximate upper altitude limit for the preponderant number of smaller general aviation aircraft; and (3) the need of a great deal more time to correlate PWI-related experiments done conveniently at low altitudes, or on the ground, with the high altitude radiation and propagation ambient.

The environmental aspects of most interest are those characteristic of the sea-level to a 10,000-foot range. In terms of lateral location, it is noteworthy that the terminal or high-traffic-density situations for which this PWI is hoped to be most effective are often located near enough to metropolitan complexes to suffer from their general smoke and haze. Thus, this section will be primarily concerned with discussing values for the environmental extrema that are likely to affect an optical PWI. If the device can be designed to meet these extrema, its effective operation under less stringent conditions will, of course, be assured. This disregards, to some degree, the consequences of the possible simultaneous occurrence of these extrema. Present knowledge is really inadequate to cover this more complex case meaningfully.

An optical channel between aircraft is subject to atmospheric attenuation, scattering, and refraction, as well as presenting a heterogeneous collection of unwanted or background radiance to the receiver. The radiative background aspects of the problem will be discussed first, followed by pertinent comments on some aspects of PWI propagation.

The PWI Radiative Background

A short catalog of radiative sources contributing to the PWI background has been prepared at ERC. Self-radiating sources, as well as those that only redirect otherwise mostly innocuous radiative flux, have been included in this catalog which is presented in Table I.

The "clutter," as the radar people accurately call it, is made up (by numerical count, at least) mostly of sources not thought to be of significance in this problem. These will not be considered further. In the subsequent detailed treatment of most of the remaining 12 or so PWI-relevant sources, all possible temporal modes of the radiator in question should be considered. An optical daytime PWI is feasible only because the sun and most

TABLE I

PWI RADIANCE SOURCES*

Celestial*	
Sun	Moon [Planets] [Stars] [Meteors]
Direct incidence Atmospheric scatter Cloud reflection Ground reflection [Auroras] [Cloud refraction, such as rainbow] [Minor phenomena, such as sundogs]	Direct [about same list as sun]
Natural Terrestrial	**Man-Made***
Lightning [Volcanoes] [Forest fire] [Atmospheric emission] [Fireflies]** [Sea phosphor.] [Noctilucent clouds]	Aircraft - other (such as, navigation, lights, glints) Aircraft - self (such as, exhaust stack) Fixed ground lighting Vehicle ground lighting [intermittent, pryotechnics] Satellites
Miscellaneous	
[Non-visible IR sources] [Deliberate interference]	

* May be combined resulting in such phenomena as glints--autos, planes, propeller modulation.

**Two factors could operate to make this a non-trivial source:
1) their demonstrated synchronous flashing;
2) a flashing period close to that of the PWI (ref. 14).

[ ] indicates a low estimated PWI interference capability

of its derived sources are essentially dc in nature. Also, the radiation levels in the 0.75 to 1.1 micron near-IR band, coincident with the xenon lamp energy bulge, are of primary interest, although some exceptions may be noted. A third general restriction is that the PWI field of view is essentially horizontal. Interest in background signals is greatest for this sector of the total possible elevation angle except for signals from the ground.

Direct sun. - Gates (ref. 15) provides a useful and contemporary reference to the spectral distribution and absolute magnitude of solar radiation at the surface of the Earth. The air-mass-2.0 curve (Figure 2 of ref. 15) has been redrawn as Figure 4 for discussion purposes. This value of air mass corresponds to a solar elevation angle of 30 degrees. Certain average values of water vapor, aerosol, and ozone concentration are assumed, and perpendicular incidence on the receiving surface is postulated. The given curve is accurate only for sea level conditions; the greater solar flux to be experienced at normal flying altitudes is compensated for, in a crude way, by choice of a slightly larger-than-normal PWI level flight sun view angle. (Of course, in a banked turn, any sun view angle is possible; parked aircraft are subject to a lesser range.)

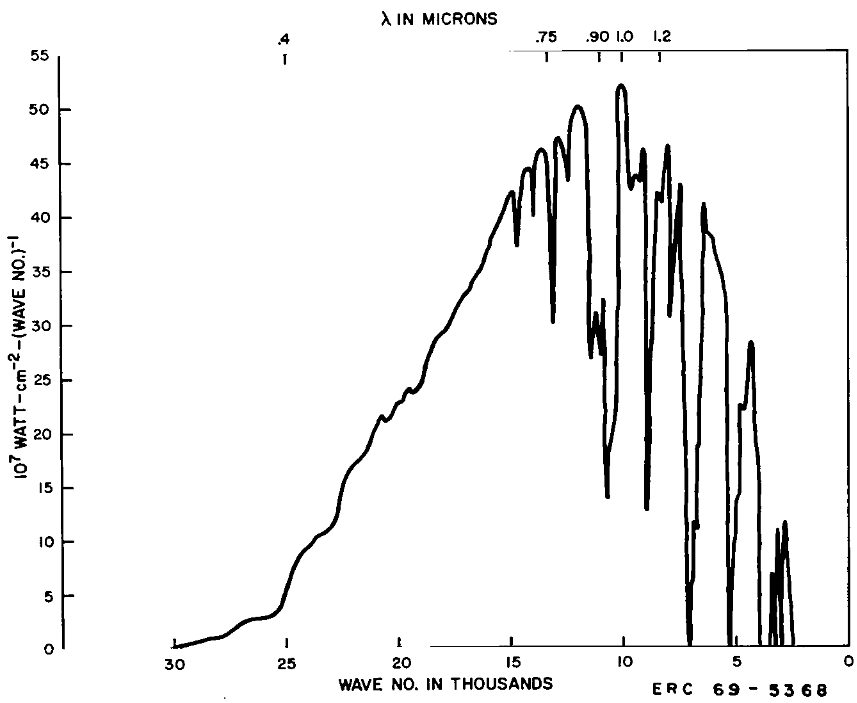


Figure 4. - Perpendicular solar radiance for air mass 2.0 (from Gates, ref. 15)

The total received flux density per reference 15 is 0.064 watt-cm^{-2}, a number not necessarily inimical to silicon detector survival, at least, even in situations having optical gain. Of course some precautions against focusing all the energy into a small spot would be required.

A simple rectangular block filter passing the energy-dense portion of the xenon lamp spectrum from 0.75 to 1.1 microns, at say 0.90 transmission, would yield a net flux density of 0.0145 watt-cm^{-2}, less than one-quarter of the unaltered spectral value. Target detection, even in the sun-exposed detector now becomes a possibility. Filters such as this need not be costly; some homogeneous optical materials already available should serve. Any attempt at more structured filtering might very well involve a "quantum jump" in price. Simple, homogeneous filters should also be capable of dissipating their (absorbed) fraction of the solar flux readily.

No PWI-significant temporal variation of flux is expected from the sun itself: Investigation is needed on the behavior of detectors in terms of pulse generation when saturated and released rapidly, as would occur when the field of view is jittered across the sun's disc by aircraft motion.

Atmospheric scattering. - By far the most pervasive and important background source for the optical PWI is that caused by atmosphere-scattered sunlight. If any proposed optical PWI system can satisfactorily cope with this source of radiation, it will not be seriously influenced by any of the others. A point of definition--the typical daylight conditions which very often involve a homogeneous cloud background, as well as clear sky conditions are included here. Cloud reflection extrema are treated in the next subsection.

Some direct measurement of expected values of daytime sky flux over spectral bands of interest in the PWI problem have been made at ERC, even though the literature references in this area are reasonably satisfactory. An Eppley 4 junction thermopile sensor bearing a field of view judged to be almost 1 steradian was used. The instrument was set up with its optical axis at a 20-degree elevation angle in a generally northern direction. Two favorable operating locations, on either the eighth floor or the roof of a 10-story building located in an urban environment, provided assurance that the sensor received very little ground radiation in these tests. The ground elevation was close to sea level.

Over an observing period of about 20 days in June 1968 the largest value of sky radiation noted was 4.75 mW-cm^{-2}-ster^{-1}. Measurements were made with a quartz window, which presumably passed essentially all possible solar scattered radiation. With a Corning CS7-69 filter, the largest value observed was 1.75 mW-cm^{-2}-ster^{-1}, after numerical adjustments had been made for filter loss and nonequivalence of this filter exactly to the desired 0.75- to 1.1-micron band. These maximum numbers were recorded near local noon in high thin overcast weather conditions. Experience has shown that this general sort of sky lighting yields radiation values about twice those of clear sky weather. Heavy or low nimbus-type clouds, of course, result in minimal readings, as low as 0.1 of the above.

How do these observations compare with the literature? Knestrick and Curcio in their Figure 1 (ref. 16), reproduced here as Figure 5, show horizon-directed clear sky radiance for three values of azimuthal sun position-view angle. These three values are 48 degrees for curve 1, 76 degrees for curve 2, and 172 degrees for curve 3. By integration and extrapolation of curve 3 to the 0.75 to 1.1-micron band, a value of $\sim$0.7 mW-cm^{-2}-ster^{-1} is yielded, to be compared with the ERC-measured clear sky value of (1.75/2) mW-cm^{-2}-ster^{-1}.

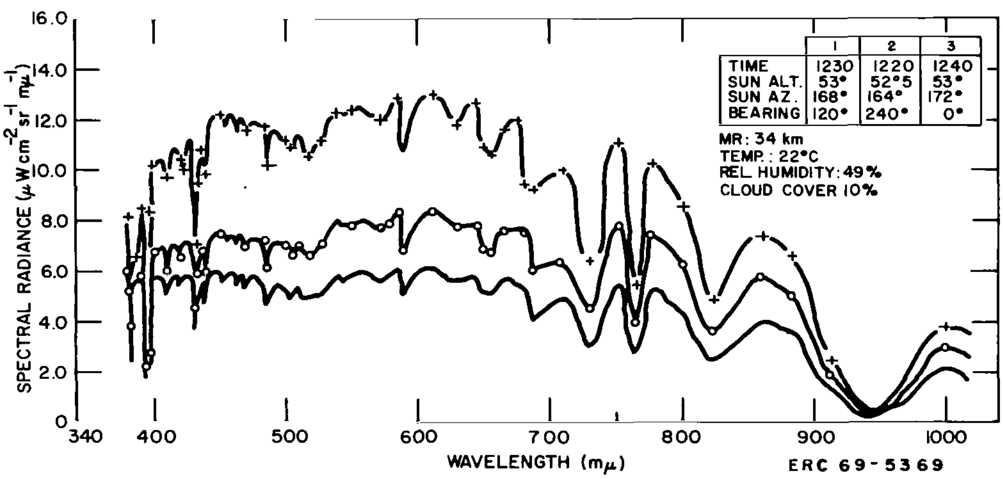


Figure 5. - Spectral radiance distribution of horizon sky for a clear day (after Krestrick and Curcio, ref. 16)

* * * * *

Figure 5 also serves to illustrate the sensitivity of sky radiance to view angle, even when these data exclude the pole of radiation near the sun. Dr. Max R. Nagel of ERC estimates partial factors operative in the total spread of PWI-concerned sky radiance as:

Location within gross area of sky	=	6X
Receiver altitude	=	4X
Seasonal and meteorological differences	=	3X.

If a composite or total multiplying factor made up of one-half of each of these partial factors is assumed, the "rarely exceeded" clear sky radiance value would be ∿7 $mW\text{-}cm^{-2}\text{-}ster^{-1}$ over the 0.75 to 1.1-micron band. Note that this is nearly one-half of the total direct sun radiance if as large as a 1-steradian PWI receiver is used.

As in the case for the sun, no significant self-induced time variation of received flux is expected from this source; radiation gradients as depicted in Figure 6 do exist, however (ref. 17). In view of recent direct observation, the ERC task force feels that even aircraft-motion-induced scans across "soft" gradients such as these need not be a source of false alarms in a properly designed PWI system.

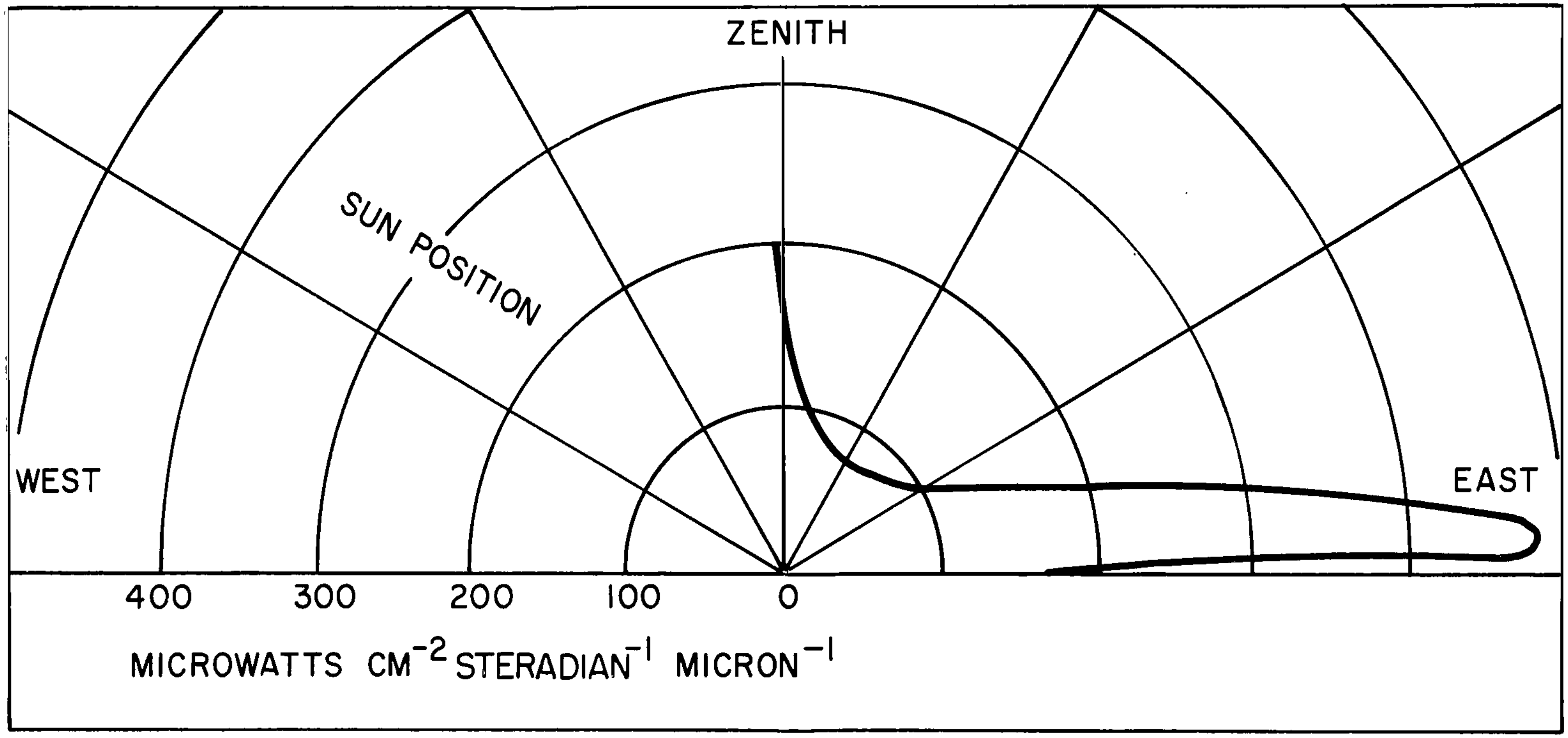
Cloud reflections. - That the brightness of many clouds is greater than that of their clear surroundings is a common observational fact. It is beyond the scope of this report to investigate many of the large number of possible sun/cloud/aircraft geometries; instead one situation possessing certain singular features is to be considered.

An aircraft flying a course parallel to the near-vertical wall of a huge, late afternoon sunlit cumulo-nimbus cloud will experience a maximum expected radiance of ∿5.3 $mW\text{-}cm^{-2}\text{-}ster^{-1}$ over the 0.75- to 1.1-micron band. This is calculated from the previously established solar radiance values over this interval, and a cloud albedo of 0.80. Because this value does represent a visible wavelength cloud albedo assumption, in fact, it may be too high by some unknown amount. It is in line, however, with the rough rule of thumb (ref. 18) that clouds may be up to 10 times brighter than adjacent clear sky.

Note that such huge clouds could readily fill the detector field of view for reasonable viewing cell sizes, say 10 degrees in elevation by 30 degrees in azimuth. Moreover, an aircraft flying in this more or less straight line sun-aircraft-cloud configuration could be "PWI blind" on both lateral extremities. This is an operationally hazardous situation, because neither aircraft of a collision-bound pair is nominally detectable. It would seem appropriate to configure the PWI to cope with steady radiances of at least 7 $mW\text{-}cm^{-2}\text{-}ster^{-1}$ to meet the challenge of both near-sun (in angle) and bright-cloud environments.

The contrast edge of many clouds, such as this one, can be effectively very sharp, partly because of the inherent nature of the cloud itself and partly because of the way it is illuminated (shadowed background, for example).

Detector field-of-view jitter tests run by ERC in a very



ERC 69-5370

Figure 6. - Horizon radiance gradients at 1.13 microns (after Bell et al., ref. 17

preliminary fashion (hand-held) on mild versions of these clouds show the expected signal transients in proportion to the jitter velocity. At present, definitive information on the motion spectrum of light aircraft, as well as means to simulate it at an observing site, is not available; the problems caused by those motions will be investigated when the information becomes available.

Ground reflections. - The ERC task force feels that the only serious problem that will arise from solar radiation over natural terrain concerns reflections from very flat surfaces, such as water, snow and ice fields, for example. A low-angle sun could possibly be visible in separate PWI detectors viewing both below and above the aircraft horizontal plane, through the often-observed "sun streak" or "sun glitter" phenomenon. If the view angle of a single detector included both the direct sun and its image, one might expect the detector to experience something like twice the direct solar radiance. However, several factors operate to make the actual situation less severe than this.

With reference alone to water, Table II lists the reflectivity characteristics of "glassy" sea water as a function of incidence angle (ref. 19).

TABLE II

REFLECTIVITY CHARACTERISTICS OF WATER

Angle of Incidence (Degrees)	Percent Reflectivity
0	2.0
10	2.0
20	2.1
30	2.1
40	2.5
50	3.4
60	6.0
70	13.4
80	34.8
90	100.0

Thus only exceptionally clear days could provide an environment in which the radiance from a 10-degree elevation sun plus the 35 percent reflection factor would exceed a standard air mass 2.0, 30-degree elevation sun value. This is understandable both from empirical evidence as well as personal observation. The low angle sun, even enhanced by sun glitter, is rarely intense enough to prevent short-period human observation into the sun field; this is demonstrably difficult to do at a 30-degree elevation.

The presence of wind on a sea surface modifies and reduces the specular reflection. This is well illustrated in Figure 7 taken from reference 20. An upwind/downwind skew that is a function of the wind velocity is introduced. The relative intensities in this figure were referenced to a white bond paper test panel, so no absolute value can be inferred.

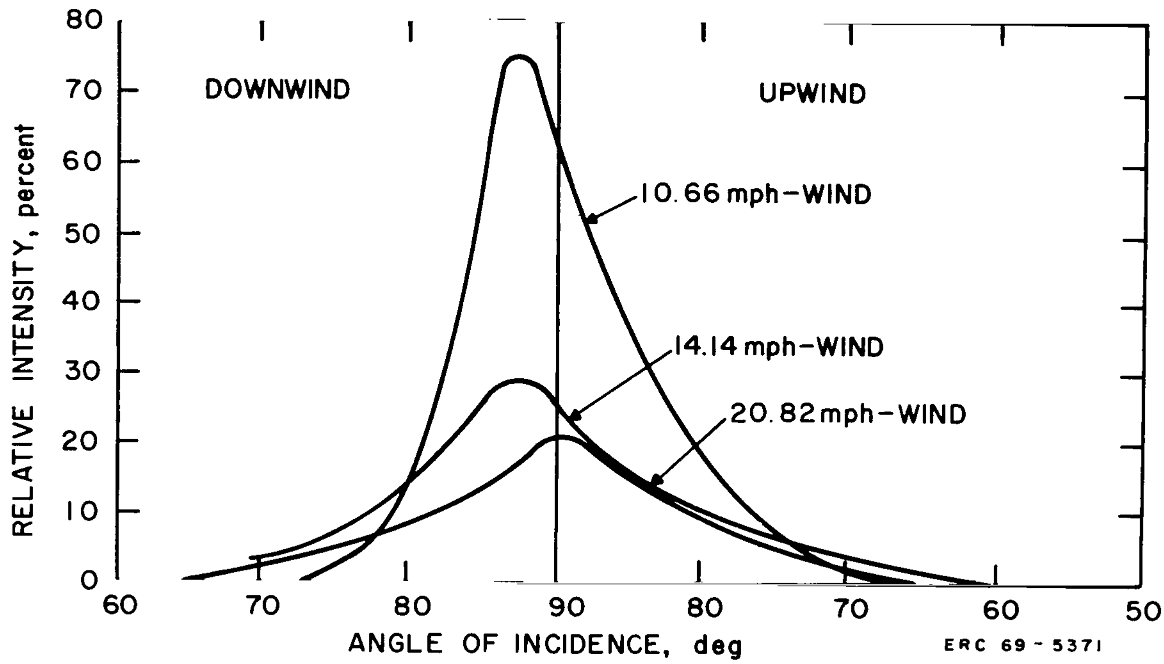


Figure 7. - Reflective wind field patterns

The reflective or scattered sea state caused by wind would also introduce a predominantly low frequency modulation on the received signal--a subject of current interest to permit remote sensing of sea state from satellites, for example. Judgment of the effect of this phenomenon on PWI operations will be deferred for the present.

The moon. - Although reflected solar light from the moon is capable of creating about the same diverse terrestrial phenomena as the sun (lunar rainbows, for instance,) their chance of becoming a significant PWI background source is very small. Only the direct lunar disc, as viewed by a PWI receiver element, could, perhaps, be a false-alarm source. No doubt the phase of the moon would be of prime importance also.

Herschel's famous Cape Town observation (ref. 21) concerning the darkness of the lunar terrain leads one to expect that the brightness of the moon's disc, if measured, will be less than that of a sunlit cloud, but more than that of blue sky. In fact, this is what has been experienced; the moon standing about halfway between these observables in brightness. During the day, then, the moon-induced impulse into a jittered PWI receiver would be no greater than that experienced from clouds or the horizon, for example. At night, however, the (full) moon becomes the "sun"; that is to say, with a minimal background, the lunar-induced transient into a background-released PWI receiver could be huge. Clearly the PWI receiver design must give full attention to the "day-night" problem as it is conveniently called. This is but one aspect of it.

Lightning. - The phenomenon of lightning is the first of the PWI background sources which may possess benign aspects for the PWI user; that is, vectored lightning detection, aside from its interference or false alarm drawbacks, could aid the pilot in emergency situations from encountering storm cells, at least those embedding lightning. For example, consider Figures 8, 9, and 10, which represent a time sequence taken from NASA/ERC on the afternoon of June 5, 1968, as a thunderstorm interfered with reception of xenon lamp optical pulses from a 1.1-mile distant source.

Figure 8 shows about 20 successive traces received just before lightning became prevalent in the area. There is less-than-usual pulse to pulse amplitude spread in the figure, concomitant with the existing heavily overcast weather. Figure 9, taken some minutes later, indicates about six non-lamp traces, verified as lightning by the simultaneous crash of static on a broadcast-band radio receiver. The third figure shows "pure lightning" with the rather narrow field of view detector aimed away from the lamp source for a period of about 2 minutes. It can be seen that the flashes possess a wide time and amplitude distribution. This is in accord with a statement made by W. Humphreys (ref. 22): "The duration of the lightning discharge is exceedingly variable, ranging from a few microseconds for a single flash, to even a full second or more, for a multiple flash . . . ."

The fact that the attending observer was not able to visually detect these (daylight) lightning flashes highlights a characteristic which may make an optical PWI more generally valuable than first thought.

Man-made radiative sources. - Because of the complexity of the subject of man-made radiative sources, only a few general comments on the four classes of such sources (see Table I) to which a PWI may be vulnerable will be made here.

a) Man-made radiative sources are about the only ones amenable to legislative fiat, should this prove necessary. It is conceivable that some one small class of lighting would destroy, for example, the night usefulness of an optical PWI; legislative relief in these circumstances may be the optimum system solution.

b) Man-made sources are surely better understood than others, or, at least, the manner in which they might be best modified for PWI use. Knowledge of the temporal variation is particularly useful. For example, the growing usage of gas and electronics derived lighting calls for careful

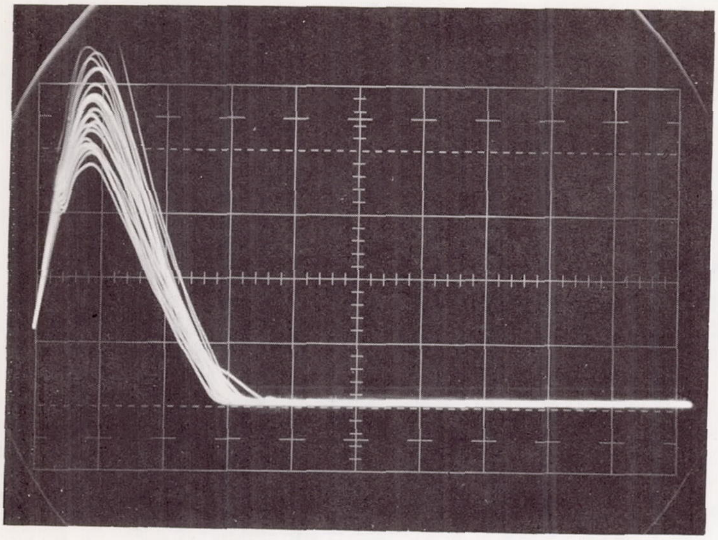


Figure 8. - Unperturbed reception of the xenon beacon flashes

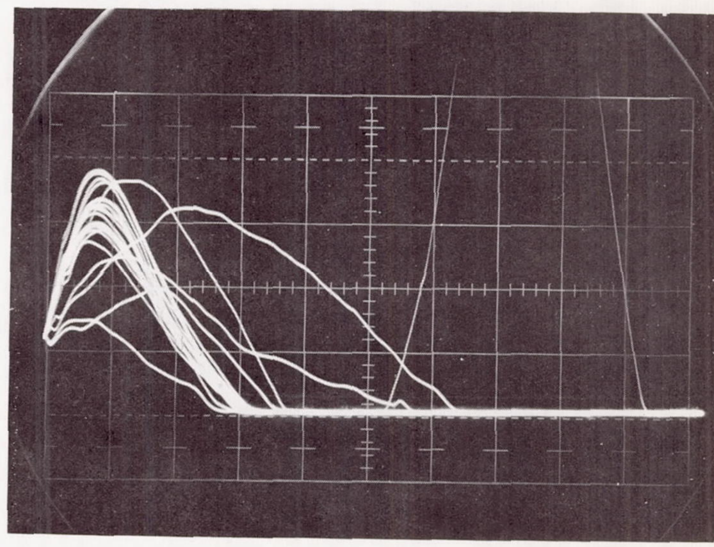


Figure 9. - Mixture of lightning traces and xenon beacon flashes

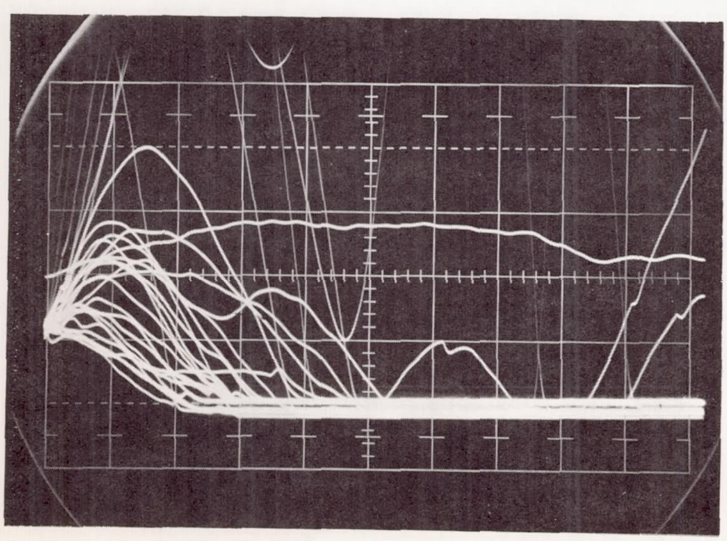


Figure 10. - Two-minute exposure of lightning only

filtering against 100 and 120 Hz modulation for best PWI use.

c) Detector placement on the aircraft is perhaps the principal weapon in self-illumination avoidance. A ventral position aft of the exhaust stack in a single engine aircraft would obviously be troublesome, for example. In general, wingtip placement appears to offer the cleanest means of coping with this problem, particularly for a system configured to have each wingtip unit look only into its own lateral hemisphere, and not back towards the aircraft.

d) Analogous to work already done on the visual or human detection of signal lights against city-light backgrounds (ref. 23), appropriate subsystem or system PWI tests in any or all of the three different modes are planned. These can be accomplished in (1) the ERC optical range, working against the high density urban structure of Cambridge, and Boston (see p.42 for details); (2) the simulator, described in detail in a subsequent section (p.81); (3) fly-bys on PWI-equipped aircraft.

e) One form of ground lighting already in existence may prove useful to PWI users; viz., the runway strobes installed at major airports, flashing in an arrow pattern at about twice a second. Conceivably these could help locate the airport and align a light aircraft with the runway in rapidly deteriorating weather.

<u>Combinations</u>. - A separate category comprising man-derived "modulation" of natural radiance sources, such as the sun, will be considered here. Consider the reflection of sunlight from flat, moving, tilted automobile windshields. Because flat surfaces can only redirect solar radiation at a loss, PWI-received reflected radiance values are not expected to exceed those for the direct sun and, in fact, they may, on the average, be less than 0.1 of the sun's value. Nevertheless, even on a dc basis the redistribution of the "sun" as points on the ground provides a significant background signal.

The modulation of windshield radiance sources can arise in at least three ways: (a) self-motion, as in a moving or, especially, in a <u>turning</u> vehicle; (b) interruption of the line of sight by opaque or refracting matter; and (c) aircraft movement itself. Some interesting cases of (b) have been observed, namely, those resulting from (1) the steam from a pile driver located almost in the line of sight, (2) what was taken to be wind-derived noise (judged by its low frequency rumble in the detector and loudspeaker), and (3) a passing train furnishing blips of light between the cars and longer dark periods as the cars themselves went by. The modulation in this last case could be very close to that of the PWI source. Fortunately, this case is also likely to be rarely seen.

Propeller modulation of the sun radiance from a fuselage-placed PWI receiver could be expected to produce approximately 1-msec long dark pulses in the forward-looking PWI receiver elements at about 80 Hz if estimates of propeller blade widths are reasonably accurate. Erroneous data may result if the dark pulse is received coincidentally with a xenon lamp pulse from an intruder, through violent displacement of the detector bias. It would appear that this particular form of background interference lends itself readily to laboratory test, perhaps on a simulator. An even better solution is to incorporate the detectors on the wingtips as suggested previously.

Finally, it may be noted that some of these backgrounds appear to be polarized to some degree--certainly blue sky is. Use of this extra degree of freedom may prove to good advantage as further work shows which of these are truly the performance-limiting background situations.

Some Aspects of PWI Propagation

The components of transmission loss. - Probably the most useful way of treating the attenuation aspects of the PWI-concerned atmosphere (briefly, up to 10,000 feet, essentially horizontal, and instrumentally directed at 0.75 to 1.1 microns) is through the concept of visibility. A current numerical value for this atmospheric parameter is always available at major airports, and, of course, it will closely govern the actions of the less well-equipped aircraft portions of the aviation community when it reaches the lower end of its scale. In particular, all aircraft must fly instrument flight rules (IFR) when the visibility drops below 3 miles. This essentially removes the great preponderance of light aircraft from the airspace (except for stragglers), and the resultant lowered traffic density is placed under positive air traffic control (ATC). Interest then extends mainly to visibility readings of 3 miles or more.

From Kruse et al (ref. 24), the visibility reference is taken at the peak of visual sensitivity, viz., 0.55 micron. A number determined at this wavelength then has to be related to the more complex properties of the atmosphere in the near infrared region. In this report this is done in a tutorial or limiting-case fashion; the reader is referred to Kruse (ref. 24) for derivations permitting a more comprehensive treatment to be made.

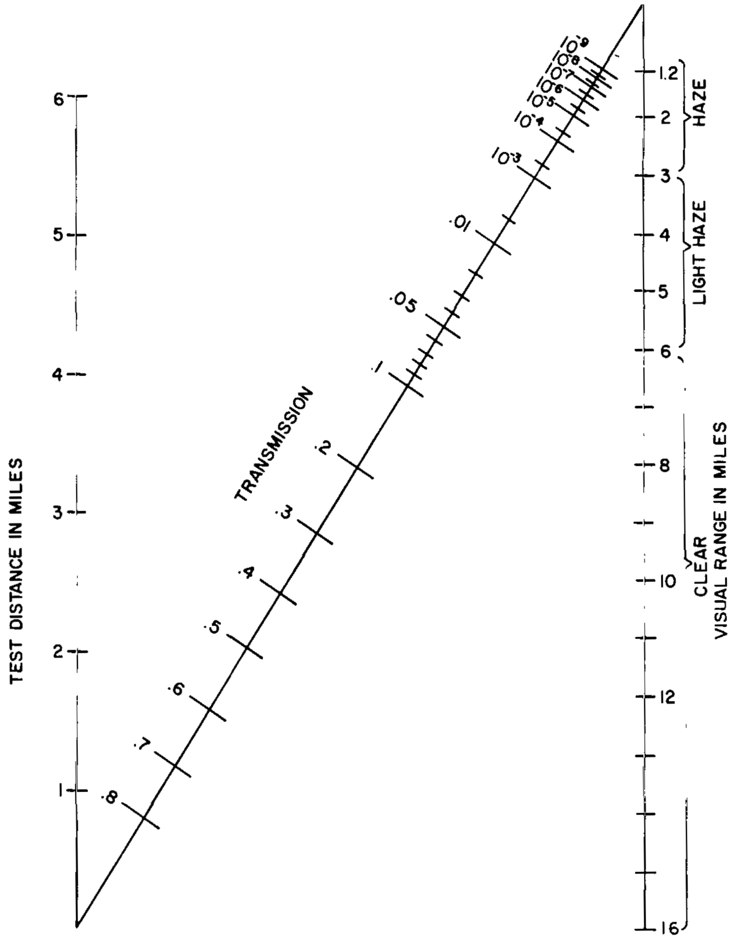
For a visibility reading of 3 miles, the atmospheric transmission for a 3-mile range at 0.55 micron, is 0.02 by the accepted visibility definition. In this green part of the spectrum, the atmospheric (molecular) absorption is essentially negligible, and wide variations in transmission values from the above are not to be expected even over a bandwidth encompassing about all the visible wavelengths. Figure 11 is a monograph made up by the ERC task force to facilitate reading off (visible) atmospheric transmission values for other visibility and range values. If the larger of the two range criteria mentioned in the PWI "model" (see Introduction) is met, the visible transmission for this 5-mile distance will be ∿0.002. It often comes as something of a surprise that these modest ranges can exhibit attenuation losses of almost three orders of magnitude, in addition, of course, to the $1/R^2$ spreading factor. The minimum loss, or maximum transmission, over this distance in exceptionally clear weather can be ∿0.5, a number 250 times as large as that given above. These all essentially refer to sea level conditions.

The loss mechanism for the visible wavelengths is primarily caused by the scattering of particles, although Möller (ref. 25) references two Russian authors who show that the atmospheric haze is also absorptive. Möller's equation for the sea level, horizontal beam, mean scattering loss has been graphed as Figure 12. Contributions from both Rayleigh and haze scattering make up this loss. The wavelength dependence remains pretty much unchanged with increasing haze formation, i.e., with increasing number and size of wet particles as the humidity grows. So this gives us our first extrapolation from the visible to the near infrared, in a direction creating increased transmission with wavelength.

The effects of molecular absorption from one or the other of the many constituents of the atmosphere begin to manifest themselves at wavelengths longer than about 0.7 micron, and certainly play a role in the PWI problem. Figure 13, adapted from Kruse (ref. 24) shows in a graphic form the irregular nature of this absorption over the interval of interest. This figure, of course, must--and does--show essential "dip and ridge" agreement with figure 4, demonstrating sea level solar radiance. The absorption valleys of the limited wavelength range of Figure 13 are all caused by atmospheric water vapor.

Elder and Strong (ref. 26) found it convenient to divide the whole infrared transmission structure into eight intervals or "windows", only two and a fraction of which are shown. A τ_{ai} (i = I, II) can be defined as the area under the broken line curve in window i, and hence represents the added loss over scattering, averaged over the unequal but natural divisions made by Elder and Strong.

The τ_{si}, or scatter loss transmission factor, for the midpoint of these intervals is:



ERC 69-5372

Figure 11. - Visual range to optical transmission nomograph

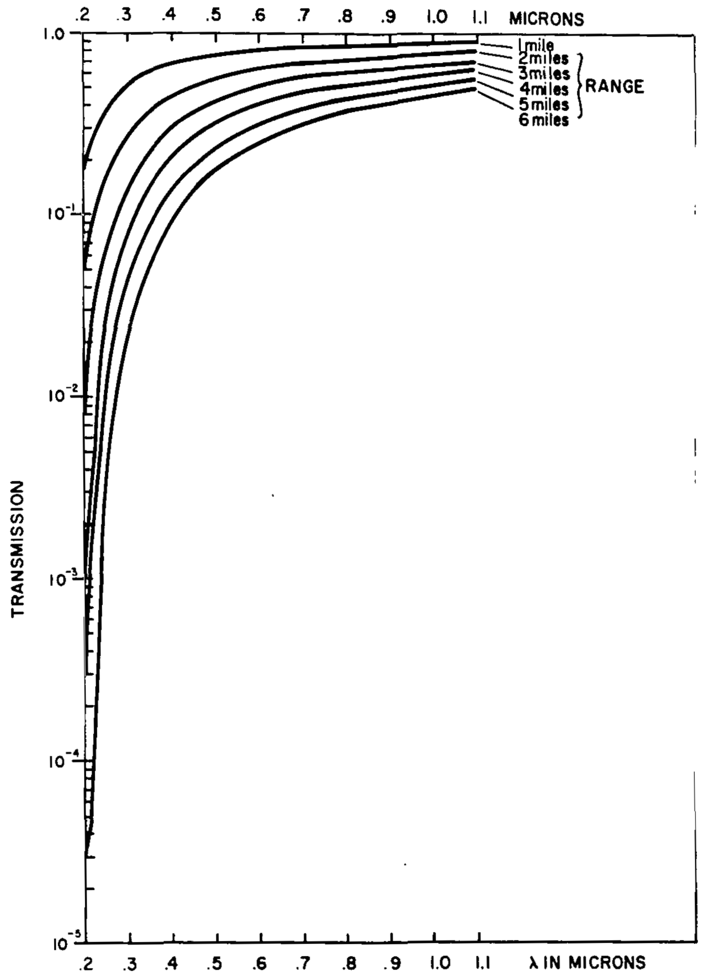


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Figure 12. - Mean scattering loss for horizontal beam at sea level

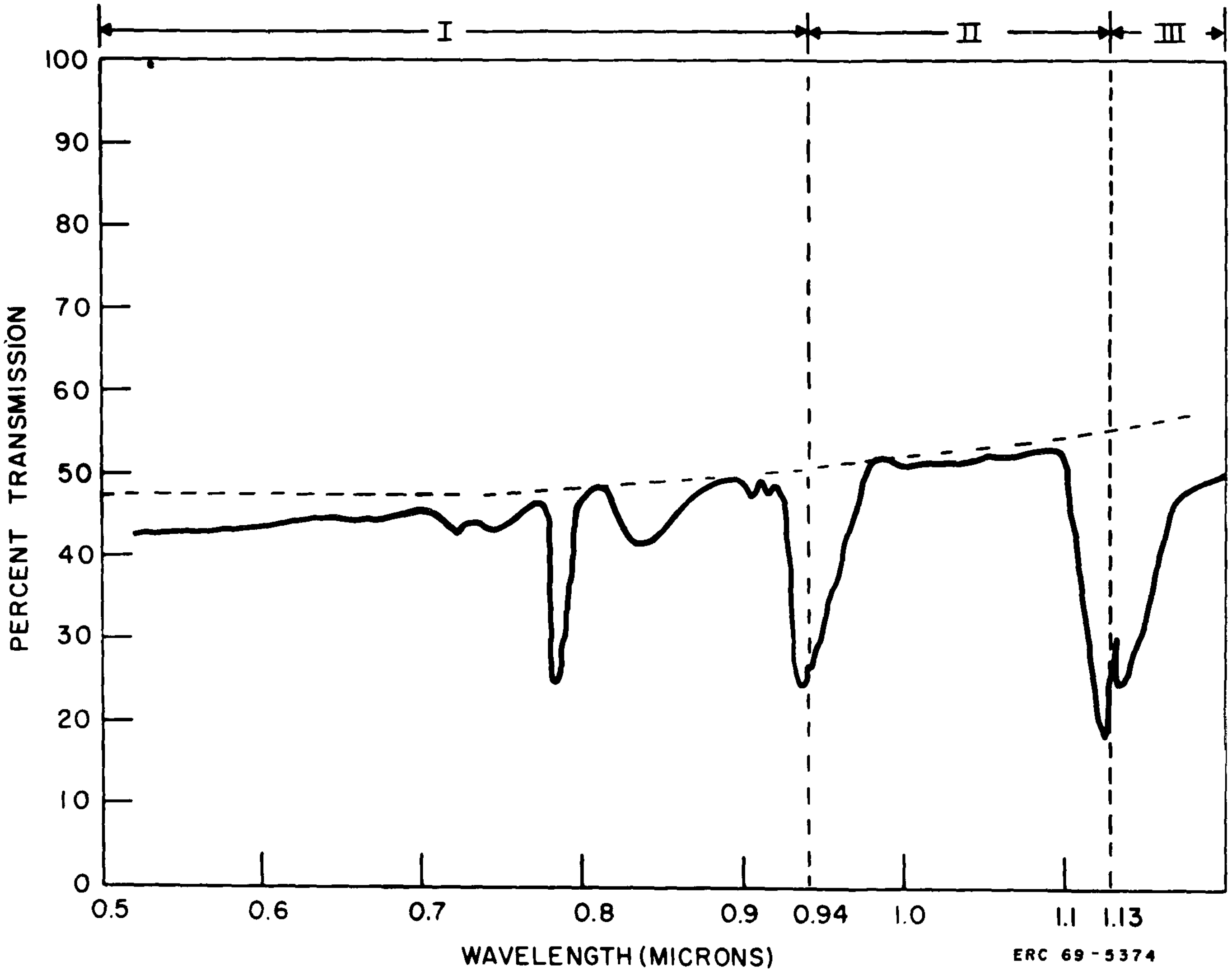

Figure 13. - Atmospheric transmission from 0.55 to 2.2 microns

$$\tau_{s_i} = \exp\left\{-\frac{3.91}{V}\left[\frac{\lambda_i}{.55}\right] - qX\right\}$$

where V = visibility and X = range in consistent units, λ_i = mid-internal wavelength, and q = 1 for visibility = 3 miles. Also, λ_I = 0.83 micron; λ_{II} = 1.03 microns.

For this value of q, this equation does nothing more than modify the exponent of the transmission factor as λ^{-1}.

Putting in some numbers for the limit case of 3-mile visibility, 3 and 5 mile ranges, 90°F and 90 percent relative humidity, yields, from Kruse's table:

$\left.\tau_{aI}\right]_{3\ \text{miles}} = .715$; $\left.\tau_{aII}\right]_{3\ \text{miles}} = .670$

$\left.\tau_{aI}\right]_{5\ \text{miles}} = .670$; $\left.\tau_{aII}\right]_{5\ \text{miles}} = .625$

The τ_{aII} are less than the τ_{aI}, even though the τ_{s_i} curve is higher for τ_{aII}, because the valley at 1.13 microns is especially wide and deep. Deeper entry into the water vapor absorption region is resulting.

The τ_{s_i}'s are:

$\left.\tau_{sI}\right]_{3\ \text{miles}} = .0747$; $\left.\tau_{sII}\right]_{3\ \text{miles}} = .123$

$\left.\tau_{sI}\right]_{5\ \text{miles}} = .0133$; $\left.\tau_{sII}\right]_{5\ \text{miles}} = .0308$

The products are:

$\left.\tau_{I}\right]_{3\ \text{miles}} = .0535$; $\left.\tau_{II}\right]_{3\ \text{miles}} = .0824$

$\left.\tau_{I}\right]_{5\ \text{miles}} = .0089$; $\left.\tau_{II}\right]_{5\ \text{miles}} = .0193$

These may be compared with the visible transmission of $.02]_{3\ miles}$ and $.002]_{5\ miles}$. Roughly, the infrared is about 3 times as transmissive at 3 miles and 5 times as transmissive at 5 miles in marginal weather. Examination of the xenon lamp spectrum (figure 14) shows no undue energy concentration at or near the absorption valley at .94 micron which could invalidate these average results. Very clearly, the received xenon spectrum shape is a function of range, and use might be made of this fact to achieve a display of this parameter; however, the received shape is also a function of the prevailing weather, and adequate interpolation for this disturbance, as well as for lamp aging, may be difficult in a low cost PWI.

The effect of altitude is a lengthy subject in itself; it is certainly generally true that the atmosphere becomes more transparent for all wavelengths with increasing elevation. Similarly, the distinction between dry or continental, and maritime hazes, and numerous other satellite topics must necessarily be deferred. References 27 and 28 offer additional details on this topic.

The nomograph of Figure 15 is introduced at this point to help tie together some of this discussion and the earlier section on xenon light source work. This graph yields the received optical flux density in W/cm^2 from a lamp of given estimated or measured characteristics, the radiating geometry, the pulse length, and the range for two singular values of atmospheric transparency. Cognizance is also given to the lamp pulse shape through the factor (F) (see Figure 3). The received flux density values are nominally accurate only for the visible spectrum; multiplication by factors of 3 and 5 would be necessary for average infrared reception at 3- and 5-mile ranges in haze as discussed above.

Atmospheric refraction effects. - The refractive or turbulent nature of the lower atmosphere manifests itself over an optical transmission path by phenomena given expression such as "image dance," "scintillation," "atmospheric boil," "beam breakup," and the like. The names themselves are adequately descriptive of the general nature of this subject matter; fine distinctions between them do exist; however, the term scintillation is best used as the most apt descriptor for the subsequent discussions.

Investigation of the laser as a source for terrestrial optical communication has yielded considerable analytical and experimental data which may prove advantageous. Kurtz and Hayes (ref. 29) find upper limits on the angular deviation experienced on 3200 meter paths at 6328 Å wavelength. These are <100 microradians and, inasmuch as the PWI angle-of-arrival accuracy needs

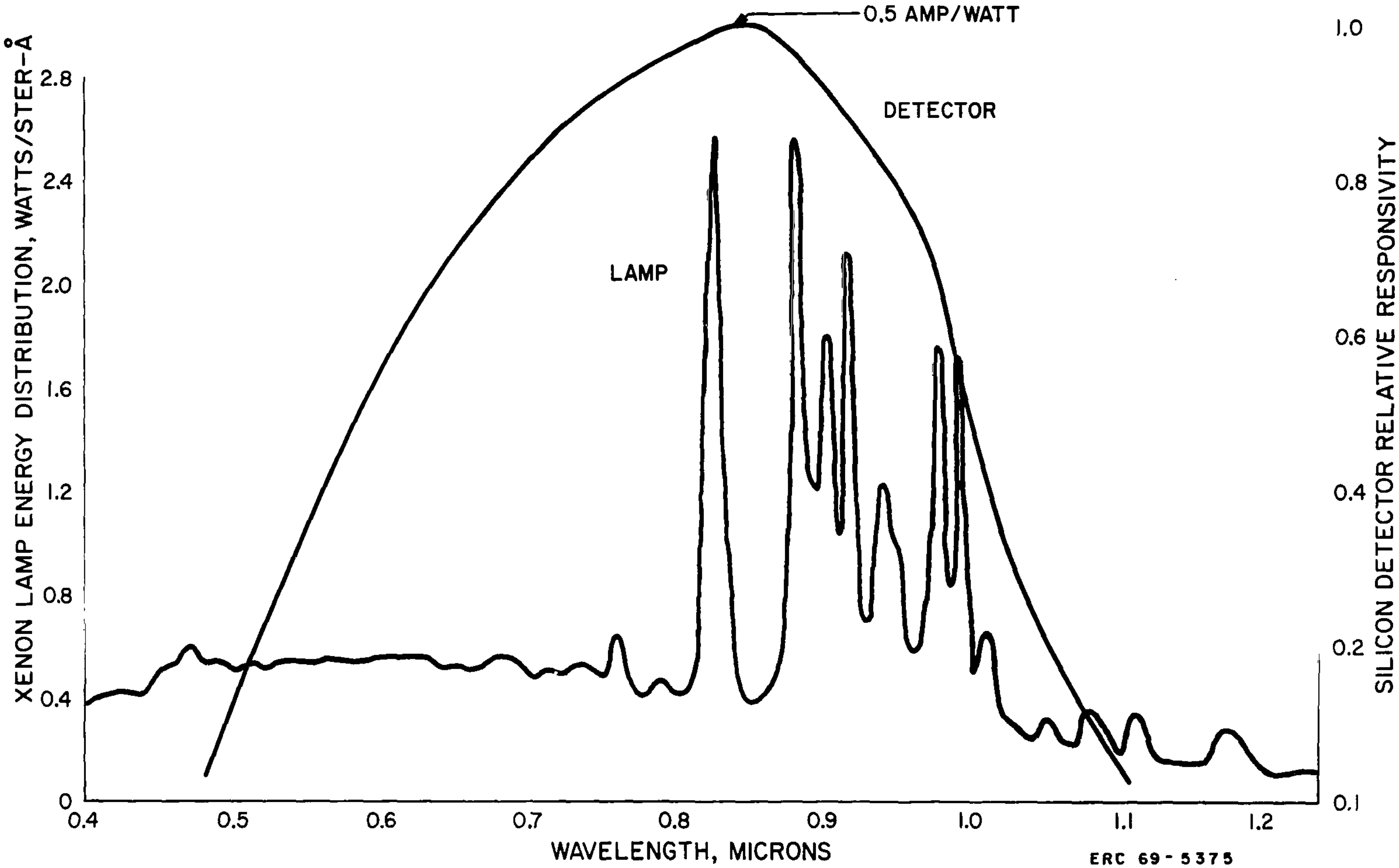

Figure 14. - Spectral intensity of a xenon lamp and spectral response of a silicon detector

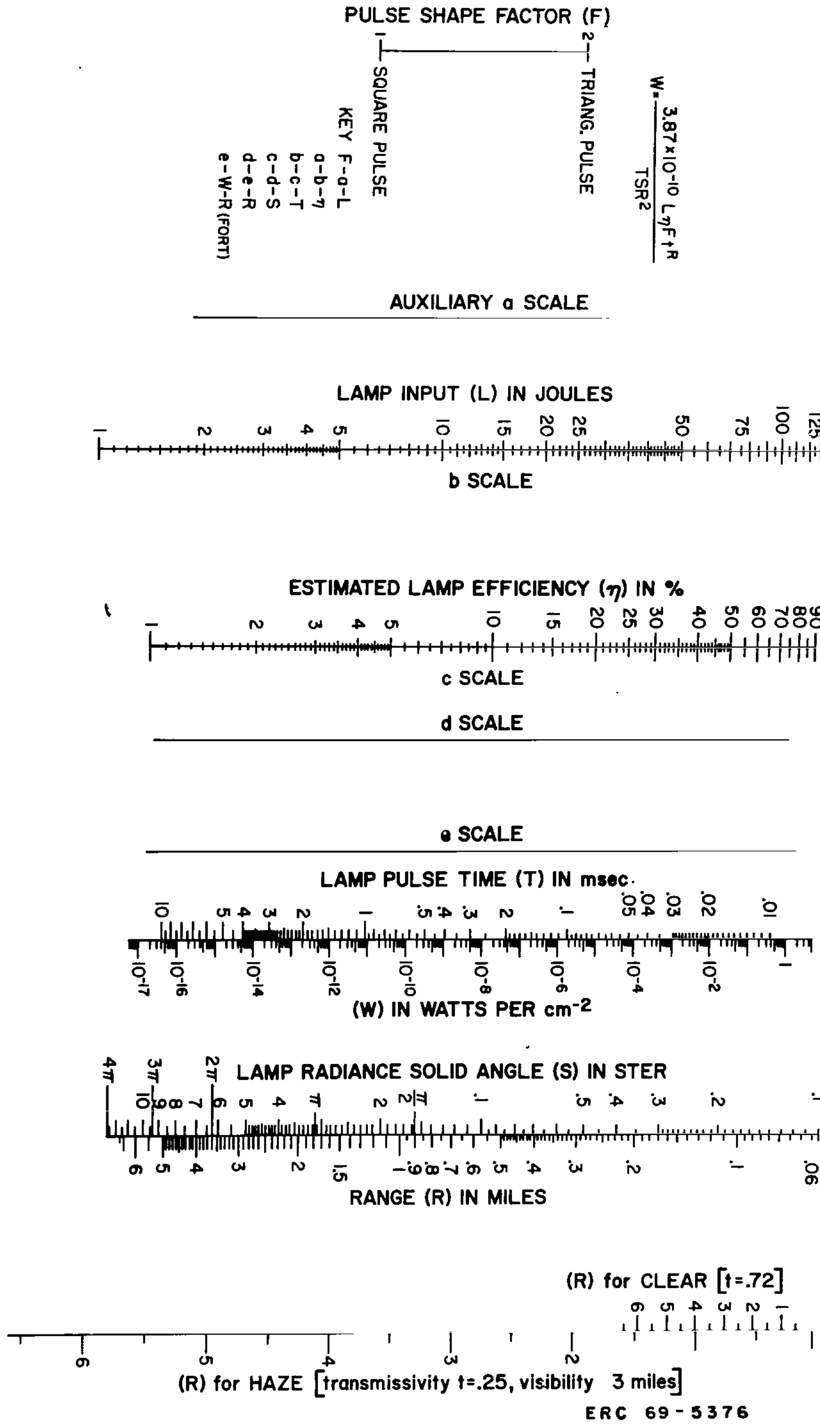

Figure 15. - Seven-element nomograph for received flux density

surely are not smaller than 1 degree, it can be safely said that amplitude scintillation alone is of concern.

The effect of receiving aperture size on the degree of received signal fluctuation has been rather well documented. Experimenters find a complicated dependence between these two factors, with the fluctuation saturation "knee" occurring for diameters greater than the characteristic length of the turbulence elements. Here it can be assumed that a linear relationship holds between some measure of the fluctuation and 1/D.

One might think intuitively that the magnitude of scintillation increases indefinitely with range. Fortunately this is not so, saturation being reached in as short a distance as 700 meters.

The power spectra of the received signal fluctuations falls off from its peak at or near zero frequency to a characteristic value two orders of magnitude down at ∿200 Hz. Special exceptions to this rule were noted by Subramanian and Collinson (ref. 30) in violently gusty and rainy weather, where the spectrum was down 15 dB at ∿1000 Hz. For the PWI situation, these numbers imply that the received pulse-to pulse amplitude variation (at $f_1 \sim 1.5$ Hz) will be large, while any intrapulse variation (at $1/T_2 = f_2 > 1000$ Hz) must necessarily be minimal.

In all of the above, the atmosphere is the only source of "motion" so that the nature of the received spectrum tells something about atmospheric movement itself. But what if the receiving aperture, or the transmitting source, or both are in the aircraft? Consider the case where the receiving aircraft is viewing at 90 degrees from its motion vector, so that, in effect, it is "scanning" the turbulence. If this motion is assumed to be rapid enough to have the turbulence "frozen in", a curve, such as that of Figure 16 (from Dietz, ref. 31), may be used to estimate the highest motion-scintillation frequency. For a speed of 250 knots, and an aperture small enough (less than 4 cm) to resolve the structure of Figure 16, f_{max} equals 2500 Hz. The internal structure of the received pulses very definitely would show this effect as gross and continual shape changes.

It would be perhaps unwise to attempt further or more detailed extrapolation of laser-derived propagation results for the PWI case. The effect of obvious differences between monochromatic and coherent versus wideband, non-coherent propagation may not yet be fully rationalized. Some of the laser propagation work was undertaken over paths but a few meters above local terrain. A wavelength difference also exists.

The line-of-sight availability of a xenon beacon from one of the ERC laboratory windows has allowed direct propagation observations, which confirms, insofar as the data taken by the ERC technical staff permit, the general laser-derived abstractions just cited. This beacon is located on the roof of the Museum of Science building in Cambridge, Mass., about 1.1 miles from the observation point. A short part of the path, perhaps 80 feet, traverses the roof at a roof-beam elevation of about 4 feet. The remainder of the path is ∿100 feet above urban-industrial land. The beacon operates at about 1 pulse/sec.

Figures 17a and 17b show 10 sequentially received lamp pulses for two sizes of receiving apertures--6 and 1-3/8 inches in diameter. These were taken at substantially the same time in the forenoon of a partly cloudy June day. The visibility--about 4 miles--was rather low. The amount of fluctuation in these photos is quite representative of the average experienced in about 20 daily observation periods. Note that the larger aperture fluctuation ratio of 2.1 (maximum excursion divided by minimum excursion) is about 1/5 the small aperture ratio of 10.2. The diameter ratio is 6 to 1.375 = 4.37. No definitive pulse shape variation is discernible.

The oscilloscope gain is 10 times greater in Figure 17b than in Figure 17a. When the collector area ratio and the average signal value for the two figures are taken into account, the resulting agreement is rather good.

Figures 18a and 18b illustrate more drastic fluctuations as observed shortly after noon on a clear and not too warm (80°F) June day 1968. The amplitude fluctuation range for the smaller aperture must be ∿25/1. The diurnal variation of fluctuation on clear days was like that reported by essentially all observers of any kind of optical propagation--greatest in the afternoon, least in the early morning hours.

The preceeding four photographs cannot show the time sequence variation of successive pulses. This aspect, and the signal diversity arising from even close-spaced separate detectors, is illustrated in Figures 19a and 19b. The apertures are 6 inches in diameter for both detectors and their lateral spacing was 15 inches. The weather for Figure 19a was sunny and the data was taken at noon; for Figure 19b the weather was partly cloudy, and the exposure was made at 11:00 a.m. Note the sharp drop in signal strength in the lower part of Figure 19a, a drop which is observed in the upper trace 1 second later. One can almost visualize a refractive blob drifting by.

The prospects of obtaining range information from received signal strength in an advanced form of an optical PWI can now be briefly investigated. Clearly, the effects of two kinds of vari-

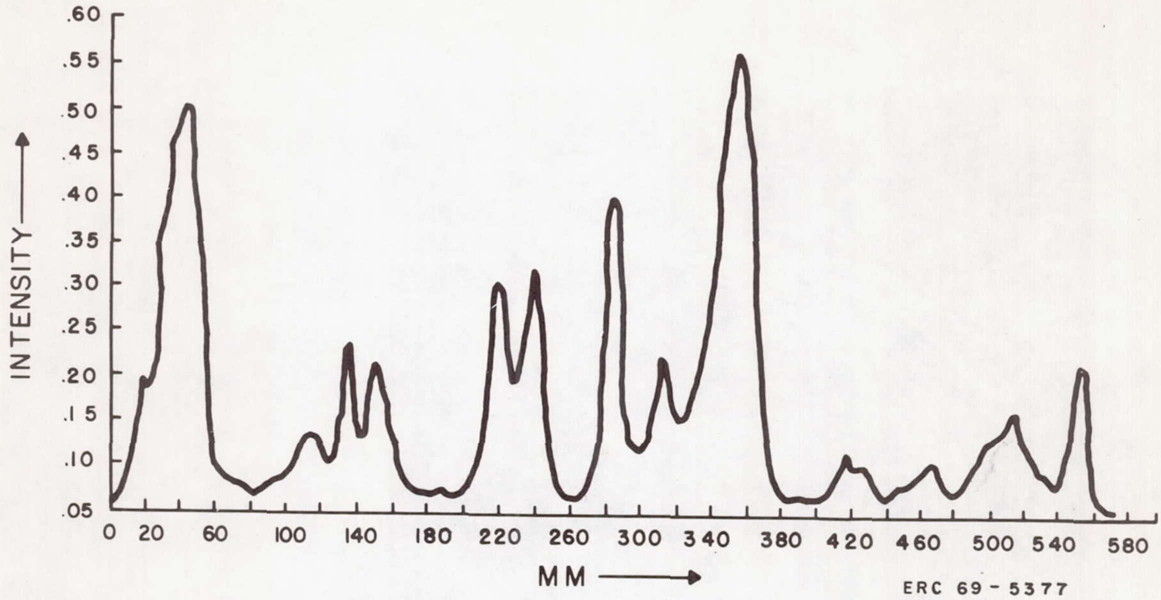

Figure 16. - Horizontal intensity profile of beam cross-section

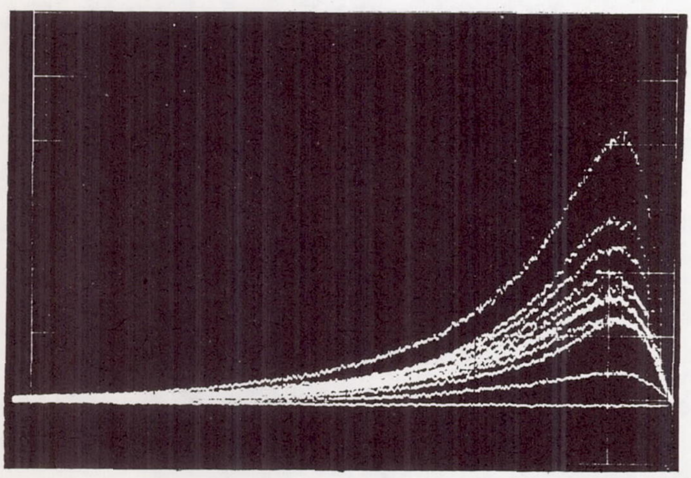

Figure 17a. - Large-aperture (6-inches) reception of xenon beacon pulses (100 microseconds per major division)

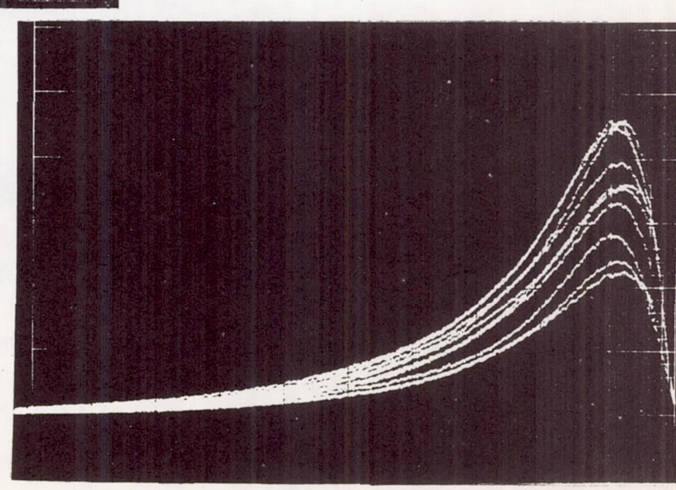

Figure 17b. - Small-aperture (1-3/8 inches) reception of xenon beacon pulses

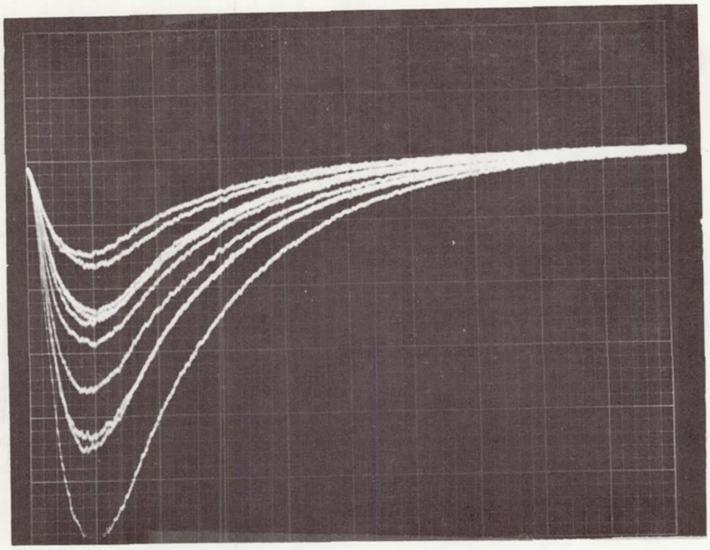

Figure 18a. - Worst-case large-aperture (6 inches) reception of xenon beacon pulses

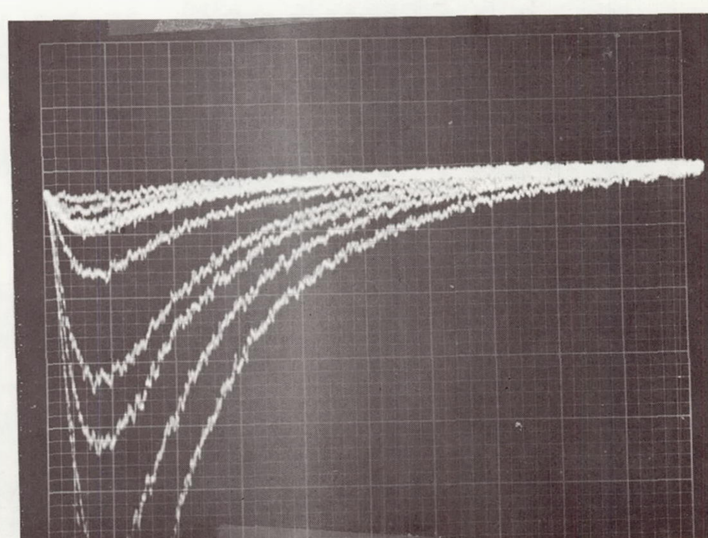

Figure 18b. - Worst-case small-aperture (1-3/8 inches) aperture reception of xenon beacon pulses

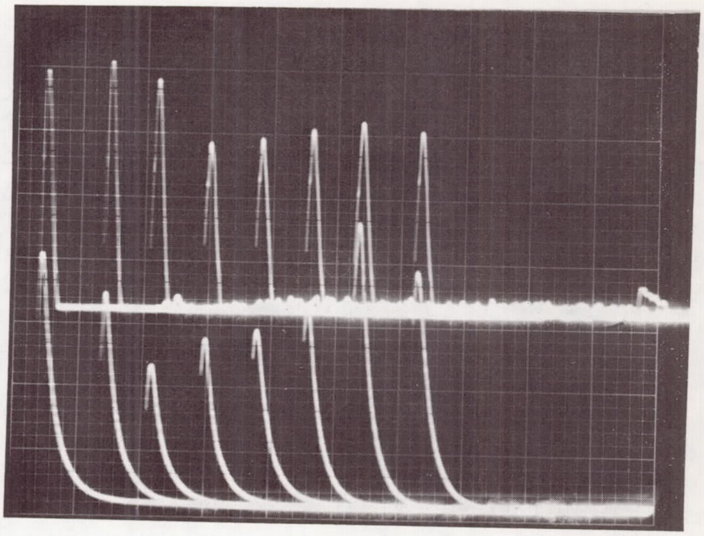

Figure 19a. - Simultaneous pulse reception by laterally separated detectors--Example 1, 12:00 noon

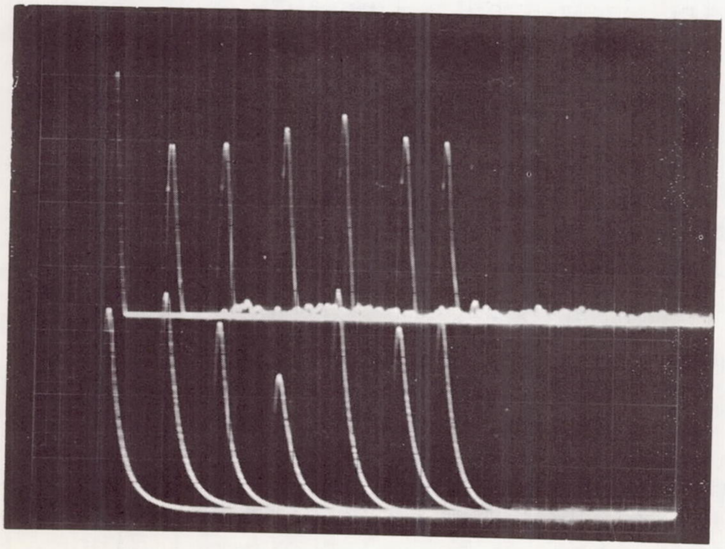

Figure 19b. - Simultaneous pulse reception by laterally separated detectors--Example 2, approx. 11:00 a.m.

ation must be considered: (1) the slow but deep transmission losses discussed earlier caused by the hazes, and the like; and (2) the choppy sort of variations just now treated.

Being slow, the first sort of variation could be ameliorated by pilot setting of the current visibility condition into the instrument. On long flights this function could readily be overlooked, unfortunately, as new weather is encountered. The second variation probably is best handled by averaging over some number of pulses before range information is displayed. This number may be distressingly small, however, say 3, so that range presentation to the pilot is not delayed. Note that pulses 4, 5, and 6 of Figure 19b upper are 75 percent or less of the heights of pulses 1, 2, and 3, so any attempt at fine-grained range resolution through this mechanism must be considered risky.

One form of range information, or more properly range sorting, may circumvent the difficulties associated with the slow or secular variation of optical transmission. Suppose an adaptive threshold is implemented on the PWI receiver to let through, or display, only some selected number, say four, of intruders, chosen as the strongest four in signal strength from a (perhaps) larger class. If the visibility is truly isotropic, these four threats clearly should receive the pilot's first attention. The system is adaptive in the sense that, as a fifth intruder's signal increases, the threshold increases enough to keep his signal off the display <u>until</u> his signal strength surpasses the weakest of the four already being displayed. Then, of course, an exchange is made.

PWI development requires increased effort on the experimental and analytical aspects of optical pulse propagation, including wavelengths flanking the visible, near infrared spectral band. Figure 20 shows the ∿2-mile-distant Boston skyline as viewed from NASA/ERC, and the planned locations for two xenon lamp installations which will be under direct control. These lamps will be operable in any of three pulse lengths and will allow close control of the pulse energy. Their quartz construction permits the ultraviolet and mid-infrared (IR) assessment mentioned above. Note that the propagation paths will now have minimum altitudes of ∿100 feet, with no part of them over adjacent horizontal surfaces.

These sources, plus aircraft in the Logan Airport climb corridor for runway 22, which passes behind these buildings, should allow, in addition to the sort of work already described, (1) evaluation of the multiple-target situation, (2) false alarm evaluation from the urban complex background, and (3) general post-detection electronics assessment in a realistic fading channel.

Figure 20. - Boston skyline as viewed from PWI laboratory location with arrows showing placement of xenon beacons

V. RECEIVER ANALYSIS

Introduction

Choice of a receiver design has been predicated on an understanding of the limitations imposed upon a pilot warning instrument. Chief among these are cost, flash lamp characteristics, and operational requirements, particularly during bright sunlight. The set of values for operational parameters appears both implicitly in the form of the receiver analysis and explicitly in the signal-to-noise estimate which terminates this section. The sample signal-to-noise calculations are preliminary, however, and do not represent an optimized design. Generally pessimistic values have been used to arrive at this signal-to-noise ratio value.

An important decision, taken early in the program, was to reject scanning systems from consideration. Apart from mechanical problems in implementing a low-cost, ultra-reliable scanning receiver, there are basic lamp properties which adversely affect the design of a suitable scanner. Lamp flash duration, repetition rate, and peak power have been chosen for reasons independently from PWI considerations to satisfy (1) maximum visual conspicuity, and (2) to provide a reasonable lamp lifetime. The pulse duration from a typical flash lamp (full width to half optical power) is 250 microseconds. For a scanned receiver to identify the location of a lamp in the field of view within one lamp flash period, the scan of the entire field of view must be completed within a time which approximates the pulse duration. Since flashes only repeat once every second or less, that time constitutes a limit on the period of time between display updates. Even statistical arguments based upon less frequent display updating will not greatly modify the scan requirements. The rapid scan rate implied by these arguments has led to an unfavorable assessment of scanning systems proposed for the location of random position, random flash-occurence lamps.

Some detector types have also been excluded from this study. Neither photoemissive tubes nor avalanche multiplication photodetectors have been extensively studied at ERC. This decision was made on the basis of the cost of these detectors and their power supplies. It will also be shown that a dominant noise source is shot noise caused by background flux falling on the detector, so that the high intrinsic multiplication inherent in these devices does not improve the signal-to-noise ratio.

Problems in receiver implementation have also had a bearing on some of the system specifications. For instance, if implementation were readily imaginable, it would be tempting to cover the entire 4π steradians surrounding the airplane, with resolution as great as a tenth of an arc-degree. It can readily be shown that this is an unreasonable requirement, based upon the receiver complexity required.

Receiver Optical Systems

The PWI operational requirement of a very large field of view coverage places strong constraints upon optical systems for a PWI receiver. Two divergent approaches have been explored. On the one hand, it is possible to find optical designs for very wide field-of-view lens systems. These systems, two of which are discussed below, will allow fabrication of a single detector -optical package receiver, although with some drawbacks. An alternative is to construct the PWI receiver from modules, each of which covers a fraction of the total field of view. While the modular system offers generally enhanced performance, fabrication of such a system will clearly require more attention. An intermediate case is also discussed.

An entire 180- to 200-degree field of view may be imaged onto a detector plane by means of Hill's sky lens (ref. 32), or a variation described by Havlicek (ref. 33). The optical arrangement of the original Hill scheme is shown in Figure 21a. It can be seen that the projected area of this system varies greatly with direction of incidence, which is one disadvantage. Another potential problem lies in the limiting resolution of this lens system. It is not clear from information at hand how constructional tolerances affect the system's resolution. Despite these objections, it would appear that the sky lens has merit, especially if it proves possible to fabricate the required large dimension elements in an inexpensive manner, perhaps from pressed plastic.

Another lens system with a large usable field of view is the "eyeball" (ref. 34), depicted in Figure 21b. A detector array, or even a single detector element, may be readily attached over the eyeball's unilluminated hemisphere. However, the eyeball lens has two disadvantages. First, the image quality of the lens depends absolutely on the index of refraction of the material from which the lens is formed, since it is not possible in this design to adjust radii of curvature independently from index of refraction to achieve best imaging qualities. Secondly, the imaging properties of the eyeball lens may be marginal for application in a PWI receiver. Severe spherical aberration characterizes the image of a point source of infinity. In the paraxial approximation, the index of refraction must be 2 so that the image of a point source at infinity will lie on the surface of the unilluminated hemisphere. However, rays at heights approaching the radius of the sphere are reflected at too great an angle to meet the paraxial rays on the unilluminated hemisphere. Lowering the index of refraction from 2 to some lower value will improve the imaging of these rays while degrading the paraxial ray

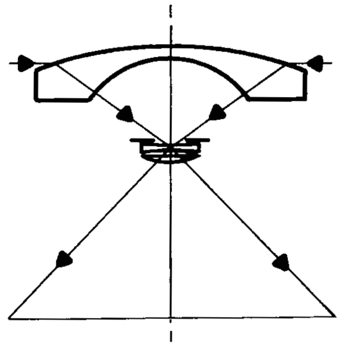

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Figure 21a. - Hill's wide-field "sky" lens

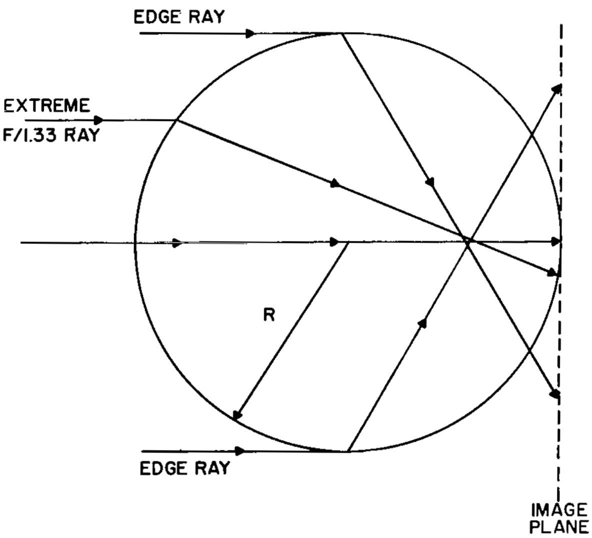

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Figure 21b. - Spherical lens with rays appropriate for index 2

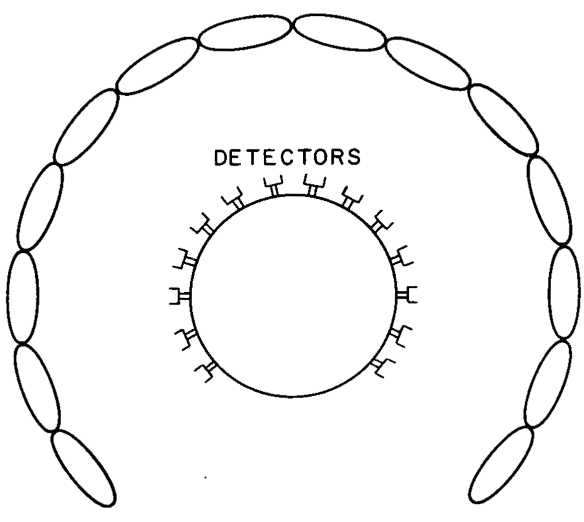

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Figure 21c. - Multiple lens and detector array imaging. A complete analysis has not been performed, so it appears unwise to estimate the best angular resolution to be expected.

A lens assembly which is transitional between modular and single-element optical systems is the multilens matrix depicted in Figure 21c. A receiver using this optical system will require a detector array formed on a curved surface concentric with the curved surface formed by the lens system envelope. The lens system may either be formed out of a single mold or a modular system may be prepared from single-lens/single-detector element building blocks. Care in baffling must be maintained; stray light from lenses other than the one devoted to a given detector element must be eliminated. The flux collection capabilities of the multielement lens matrix are uniform but uninspiring; the collecting area appropriate to the range equation is the area of a single-component lens. Flux from a flash lamp located anywhere within the field of view is collected with the same apparent collecting area.

With the multilens matrix approach, it is desirable to use simple field optics. The field system has the advantage that the same flux is delivered to the detector, independent of the location of the intruder within the field of view.* The simplest form of field optics consists of a lens replacing the detector in the focal plane of the primary objective (Figure 21d). The lens-detector separation is adjusted so that the field lens images the objective onto the detector. A stop in the plain of the field lens defines the field of view.

The simplest optical system considered is the single aperture (Figure 21e). Its field of view is less than 180 arc-degrees, so that it is only considered as one element of a modular system. For the resolution required, the simple aperture will be large enough so that diffraction phenomena are negligable. Aberrations are of trivial simplicity so that it is the easiest optical system to analyze. An array of detector elements lying in a plane behind the aperture provides a convenient method of reading out lamp position.

One disadvantage of this simple scheme is that the image of an intruder's lamp may lie between two elements of the array, so that both show the aircraft to be in their fields of view. This problem does not appear to be easy to overcome.

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*To within a factor cos θ, with θ the angular displacement of the incoming rays from the optical axis.

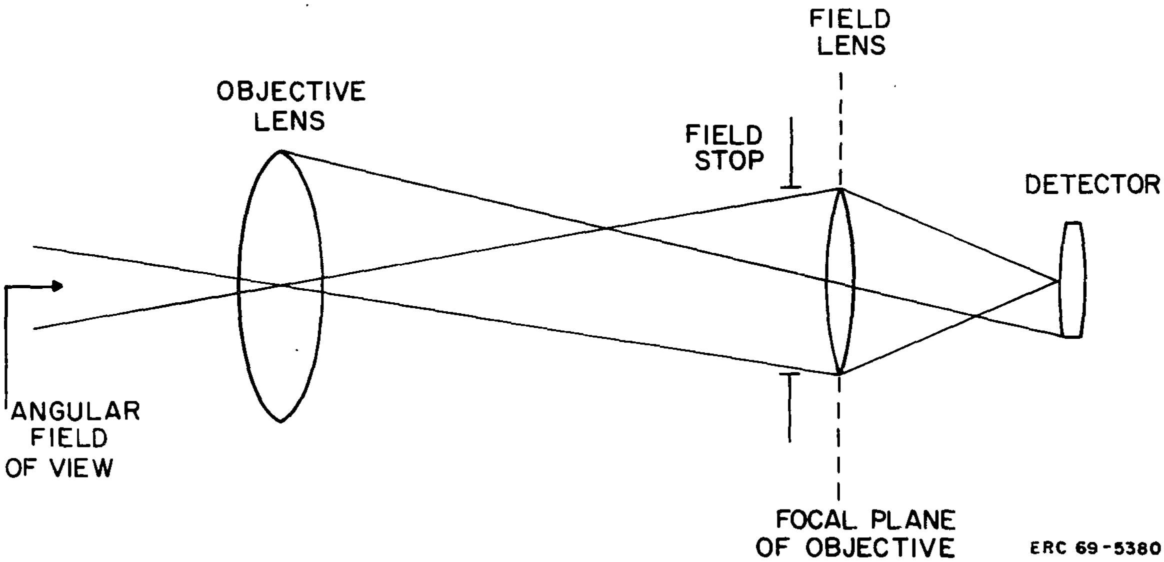

Figure 21d. - Field lens optical system

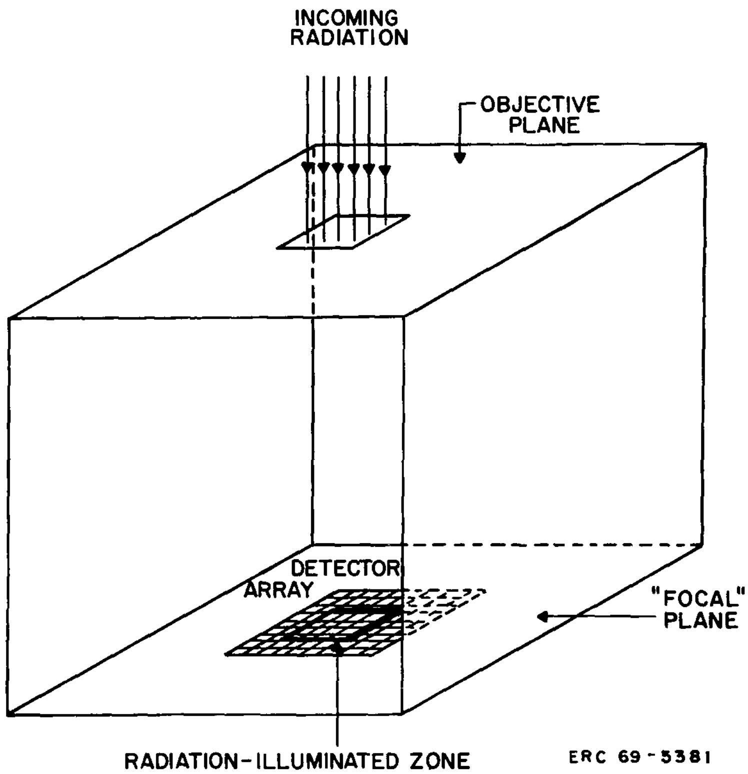

Figure 21e. - Single-aperture optical system

One additional system, the one-dimensional binary readout receiver, has been investigated. The optical elements required for this receiver are either a cylindrical lens or a slit aperture. In both cases, a long thin image is formed which is then processed by a detector. This will be described in the next section. The field of view of either slit or cylindrical lens is less than 180 degrees and is one-dimensional. An array of at least four optical system-detector packages would be required to cover a 2π-steradian field of view.

Detector Configurations

Both spatial multiplex and multielement detector configurations have been investigated for the PWI receiver. One example of a spatial multiplex sensor is the four-lead photoconductor (ref. 35), (or variations thereof) shown in Figure 22a. The four-lead photoconductor is unsuited to this application because of its propensity for collecting sky background. Another monolithic detector which would segregate events according to their location within the whole field of view is the image-dissection photomultiplier and its variants. As mentioned above, these have been eliminated from further consideration because of cost expectations.

One simple detector system is an assembly (perhaps discrete) of individual detector elements on a single substrate. This method of fabrication is fairly simple, since PWI operational requirements on resolution are not excessive. A typical detector array of this kind is schematically illustrated in Figure 22b.

A detector configuration suited to the one-dimensional lens systems, the binary array, has recently received some attention (ref. 36). Figure 22c shows a typical example of a four-strip detector over which a photomask has been superimposed. A point target is imaged by the cylindrical lens as a line element transverse to the long dimension of the array. The photomask is arranged so that 2^n (n = 4 is the case illustrated) separate binary indications are realized in the outputs of the n detector strips. The advantage of this approach is that it provides potentially very high resolution with few parallel channels. When combined with a slit or cylindrical lens, the field of view can be as large as 100 arc-degrees with reasonably uniform received flux over the entire field. It will be shown that excess background flux is a problem with this system. Also, since only one-dimensional optical gain is experienced, the signal flux levels are relatively low for comparable mechanical packages, as compared with (for instance) the two-dimensional array.

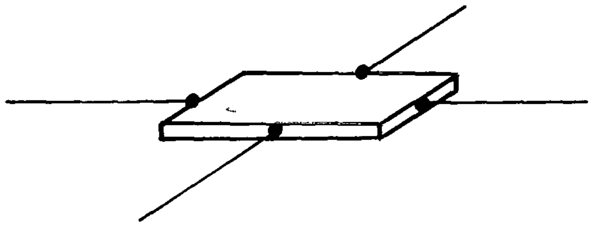

Figure 22a. - Four-lead photodetector

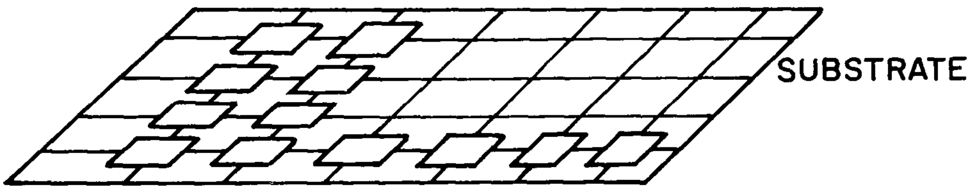

Figure 22b. - Detector fabricated from discrete elements

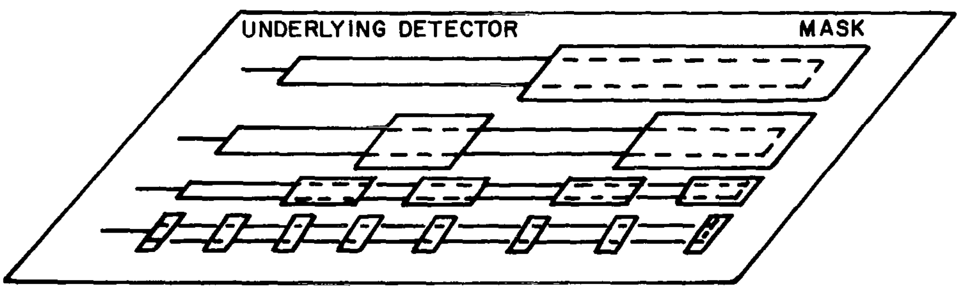

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Figure 22c. - Four-strip masked binary detector assembly

Background Collection

The previous sections of this report dealing with optical system and detector configurations have referred to the unsuitability of devices which collect excess background radiation. This section provides an explanation. In the sample analysis presented below, it is shown that shot noise arising from background radiation is a dominant source of noise for a PWI system which must detect aircraft-borne flash lamps against a sky background containing clouds. Each proposed configuration of detectors and optics will be characterized meaningfully by both the signal collection efficiency and a background collection efficiency.*

The worst background collector is easily shown to be the combination of sky lens and four lead detector. Consider the case of detection of one airplane with a 2π-steradian total field. Only one (almost elementary) area of the detector will be irradiated with signal flux. However, the whole area of the detector will receive background. Baffling will only restrict signal flux arriving at other spots on the detector from other aircraft, if present.

An intermediate case is that of the binary detector, as illuminated by either a slit aperture or a cylindrical lens. Although the background solid angle seen at the detector is very much greater than the signal solid angle, there are n elements, each of which sees less background than the four-element detector sees, since the total collecting area is less.

The best case is that of individual detector elements, each of which is illuminated by its own lens. Each of the parallel channels collects minimum sky noise consistent with the constraint that it detect signal presence within only a given angular resolution cell. An underlying dependence must be observed, however. For a fixed total optical system aperture, dividing up individual cells as finely as possible leads to ever-decreasing signal and background flux collection for each cell as the aperture of each lens tends toward zero. The cost and complexity of a post-detection signal processing increase and noise sources, other than background-induced shot noise, will eventually predominate.

Although arguments of the sort presented above may be reliably used to exclude detector-lens combinations which are extremely unfavorable, the best test of a proposed configuration

*As discussed below, both signal and background magnitudes must be known, since background-induced shot noise must be compared to other noise sources.

is a complete signal-to-noise analysis. The equations for performing this analysis are presented in the next section, while a sample calculation completes the discussion of receiver design.

Signal-to-Noise Analysis

The analysis presented here follows the form given in Jamieson et al (ref. 37). The symbols employed, in approximate order of occurrence, are presented in Table III on the following page.

Jamieson's convention on responsivity notation is followed throughout this analysis. The detector responsivity $S(\lambda,f)$ is assumed to be factorable into

$$S(\lambda,f) = S_{f_o}(\lambda)\left[\frac{S_\lambda(f)}{S_{\lambda,f_o}}\right]$$

according to which time response and wavelength response are mutually independent. The factor in brackets is wavelength-independent, the subscript λ serving to point out that it may be measured at any reference wavelength. It is equal to unity at f_o. In the analysis presented below, a departure from convention has been made in that detector impedance, load impedance, and amplifier input impedance have been lumped together in the equivalent circuit which has been taken to define the bracketed factor.

The peak signal current i_p which would be generated by the detector in the case of an arbitrarily fast detector time response is given by the following equation:

$$i_p = \frac{k_t k_d A_o}{R^2}\int_0^\infty J(\lambda)k_a(\lambda)F(\lambda)S_{f_o}(\lambda)\; d\lambda$$

where k_t is transmission of the optics, k_d is a detector mismatch factor, A_o is the collecting area of the main lens, R is the range, J is the lamp intensities, k_a is the atmospheric transmission, and F is the filter function.

To allow for the finite response time of the detector, the output pulse peak height factor k_o is calculated for a peak-normalized input x(t) which is the lamp radiance pulse shape. When recalling that the lamp fires periodically, with period T_1, the Fourier series coefficients $X(f_n)$ may be given as

TABLE III
SYMBOL DEFINITIONS

λ	wavelength, micron
f	frequency, Hertz
$S(\lambda,f)$	wavelength-dependent response, amp/watt
$S_{f_o}(\lambda)$	wavelength-dependent response, amp/watt
$S_\lambda(f)$	frequency-dependent response, dimensionless
f_o	a reference frequency, Hertz
S_{λ,f_o}	normalizing constant, dimensionless
i_p	peak signal photocurrent, amp
k_t	transmission factor of optics, dimensionless
k_d	factor to account for mismatch of detector area and image area, dimensionless
A_o	collecting area of primary optics, cm^2
R	ange, cm
J	lamp peak spectral radiant intensity, watt/(ster-micron)
k_a	atmospheric transmission, dimensionless
F	filter transmission function, dimensionless
X	Fourier series coefficients of lamp pulse, sec.
T_1	Repetition period of the pulse, sec.
t	time, sec.
x	lamp pulse time variable, dimensionless
f_n	Fourier frequency, Hertz
N	Fourier harmonic number, dimensionless
o	output pulse time variable
k_o	output pulse peak height factor
h	impulse response of matched filter, sec^{-1}
R_e	equivalent resistance, ohm
R_L	load resistance, ohm
R_j	junction resistance, ohm
R_a	amplifier input resistance, ohm
C_j	junction capacitance, farad
C_a	amplifier input capacitance, farad

C_e	equivalent capacitance, farad
$\langle V^2{}_{th}\rangle$	total mean square thermal noise voltage, $volt^2$
k	Boltzmann's constant, joule/Kelvin
T	temperature, deg. Kelvin
$\langle V^2{}_{sh}\rangle$	total mean square shot noise voltage, $volt^2$
I_o	junction dark current, amp
I_B	background-generated current, amp
e	charge on electron coulomb
$\langle V^2{}_A\rangle$	total mean square amplifier noise voltage, $volt^2$
i_a	amplifier current noise, amp/$(Hertz)^{1/2}$
e_a	amplifier current noise, volt/$(Hertz)^{1/2}$
A_D	detector area
Ω_B	field of view through which the detector views background flux, ster
B	background spectral radiance, watt/(cm^2-ster-micron)
N_o	effective noise contribution, amp/(cm^2-ster)
A	peak power, watt
b	effective time over which pulse is non-zero, sec.
J'	averaged lamp spectral radiant intensity, watt/(ster-micron)
λ_o	averaging central wavelength, micron
H_λ	background irradiance, watt/cm^2
Ω_{FOV}	field of view of primary optics, ster
$\langle V^2{}_T\rangle$	total mean square noise voltage, $volt^2$
H	fourier transform of impulse response, dimensionless
ρ_c	cloud total hemispherical reflectance, dimensionless

$$X(f_N) = \int_{-T_1/2}^{T_1/2} x(t)e^{-2\pi i f_N t}\,dt$$

where $f_N = N/T_1$. The output pulse from the preamplifier-matched filter network will be

$$o(t) = \frac{1}{T_1}\sum_{N=-\infty}^{\infty} \frac{S_\lambda(f_N)}{S_{\lambda,f_o}} H(f_N)X(f_N)e^{2\pi i f_N t}$$

where $H(f_N)$ is the Fourier transform of the impulse response of the matched filter-preamplifier combination.

The signal out of the matched filter-preamplifier will be proportional to $i_p o(t)$, the constant of proportionality being dependent on the mode of preamplification. In the equivalent circuit used below, this constant is R_e. Then, if the peak value of $o(t)$ is denoted by k_o, the peak signal power is $k_o^2 i_p^2 R_e^2$.

To perform the noise analysis, it was convenient to adopt a rather specific electrical equivalent circuit of the detector-preamplifier-matched filter, as shown in Figure 23*. By reference

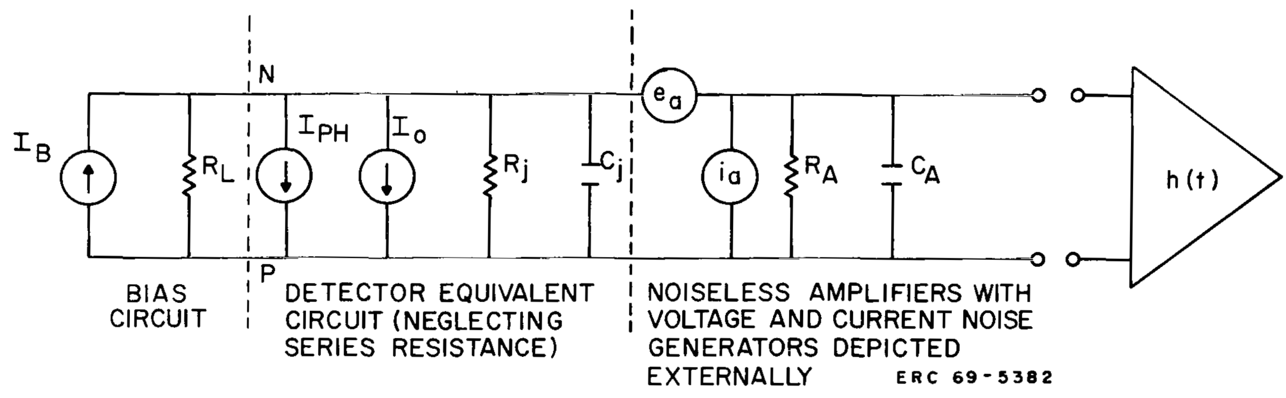

Figure 23. - Equivalent circuit of a silicon detector with bias components and voltage amplification

*This is an appropriate circuit for a voltage-amplified silicon detector, as discussed by Williams (ref. 38).

to this figure, the detector responsivity time dependence is given in terms of detector, amplifier and load resistance values as

$$\frac{S_\lambda(f)}{S_{\lambda,f_o}} = \frac{1}{1 + j2\pi f R_e C_e}$$

with $\frac{1}{R_e} = \frac{1}{R_L} + \frac{1}{R_j} + \frac{1}{R_A}$ and $C_e = C_j + C_A$.

Two kinds of noises are present--thermal noise and shot noise. The thermal noise of the whole network may be written by inspection (ref. 39).

$$\langle V^2{}_{th}\rangle = 4kTR_e^2\left[\frac{1}{R_L} + \frac{1}{R_j}\right]\int_o^\infty \frac{|H(f)|^2\, df}{1 + 4\pi^2 f^2 R_e^2 C_e^2}$$

The shot noise contributions arise in the junction dark current I_O and in the radiation-induced signal and background currents, the background current I_B of which is by far the greater source. The shot noise contributions are written

$$\langle V^2{}_{sh}\rangle = 2e(I_O + I_B)R_e^2\int_o^\infty \frac{|H(f)|^2\, df}{1 + 4\pi^2 R_e^2 C_e^2 f^2}$$

The amplifier noise, when uncorrelated noise sources are assumed, is given by

$$\langle V^2{}_A\rangle = \int_o^\infty \frac{i_a^2(f)\,|H(f)|^2\, df\; R_e^2}{1 + 4\pi^2 f^2 R_e^2 C_e^2}$$

$$+ \int_o^\infty \frac{R_e^2 e_a^2(f)\left[\left(\frac{1}{R_j} + \frac{1}{R_L}\right)^2 + 4\pi^2 f^2 C_j^2\right]|H(f)|^2\, df}{1 + 4\pi^2 f^2 R_e^2 C_e^2}$$

The convention of specifying amplifier noise sources (as has been done here) was standardized by Haus' committee (ref. 40).

A concise exposition of the theory is given by Nielsen (ref. 41). Note that Johnson noise in R_A appears as part of $i_a(f)$. The functions e_a and i_a are plotted as part of the manufacturer's specifications for the best documented low-noise amplifiers.

The only value not yet given to complete the analysis is the background current I_B. This is computed for a rather simple model in which the background radiance is assumed to arise wholly at a surface lying behind the airplane to be detected. This assumption allows one to avoid a complete analysis of the radiative transfer equation, which seems unwarranted in terms of the complexity of cases analyzed below. To be pessimistic, the background surface is assumed to lie near the intruding airplane, so that the same value of atmospheric transmission k_a applies to both signal source and noise source. Then:

$$I_B = k_t A_D \Omega_B \int_0^\infty B(\lambda) F(\lambda) S_{f_o}(\lambda) k_a(\lambda)\, d\lambda$$

where A_D is the detector area, Ω_B is the solid angle over which the detector sees background radiance $B(\lambda)$, and the other symbols are as presented in the signal discussion. It has been assumed that the background source fills the field of view of the system, a suitably pessimistic assumption for the relatively narrow field of view modules which are used in the illustration given below.

Two unspecified filtering functions have been included in the analysis, $F(\lambda)$ and $H(f)$. The former function is used to produce a maximum value of the signal-to-noise ratio as defined by

$$\left[\frac{S}{N}\right]^2 = \left\{ \frac{\left[\int_0^\infty J(\lambda) F(\lambda) S_{f_o}(\lambda) k_a(\lambda)\, d\lambda\right]^2}{N_o^2 + \int_0^\infty B(\lambda) F(\lambda) S_{f_o}(\lambda) k_a(\lambda)\, d\lambda} \right\} \cdot M$$

where

$$M = \frac{k_t k_D^2 A_D}{2e\Omega_B \int_0^\infty |H(f)|^2 \left[1 + 4\pi^2 f^2 R_e^2 C_e^2\right] df}$$

The numerator is the peak signal current, while the denominator is the sum of mean square noises caused by background-induced shot noise, plus the other noises, as lumped into N_o. Some insights on maximizing this ratio has been given by Eldering (ref. 42). In particular, he has shown that the optimum $F(\lambda)$ has either the value 0 or 1, depending on what specific λ_o is considered.

However, he has not given a method for choosing the set of wavelengths where the filter should have a value of unity, given $J(\lambda)$ and $B(\lambda)$.

The electrical filtering function $H(f)$ is also adjustable to maximize the ratio of k_o, the peak height factor, to the total rms noise. For the case in which the noise is entirely independent of frequency, one may use a result which is discussed in many treatises on matched filtering (refs. 43, 44). Extensions to the more realistic case are difficult, but some attempts have been made (ref. 45). For the estimate presented below the simplest filter function, the RC single roll-off low pass filter, has been chosen, but some additional research is warranted.

PWI Receiver - Sample Computations

The preceding mathematical analysis terminates in the formula for the power signal-to-noise ratio for a PWI receiver. It is appropriate to supply a set of trial values to establish feasibility.

Two cases have been considered for this evaluation corresponding to two different visibility conditions. The signal-to-noise ratio for one postulated receiver is analyzed under these two cases. Detection of an intruder whose range is 3 miles under visibility conditions, the lowest visibility under which VFR flying rules permit non-instrument flying, is desired. The postulated visibility and range allow choice of an atmospheric transmission for this case. Under these conditions, though, sensible background flux would originate at virtually all points along the path between the transmitter (the lamp) and the receiver. To avoid the difficult radiative transfer calculation which would be required to model this situation adequately, the background flux at the receiver has been assumed similar to that which would originate in a brightly sunlit cloud lying behind the aircraft, with the same value of atmospheric transmission assumed for cloud apparent radiance as for lamp intensity. The estimated atmospheric transmission for both cases is $k_a(\lambda) = 0.05$ in the wavelength region appropriate for the PWI detector. This value is applied to both signal and background fluxes. The second case has been called the "bright sunny day." In this case range is taken to be 5 miles, with visibility of 15 miles. The estimated infrared atmospheric transmission for this case is $k_a(\lambda) = 0.7$.

Other operational parameters assumed are: azimuthal field of view, 240 degrees; elevation field of view, ±20 degrees about the horizontal; and resolution element, 20 by 20 degrees, rectangular. As stated above, it was assumed that the background flux apparently originates in a cloud lying behind the airplane to be detected, and fills the 20 by 20 degree field of view of a single resolution element. The signal to noise ratio will be calculated for that resolution element.

The transmitter assumed is arrived at by hypothesizing the Eimac 150x8R arc lamp, with the following electrical and optical values:

Electrical input: 20 joules
Efficiency (optical output/electrical input):0.5
Radiating solid angle: 5.3 ster (corresponds to a "wedge of rotation" ± 25 deg in elevation by 360 deg in azimuth
Spectral characteristic: as given in the Eimac literature (see Figure 14, in which the spectral characteristic is one of the plotted curves)
Pulse shape: a typical shape and duration for other lamps tested* (see Figure 24, in which the pulse shape is one of the plotted curves)

An estimate of the peak power is obtained by performing the energy integral

$$10 \text{ joules} = A \int_0^b x(t)\, dt$$

where A is the peak power, since x(t) is a peak-normalized function. The calculation, performed digitally, yields A = 31,200 watts, from which it is possible to estimate the integrated value of $J(\lambda)$, since the solid angle is fixed at 5.3 ster:

$$\int_0^\infty J(\lambda)\, d\lambda = 5900 \text{ W/ster.}$$

Since the Eimac literature gives the fraction of the total optical output within each 0.005 micron frequency increment between 0.2 and 2.1 microns, enough information has been gathered to ascertain the absolute value of the smoothed version $J'(\lambda_o)$ which is given by

*The actual curve shown in Figure 24 was measured for the Honeywell ARLS lamp, but has been slightly smoothed.

$$J'(\lambda_o) = \frac{1}{0.005}\int_{\lambda_o-0.0025}^{\lambda_o+0.0025} J(\lambda)\, d\lambda$$

where the numbers quoted are in microns, the unit of λ_o. It is this function, $J'(\lambda_o)$, which has been plotted in Figure 14, with the units on the ordinate as given by the above normalizing analysis.

The receiver configuration which is treated here is similar to the one shown in Figure 21c, the multi-lens matrix. The proposed system is fabricated from 24 separate modules, each of which has a rectangular collecting aperture of 6 cm^2 area (length of a side is about 1 inch). A square-edged field lens (with 0.7 inch length of a side) defines the field of view and images the objective on the 1-cm^2 detector. This system is characterized by $A_d\Omega_B$ = 0.72 cm^2-ster. The inclusion of field optics allows the approximation $k_d = 1$.

The transmitter having been chosen and the receiver configuration having been selected, there is enough information on which to base the choice of a detector material. Choice of a detector material should be guided by some obvious precepts. For instance, to optimize background rejection, it is desirable to pick a detector for which $S_{f_0}(\lambda)$ overlaps the lamp radiance spectrum $J(\lambda)$, without significant overshoot on either short or long wavelength ends. Over the region of maximum lamp radiance, the detector should exhibit responsivity values reasonably near the theoretical maximum values. The electrical and optical properties of the detector should be temperature-insensitive over a wide range of outdoor ambient temperatures. The detector's intrinsic speed of response should be sufficient to reproduce the frequency spectrum of the lamp pulse. Finally, it is desirable to pick a material which has been exhaustively researched and is inexpensive.

The silicon photovoltaic detector meets these conditions, as will now be shown. Figure 14 shows the response curve $S_{f_0}(\lambda)$ for a selected silicon photovoltaic detector, plotted with the same abscissa as the function $J'(\lambda)$. At its peak the silicon detector shown has a quantum efficiency of 0.9, with reflection losses neglected. These data are representative of room temperature detectors, but apply with minor modifications to detectors at a wide range of near-ambient temperatures. It is felt that Figure 14 exhibits satisfactory adherence to the salient portions of the precepts given above.

Figure 24 shows the spectrum $X(f_N)$ of the pulse response $x(t)$ which was observed in the ERC laboratory, as previously

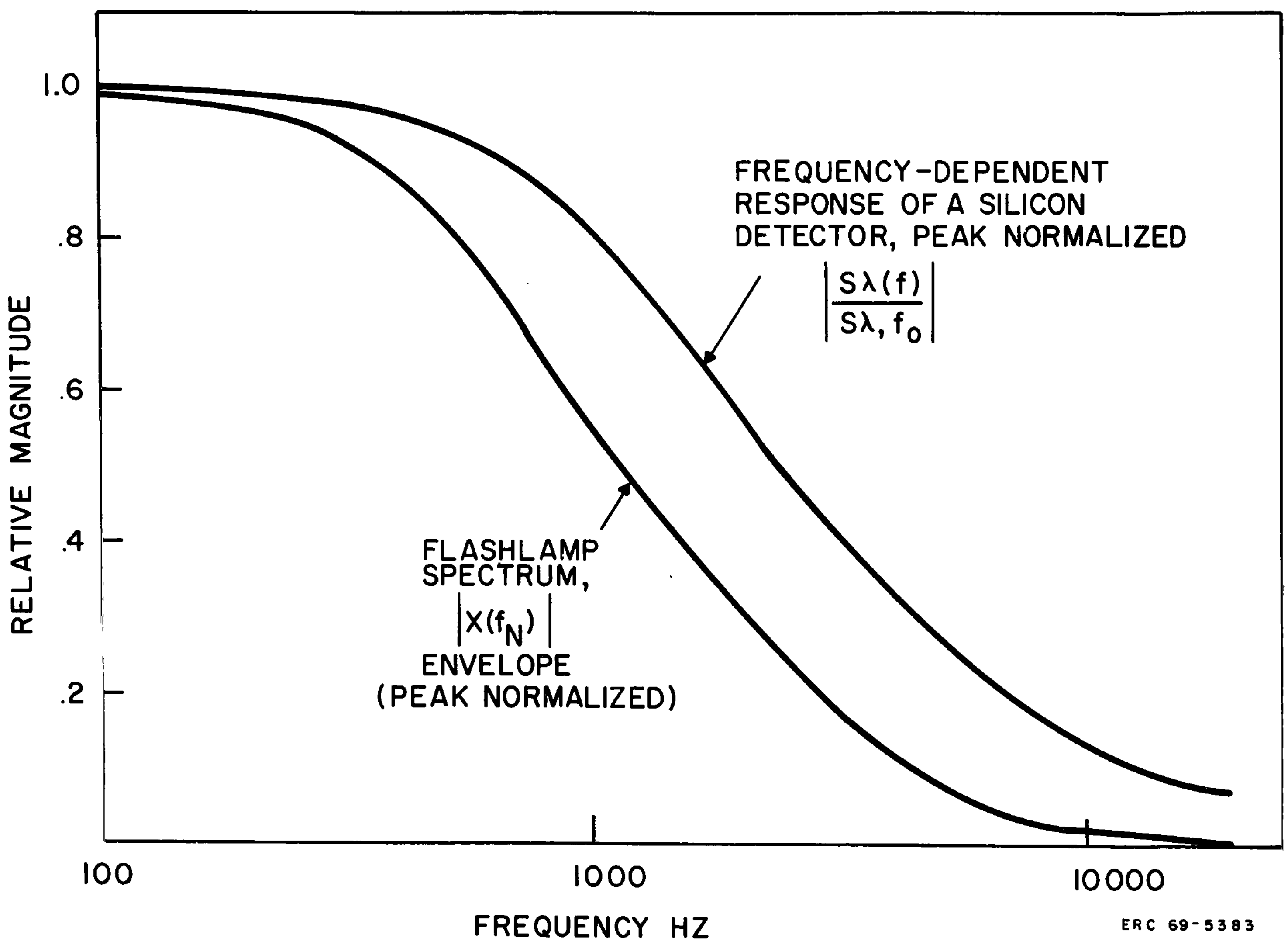

Figure 24. - Frequency-dependent response of a silicon detector and envelope of lamp flash Fourier components

mentioned. Sharing the abscissa with this spectrum is the function $S_\lambda(f)/S_{\lambda,f_0}$ of a selected silicon detector as amplified by an unfiltered preamplifier. The response time of the silicon detector itself is much faster than one might infer from this curve. The slow response has been deliberately chosen as a type of matched electrical filtering. The final precept, relating to cost and research understanding, is perhaps better satisfied for silicon than any other semi-conductor material. These factors have led to the adoption of silicon as the detector material.

For the purpose of calculation, a specific silicon photovoltaic detector has been chosen.* (A comprehensive paper has appeared, describing commercially available units of this type (ref. 38).)

The specification of detector characteristics allows estimation of the background and signal currents and their ratio. A spectral distribution for the background flux has been adopted from Gates (ref. 46). It is assumed that the cloud will redirect solar energy incident upon it uniformly into π steradians, with a diffuse reflection coefficient ρ_c. Referred to the solar irradiance H_λ given by Gates, the reflected energy redirected into the receiver will be

$$B(\lambda) = \frac{\rho_c}{\pi} \Omega_{FOV} H_\lambda$$

where Ω_{FOV} is the solid angular field of view of the receiver= 0.12, and ρ_c is estimated as = 0.75.

The choice of an optical filter function was made in a very simple manner. It is known from Eldering's treatment that the optimal filter function has either a transmission of 0 or 1. It is suspected that interference filters may be too expensive to be included in the system. Since plastic filters with a sharp cuton characteristic may be fabricated inexpensively (ref. 47), the following filter function was chosen:

$$F(\lambda) = 0 \qquad \lambda < \lambda_c$$

$$F(\lambda) = 0.75 \qquad \lambda \geqq \lambda$$

*R.C.A., Ltd., Montreal, Canada

This is a fair approximation to the shape of the filters described in reference 47. For background-limited conditions, the optimal value of λ_c was computed by maximizing the S/N ratio and is given by

$$\left[\frac{S}{N}\right]^2 \approx \frac{\left[\int_{\lambda_c}^{\infty} J(\lambda) S_{f_o}(\lambda)\, d\lambda\right]^2}{\int_{\lambda_c}^{\infty} B(\lambda) S_{f_o}(\lambda)\, d\lambda}$$

This is proportional to the power signal-to-noise ratio when shot noise caused by the background current is the dominant noise source, a good approximation in this case. The value which results from this computation is $\lambda_c = 0.82$ micron.

The electrical filter function was also chosen to have a simple form. It was decided to set the frequency response H(f) above 140 Hz equal to that of a single RC filter with RC = 2.5×10^{-4} sec. and with sharp cutoff at frequencies below 140 Hz. The low-frequency cutoff is provided to decrease the response of the system to 60 and 120 Hz interference from stationary sources on the ground. This response is separate from the single RC response time of the detector which has been set at 1.15×10^{-4} sec. That detector response, shown in Figure 5, can be achieved by a detector with the following characteristics (ref. 38):

Resistivity:	200 ohm-cm
Hole mobility:	400 cm^2/(volt-sec)
Bias voltage:	5 volts reverse, minimum
Area:	1 cm^2
Dark current:	1 microamp

The actual bias voltage (when voltage amplification is assumed) must be somewhat greater than 5 volts, since background-generated photocurrent operates to forward-bias the cell. Generous allowance for that effect will be made if bias voltage exceeds (by at least 5 volts) the value $I_B R_L$. In the case of maximum background flux, it will be shown that bias voltages of about 8 volts are realistic.

The amplifier and load resistor characteristics chosen were:

R_A = 10 megohms

$C_A = 10$ pF

$R_L = 10^5$ ohms

$i_a(f) \leq 0.4$ pA/$\sqrt{Hz}$ } overall frequencies greater than 100 Hz.

$e_a(f) \leq 30$ nv/$\sqrt{Hz}$

Detector capacitance for the cell quoted above will be about 1150 pF so that C_A is negligible, as is R_A. A reasonable value for R_j is 5 megohms (ref. 36).

Estimates of the magnitudes of case-independent noise voltages are:

$<V^2_{th}> = 0.86 \times 10^{-12}$ volt^2

$<V^2_{sh}> = 1.64 \times 10^{-12}$ volt^2 (for dark current I_o only)

$<V^2_A> = 1.58 \times 10^{-12}$ volt^2

In case 1, a summary of the values adopted is:

$k_t = 0.5$

$k_d = 1$

$A_o = 6$ cm^2

$k_a = 0.05$

$R = 4.8 \times 10^5$ cm (3 miles)

$A = 5900$ W/ster

$A_D\Omega_B = 0.72$ cm^2-ster

$\Omega_{FOV} = 0.12$

$\rho_c = 0.75$

These values, taken together with the results of the numerical integration program which evaluates

$$\int_{0.82}^{\infty} J(\lambda)S_{f_o}(\lambda)\, d\lambda ,$$

give i_p = 600 pA. The background shot noise is determined from the background current, the above values and the results of the numerical integration:

$$\int_{0.82}^{\infty} H_\lambda(\lambda) S_{f_o}(\lambda)\, d\lambda \ ,$$

The background shot noise (given 2 μA background current) is calculated to be

$$\langle V^2_{sh} \rangle = 3.3\text{x}10^{-12} \text{ volt}^2 \text{ (background current only).}$$

Thus, the total noise voltage $\langle V_T^2 \rangle$ is determined by summing the squares of each of the individual noise contributions

$$\langle V^2_T \rangle = 7.38\text{x}10^{-12} \text{ volt}^2.$$

The factor k_o is estimated to equal or exceed 0.5. With these values the total signal-to-noise power ratio is

$$\left[\frac{S}{N}\right]^2 = \frac{i_p^2 k_o^2 R_e^2}{\langle V^2_T \rangle} = 115.$$

In case 2, the only values changed are k_a = 0.7 and R = 8.0x 10^5 cm (5 miles). The resultant numbers are:

$$i_p = 3000 \text{ pA}$$

$$I_B = 28 \ \mu \text{A}$$

$$\langle V^2_{sh} \rangle = 46\text{x}10^{-12} \text{ volt}^2$$

$$\langle V^2_T \rangle = 50\text{x}10^{-12} \text{ volt}^2, \text{ and}$$

$$\left[\frac{S}{N}\right]^2 = \frac{i_p^2 k_o^2 R_e^2}{\langle V^2_T \rangle} = 420.$$

In these conditions of high background current, the bias voltage required will be $R_e I_B$ = 2.8 volts. However, if -5 volts bias must be exceeded at all times to maintain the specified capacitance of the diode,* a bias voltage delivered from about an 8-volt source should be sufficient.

*Diode capacitance is a function of bias voltage (ref. 38).

VI. POST-DETECTION ELECTRONICS

Post-detection electronic processing components include a preamplifier, a threshold detector, a blanking circuit to forestall being electronically blinded by one's own flash, and a power source.

To this category might be added a self-test circuit, although the implementation of an efficient device in this regard is not altogether a trivial matter. These four or five functional units are important from a cost consideration, of course, especially when it can be seen that three of them would be essential in each of many detector channels in a segmented-view detector system.

This section will present an exposition of a few of the more subtle aspects of signal processing.

Linear Filtering

The concept of the matched filter as developed by North (ref. 48) and elaborated upon by Turin (ref. 49) and others is one that would seem to fit well in the framework of the optical PWI. The use of a matched filter in a signal and noise situation guarantees optimum reception. But what are the compensating restrictions in its use? First, the transmitted signal waveform must be known, because the filter will be "matched" to it. Second, not all filters meeting the first criterion are readily realizable, except at great expense through delay lines and other exotic techniques. In fact, Turin points out that it may be easier to look for a signal or waveform that matches a given realizable filter than the other way around. Third, the frequency response, H(f), of the filter is necessarily a function of the noise spectrum shape to which it is subjected.

In terms of optical PWI service, it can surely be stated that the transmitted signal is known (see Figure 3). Insofar as it is considered to arise from the linear discharge of an RLC circuit, the appropriate expressions for the waveform can be written. The physical realizability of the matched filter for this waveshape has not been investigated in any detail. Mr. A. Devaney of ERC suggests a complementary RLC circuit with the required negative resistance to be supplied by a tunnel diode. The options of lamp waveform modification have not been explored to any extent. More importantly, no hard evidence exists on the relative strengths of the white noise background versus clutter. The spectrum of the latter, the ERC group feels, will be only coincidentally flat.

These information gaps prevent pursuit of this subject to a detailed circuit-type of answer presently. Very likely the first system synthesis at ERC will see the incorporation of any one of several "practical" filters, the performance of which for elementary waveshapes, at least, is not seriously degraded from that of a matched filter (ref. 50). The optical range discussed in the section on Atmosphere and Backgrounds, should be useful for final "trimming" on the filter in an actual fading and false-alarm environment.

Non-Linear Filtering

A pulse-width filter, built on one of several possible logic principles, would be desirable for sorting false alarm signals, particularly clutter-derived ones. These signals will unavoidably reach peak heights larger than any reasonable threshold setting, so their rejection is most effectively accomplished on a pulse width basis. One must remember, however, that the output from a truly matched filter is <u>not</u> a replica of the input signal--it is more peaked in shape. Presently the relative advantages of these forms of linear and non-linear filtering in the PWI situation are not clearly defined, nor is the method by which they can most effectively be combined. The incorporation of an efficient pulse-width filter, even if it means sacrificing some of the matched filter S/N gains, appears desirable.

The circuitry for a pulse-width (P-W) filter probably could be as well employed to regenerate the received pulse into a standard width-height unit for subsequent processing. This operation, of course, would ease the pulse acceptance tolerances in this processing. One conceptual form of the P-W filter, plus regeneration, is shown in Figure 25. A time slot width of $t_{nominal}$ = ±20 percent (the ±20 percent, covering all time perturbations whether caused by propagation, construction, lamp timing, etc.) should be achievable.

Signal Processing

The final order of business for the post-detection electronics is the making of a decision--intruder or not? Decision-making is a form of filtering and this subsection might, in this light, be incorporated with the previous subsection. However, some special situations are expected to arise in any operational PWI and it is pertinent to treat them at some length, even if full and adequate solutions for them may not yet be in hand. Three cases are cited below as situations in point.

<u>Case 1</u>: An intruder aircraft flying radially away from the subject aircraft so that it remains in one detector view cell (for simplicity) will eventually reach a range such that the

pulses are received only intermittently. At first, only occasional pulses would be dropped; then the 50/50 situation is reached; and eventually only occasional pulses are received. A PWI not capable of coping with this case would unduly tax the pilot with fresh alarms from this segment as the aircraft range opened up; that is, each dropout and subsequent pulse reception would appear as a new aircraft.

Case 2: Although in a moderately-finely-segmented field of view PWI the chance incidence of two (or more) aircraft within one detector view cell is rather small, it would be desirable to call attention of the pilot to this fact. The cell boundaries are large enough and windshield posts are wide enough to hide a real threat aircraft when the pilot makes visual and mental acknowledgement of the PWI alert of a more obvious one.

Case 3: This case can be conveniently referred to as the cell boundary crossing problem. A recognized intruder aircraft about to cross into view space of an adjacent cell, will normally be present on both cell displays, at least for a short while. (The view spaces must be made to overlap slightly.) Should the audio alarm ring as for a new aircraft? It would, of course, if steps to prevent it are not taken. The extra cell display could confuse the pilot as to the number of threats if he had not been paying attention to the trajectory of that particular aircraft. Aircraft trajectories could (less often, to be sure) take them to the "four-cornered boundary" of a PWI, one with segmentation in elevation as well as in azimuth. Now three extra lights go on!

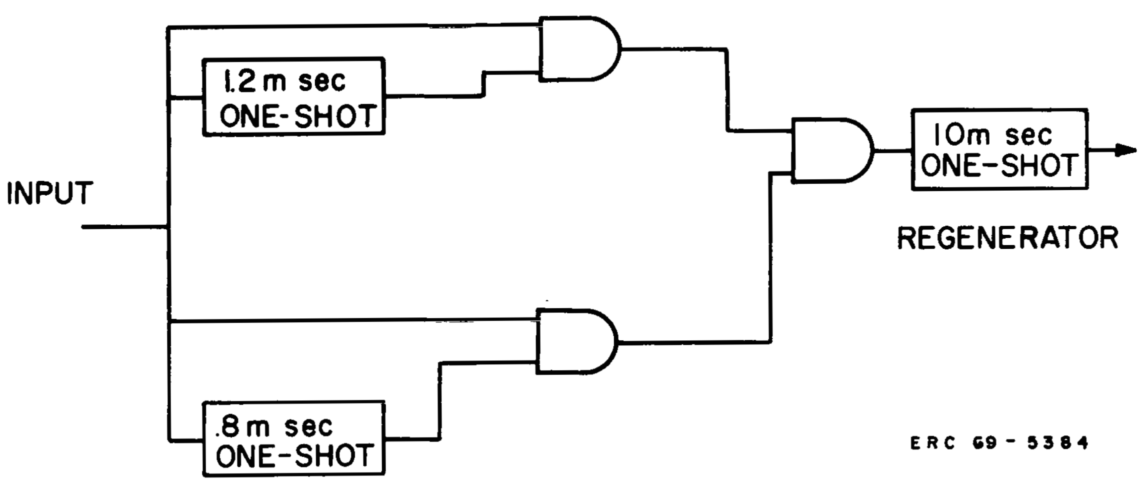

Figure 25. - One form of a pulsewidth filter plus regenerator

A combined solution for cases 1 and 2 might be worked out as follows. Consider a capacitor that receives the fixed-size (and, hence, the fixed charge) pulse from the pulse-width regenerator. The only variable then is the frequency or rate at which the pulses arrive. If the capacitor discharge rate is set properly and if certain thresholds are set at correctly chosen levels of stored voltage, an interesting pattern of operation is achieved.

In Figure 26, five consecutively received pulses building the stored charge to its asymptotic value are shown. This might arise from a reasonably near aircraft climbing, and thus passing through one of the PWI cells; the nearness ensures no dropped pulses for the sake of this argument. The pull-in threshold would operate immediately after reception of the third pulse (2 seconds) and the display would be correspondingly energized. At the same time, the dropout threshold relay would also be energized, ensuring reception of this aircraft through missing pulses, as shown to the right of the figure. On the occasion of three successive missing pulses (or probably a sequence of 00 x 00) the threshold relay would release, and the circuit would stand for the next cycle.

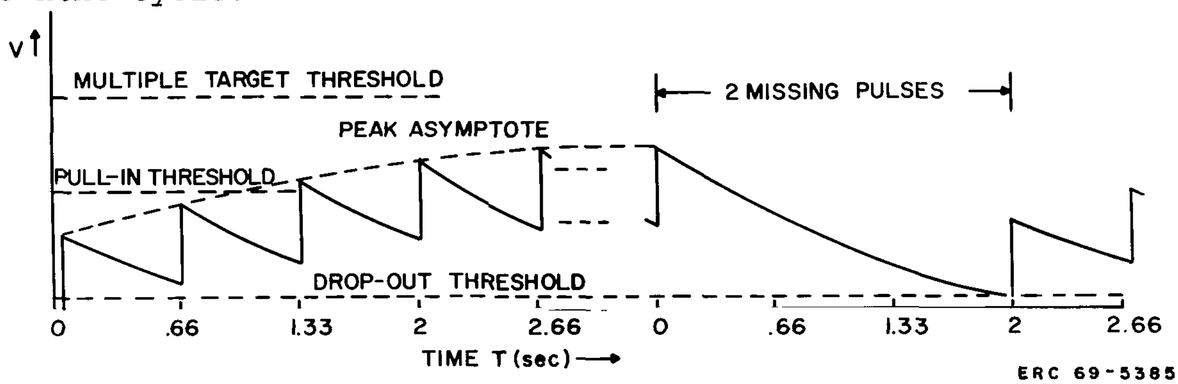

Figure 26. - Hysteresis decision circuit as part of the signal processing

It is clear that a great deal of hysteresis has been built into the device, and of course, that is the prime intent. There is very little likelihood of the circuit recapturing a range-opening aircraft; this would call for the reception of three consecutive pulses (for the shortest possible time of capture) or some longer combination of pulses and dropouts favoring the pulses.

As for the case of two intruders in the same cell, the charge will be deposited at approximately twice the rate shown, the voltage will reach the multiple target threshold again in about 2 seconds, and a special display function will apprise the pilot of the need for additional diligence in this sector.

The device has filter and limiter properties, of course. Random or chance signals can only put a fixed quantity q of charge on the capacitor, no matter what the size of the disturbance. All repetitive signals of a frequency lower than about $0.7\ f_{PWI} = 0.7 \times 1.5 = 1.05$ Hz, would fail to place charge rapidly enough to energize the pull-in threshold. The device can perhaps best be regarded as a moving averager, that is, it remembers what happened in the past two or three intervals and weighs this history in proportion to its proximity to the present.

The solution for case 3 would seem to call for some form of a coincidence circuit linking all adjacent cells pair-wise. Reception of synchronously occurring pulses (to within 10 microseconds, perhaps) in the two cells could be made to inhibit the audio alarm at least. Whether further refinement would be useful to inhibit the illumination of both displays is somewhat of an open question at present. In the form of display linked directly and synchronously to the distant aircraft flash, some of the processing may then be transferred to the pilot in that he should recognize the flash synchrony in the two cells. Of course, the pilot can also joggle the plane slightly to resolve the ambiguity too. The ERC task force believes it is essential that the audio alarm be muted, in any case.

The basic philosophy in effect here is the emphasis on circuitry or methods to ensure the activation of one alarm, and only one alarm, per aircraft, no matter where the intruder's subsequent flight path may take him. The traffic density now, and particularly in the immediate future (say, 2 to 5 years), is such that the PWI designer could well forego the last measure of range capability, for example, to deal more effectively with the false alarm problem in this aspect as well as in its other facets.

Signal processing interest extends to several other germane issues, the treatment of which will necessarily be deferred at this time. This list includes, as a minimum, an elaboration of the range sorter and adaptive threshold circuit discussed briefly in the Atmosphere and Background section, the understanding and synthesis of a possible matched filter that treats the pulses in groups of threes to conform with the operation of the aforementioned capacitor charge-threshold selection device, and the calculation of detection and false alarm probabilities using the data from previous sections in conjunction with the elegant formalism derived for radar practice (ref. 50).

VII. DISPLAYS FOR A PWI SYSTEM

As the number of aircraft in the air has increased, so have the number and complexity of instruments on the pilot's instrument panel. The crush of terminal traffic has occasioned added difficulties. Now the pilot must perform more work than formerly in the same amount of time. His increased total workload, moreover, may require more time than would be expected by simply adding the times required for performance of all the separate component tasks, for it has been found that when identical behavior sequences are performed as part of a compound task, they require longer than when performed alone (ref. 51). Therefore, under present conditions where an overload on the pilot is being approached, it is crucial to avoid further compounding of his task.

A major problem in the pilot's control task is the efficient division of his attention so that he maintains visual surveillance outside the craft while concomitantly monitoring the display panel inside the craft. In some cases, instrumentation merely introduces interference between the pilot and the real environment. Thus, because instruments are "noisy," in some cases the ideal display may be the real world. In general, however, the most important and pertinent aspects of his surroundings are best made available to the pilot by means of displays. An ideal display is one that provides necessary information to the pilot with optimal accuracy and reliability, such optimum to be measured in terms of the total system performance. Usually, the display either (1) measures and holds the data in available form, or (2), accomplishes some part of the pilot's processing of information by encoding and chunking data.

Warning indicators, however, comprise a unique category of displays. In addition to presenting data, a warning display must gain the attention of the controller and yet must focus that attention away from the display itself and toward the source of imminent danger. Furthermore, a collision warning device installed in the cockpit of an aircraft flown by visual contact must guarantee the rapid response of the pilot to this source of danger. Moreover, usually the pilot is heavily loaded with primary flight control tasks at the very times he must be most vigilant to collision threats. An apparent dilemma confronts the designer of a display that must attract, yet not fixate, the pilot's attention. The impasse may disappear, however, if (1) the pilot can do two things at once, i.e., acquire information from both inside and outside the cockpit at once, or (2), the pilot can do two things alternately at adequate rates, i.e., acquire information alternately from inside and outside the cockpit. Given a mobile system in a mobile environment, the basic question concerns the amount of warning time constituting a comfortable, or at least a safe, margin for the pilot.

No simple measure is available. At an FAA symposium on pilot warning instruments held in December 1967 (ref. 52), a warning time of "3 miles plus 30 seconds" was recommended. When aircraft speeds were taken into account, the minimum warning ranges recommended were 2 to 3 n. mi. for aircraft speeds of 150 kts and 5 to 6 n. mi. for aircraft speeds of 300 kts (ref. 52, p. 160).

It is expected that the most distant targets to be picked up by the sensors of the proposed PWI system would be displayed some seconds before the pilot could have detected the aircraft visually. The relation between the times of pick-up of the target by the instrumental PWI and the pilot are variable and depend on such factors as aircraft cross-section, weather, and time of day. A mean value of 2 seconds may be designed; that is, after the display of a signal in this system, it is hoped that the aircraft will be visible in 2 seconds or less.

The lag time of the pilot in utilizing such a display depends on several factors. Gross lags are caused by detection, decision-making, and motor response. These processes all interact, but since a display involves detection primarily, lags in the latter process are of major importance. Lag times in the detectional process, or perhaps more accurately in the predetectional process, are made up of time required for shifting from one input source to another plus times for transmission of input from the sensory organ to the cortex, an interval for vision of 30 to 35 msec and for audition of 5 msec. Man appears to be a single-channel mechanism: he can attend to only one signal at a time (refs. 53, 54). Broadbent concludes that a definite time lapse ensues when attention shifts from one input source to another (refs. 55, 56). In a series of experiments, there is evidence that some periodic mechanism drives the switching of attention and limits its occurrence to once every 124 msec (ref. 57).

It is claimed that such gating of input holds (1) for shifts between different aspects of the same input source, (2) for shifts between inputs to different sense organs in the same sense modality, such as from one eye to the other or from one ear to the other, and (3) for shifts between inputs to different sense modalities, such as from vision to audition or from audition to kinaesthesis (ref. 58). Assuming that, on the average, a switch in attention <u>per se</u> will require 62 msec, or one-half the hypothesized periodic interval, then additional lag time will accumulate as the switch in attention involves shifts between sense organs or adaptation of sense organs to new conditions.

Evidence indicates that processing of inter-sensory input is less accurate than processing of intra-sensory input. Broadbent and Gregory (ref. 56) show that visual and auditory information alternately displayed is less accurately processed than is auditory information presented alternately to the two ears.

For completely visual input, the average time, with binocular vision, for shifting the point of fixation between near and far locations successively, in a task that includes visual acuity, recognition, and response is 1.06 sec (ref. 59). For accommodation and convergence alone, the averate time for binocular refixation of near and far stimuli is 0.20 second. The total time required to shift visual fixation from the environment outside a cockpit to an inside instrument and then back to the outside environment has been shown to exceed 2 seconds (ref. 60). It is clear that a saving of seconds at the point of display input to the pilot would be worthwhile. Moreover, since there is interaction from input to output, the saving in lag time could be cumulative.

This saving of seconds, however, has cost restrictions in terms of dollars. A gold-plated system will not be installed by the owner of a $12,000 aircraft. Although a projection display might be compatible with a large jet aircraft, sheer cost eliminates such displays in small planes. Yet to be of value, a collision-warning device must in due course be installed universally.

In addition to restrictions in cost, there are restrictions in the design of any device engineered for the total market. Such a warning indicator must be designed not only to fit into all aircraft currently being built but also to retrofit all kinds of aircraft. The PWI display must not interfere with existing cockpit instrument panels and must be compatible with projected aircraft cockpits.

Taking these restrictions into account, three designs have been developed: (1) the embedded matrix display, (2) the hedge display, and (3) the Dunlap auditory display.

Matrix Display

The matrix display (Figure 27) consists of a matrix of almost invisible wires embedded in the windshield. A grain-of-wheat lamp is installed at every intersection of the wires. The illumination of a lamp alerts the pilot and the location of the illuminated lamp indicates the location of the potentially dangerous aircraft. The pilot merely searches "through" the lamp in the projected cone area of his line of sight. Flashing is used to increase the likelihood of detection of the signal by the pilot. Imminent collisions could be indicated by increased rates of flashing or increased intensities of the lamp; that is, rates and intensity of flashing could be used to encode range information. An auditory warning device would normally be employed with the matrix display to provide the pilot with an initial warning alert and to enhance the visual signal. In the ERC test model, No. 36 wire was used for ease of installation in the simulated windshield. A wire size as small as No. 50 could be used

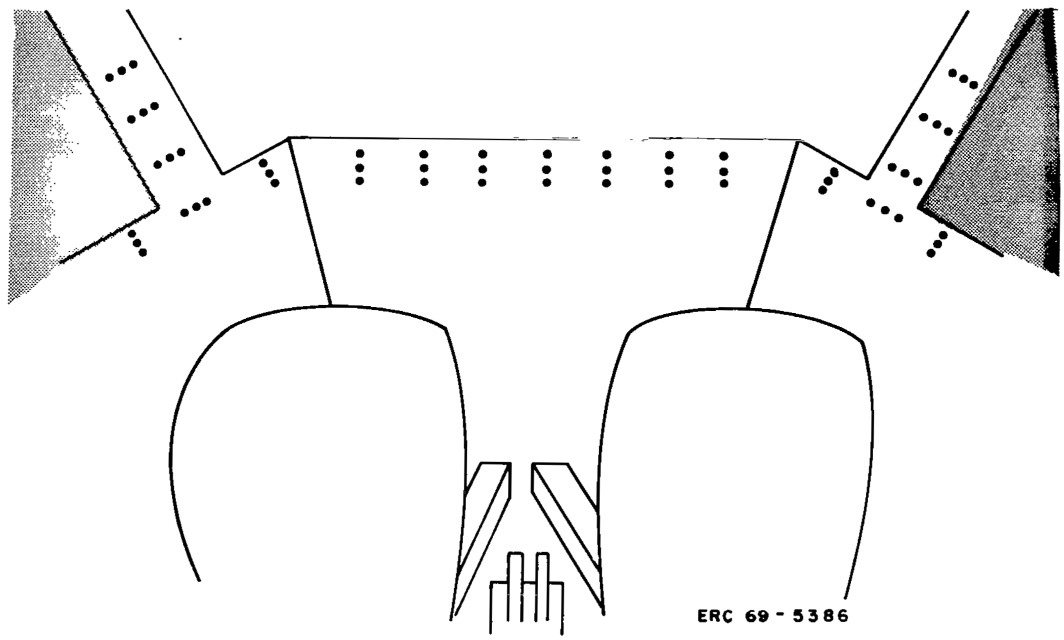

Figure 27. - The HEDGE display in the cockpit

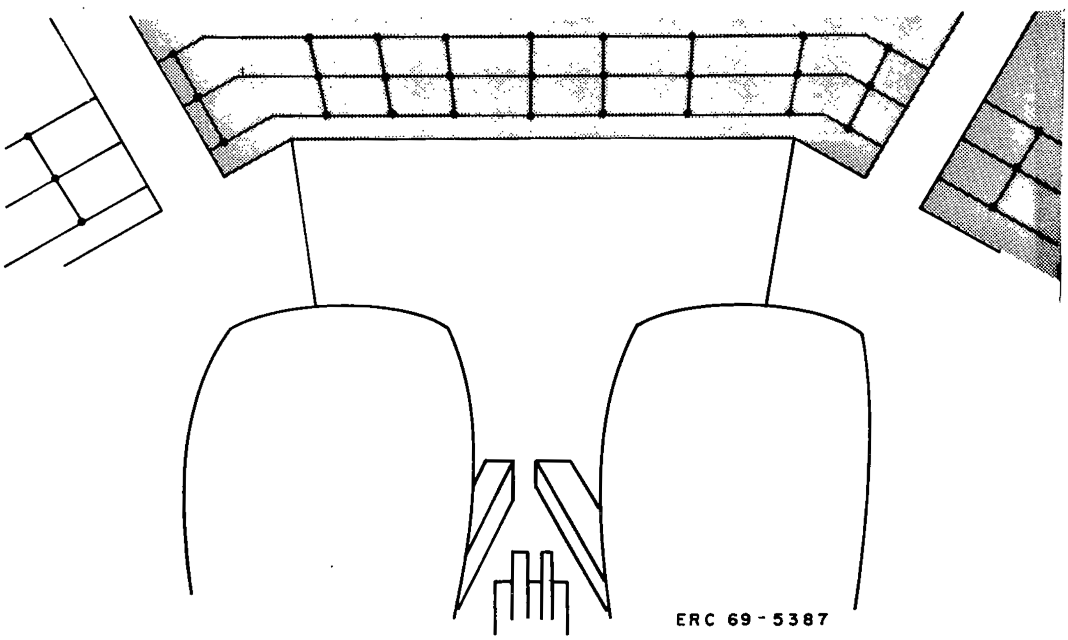

Figure 28. - The embedded matrix display in the cockpit

in the operational display. Once in production, the smaller size could be handled without difficulty. When the test model wires and lights were installed in a Piper Cherokee aircraft, the pilot experienced no interference in his surveillance of the environment. Since the windshield slants forward at the base, the distance from the pilot's eyes to the windshield varies from about 12 inches to the upper windshield, to 23 inches directly ahead, to 36 inches at the lower edge of the windshield. Lamps with a diameter no more than 0.030 inch are used. Thus, the ratio of windshield area covered by wires and lights is roughly 1/7000 and should not obstruct the pilot's field of view.

The HEDGE Display (Heads-up, EDGE-Lighted)

The HEDGE display consists of strings of lights in the periphery of the pilot's visual field, the horizontal string along the bottom frame of the windshield, and below the usual line of sight of the pilot, and the vertical string or strings to the side along the vertical frame(s) of the windshield (see Figure 28). A potential collision target is indicated to the pilot by the synchronous flashing of two lights, one on the horizontal x-axis and one on the vertical y-axis. The location of the potential collision target is in the area of a line of sight through implicit intersection of the coordinates of the two lights. The possibility of discriminating such an implicit target was tested by installing a simple HEDGE display in a Piper Cherokee. The pilot was able to indicate a "non-displayed" target with considerable accuracy and with no training. Only single pairs of lights were tested during this flight, and thus no multiple targets were displayed. To indicate multiple collision aircraft, the synchrony of pairs of flashes differs for every aircraft.

In the operational model, sets of three lights are used rather than single lamps, and increased directivity toward the point of intersection is effected by successive illumination of the lights, as in some car turn-signals. Also, successive illumination allows for the indication of potential collision targets outside the bounded area, that is, below the horizontal string of sets of lights or in back of the vertical string(s). In these cases, only one set of lamps would flash.

An auditory signal would alert the pilot whenever the number of aircraft within the area of his sensors increased. The number of beeps sounded could be made to correspond to the number of aircraft on potential collision courses.

Both these displays have multiple target capabilities, a prerequisite for this PWI system. Preliminary tests indicate that with the embedded matrix display, inputs of up to four collision targets can be detected. One problem with the HEDGE display is the possibility of occurrence of "ghosts" or imaginary targets at the points of intersection of a pair of unrelated horizontal-vertical lights. It is hoped that "ghosts" will be eliminated by variations in the synchrony or the flash rates of pairs of lights.

Flashing signals are used in both displays, since at low-signal contrast, flashing signals have greater conspicuity or attention-getting effectiveness than steady signals (ref. 61). This holds true even in a situation where physical energy is removed from a steady light to obtain the flashing signal. This may be explained by hypothesizing that the stimulus which increases the speed of response to flashing lights is the on-off cycle or the change in illumination. The most efficient flash duration has not been clarified, but indications are that "under the conditions tested so far the most conspicuous signal is one flashing three times per second when it is at least twice as bright as its background" (ref. 62).

A further problem concerns optimizing the location of flashing lights in the visual field for maximal detection. It has been found that the probability of detecting a flashing signal is independent of whether or not the pilot is fixing his attention on the location of the expected flash. If the pilot is focusing on a given point, then it is actually disadvantageous for him to pay special attention to a peripheral area where a flashing light may appear (ref. 63). He will not detect it sooner than if he were generally attentive, but he will become fatigued sooner.

In connection with the most advantageous rate of flashing for the display lamps, it may be worthwhile to slave the display flash to the flashing light source (e.g., xenon lamp) located on the potential collision aircraft. If the flash rates of the display lamps and their indicated target where synchronized, the pilot might extrapolate most rapidly from display to outside target. This possibility remains to be ascertained by empirical tests.

Experimental findings have demonstrated that the location of a flash (0.25 second) in the lower half of the visual field does not affect the speed of a simple manual response. Decrements in response time occur only for locations of the target 30 deg above the horizontal and for lateral displacements greater than 55 deg from the center (ref. 64). These findings are contrary to previous experimental results in which increased latencies were reported for visual signals as they were displaced from the center of the visual field (ref. 65). In the Kobrick experiment (ref. 64), even at a 90-deg lateral displacement on the horizontal line of sight, no significant decrement in response time occurs as compared to central fixation.

Results of the latter experiment may be caused by its rather general design. Here, contrary to previous experiments, binocular vision was used; a wide area of peripheral displacement was tested; and no preparatory signals were given. Thus, findings here may be particularly appropriate to a collision warning device. Here, fixation was on a point. Nevertheless, if warning flashes can be displaced to the periphery, then it may be possible for the pilot to fixate elsewhere as needed.

On the other hand, if the pilot is responding to a complex central input, then his reaction to peripheral signals may be lengthened. In an experiment carried out by Elliott and Howard (ref. 66), a controller performed a pursuit task with a hand control and, at the same time, responded to peripheral flashing lights by depressing a pedal with his right foot. The controller was not told that the latency of his foot pressing was being recorded. In addition, more light was transmitted directly ahead than to his side so that both the brightness and the effective size of the flashes decreased in the periphery. Thus, it is not surprising that peripheral flashes elicited slower responses than central. Here again, lights in the periphery of the upper half of the display were least effective in terms of speed of response. In an experiment carried out by Webster and Haslerud (ref. 67), the primary task was the counting of either clicks or foveal flashes, and the secondary task was turning off a hand switch when a peripheral flash occurred. The primary task inhibited the response to peripheral flashes. Here again, however, instructions emphasized the primary task.

Thus, no findings are complete with regard to lag times for responses to peripheral flashes when the controller is engaged in a complex task dependent on both central and peripheral viewing. Yet this is precisely the situation of a pilot who must rely on one of the NASA collision display designs. Therefore, a test of the two devices, under conditions in which a primary control task must be maintained but where the "secondary" task may take priority, is being carried out under contract. At the same time, the contractors are testing an auditory warning system, the DAD, developed in their own laboratory.

Dunlap Auditory Display (DAD)

The Dunlap auditory display (DAD) is designed to utilize auditory signals to provide an initial warning alert as well as location indices on the position of threatening aircraft. Auditory warning signals are considered best for alerting the pilot of imminent danger since they are omnidirectional and attention-demanding. For this reason, an auditory signal is used in conjunction with both the matrix and HEDGE displays discussed above.

In the DAD system, the fact that man possesses two ears and is able to distinguish changes in pitch, is beneficial in providing aircraft position information. Three speakers are mounted in the cockpit around the pilot--one on his left, one in front, and one on his right side; each speaker corresponds to a sector of airspace surrounding his aircraft. When a plane enters a sector, a signal is sounded for approximately a half-second through the appropriate speaker giving relative azimuth. Relative elevation is indicated by varying the pitch of the signal. Hence, the pilot simultaneously receives both a warning alert and an indication of aircraft position. When the threatening aircraft is at the same altitude, pitch remains constant; when it is higher or lower, pitch is swept either 500 Hz above or below a 2500-Hz signal which is employed as the base frequency. The 2500-Hz base frequency is generated by a simple square wave generator which produces an impure and annoying tone. Since the ear acts as a frequency analyzer, periodic signals can be detected in noise, even when they are considerably weaker than their background. This is true for both pure and complex tones.

To ensure that signals employed in the DAD system could be easily heard against aircraft noise, sound recordings and sound pressure readings were obtained during flight in a single-engine light aircraft. Levels were found to range from 90 to 102 dB with the highest levels in the lower frequency bands. During a pilot study in the laboratory, the recorded noise was reproduced at the measured levels and auditory signals tested for their distinguishability under realistic conditions. The results of this study indicate that a signal of 2500 Hz could be easily heard even when it was 20 dB below the average noise level of 95 dB. For this reason, the DAD system is considered feasible for operational use even under conditions of high ambient noise.

The multiple-target situation is not easily handled by an auditory display system since hearing is a temporal sense rather than spatial as is the case with vision. In the DAD system, the situation is handled by activating the three speakers in sequence for an interval of 2 seconds each. Multiple aircraft in one sector, therefore, are indicated by a series of auditory signals sounded in quick succession. The appropriate number of signals would be repeated again 6 seconds later, provided the aircraft remained in the same sector. The pilot is not expected to count the number of signals but merely to pay more attention to the sector with the largest number of signals. By employing this technique (i.e., speaker sequencing at periodic intervals) it appears feasible to use an auditory system to display multiple targets.

Any of the above mentioned display systems will provide the pilot with a warning alert and aid him in locating aircraft visually within his proximal air space. It is difficult, however, on the basis of past research and theoretical considerations, to determine which system is most effective and holds the most promise for further development. An effective system is one which demands the pilot's immediate attention and directs his gaze accurately to the threat without wasting precious time in visual search. Response to an impending collision must take place even under conditions of high workload where the pilot's visual mechanism and his capacity for information processing are being taxed to their maximal extent simply by tasks involving the basic control of his aircraft. Therefore, display concepts for the PWI system must be assessed and evaluated primarily on the basis of actual performance data collected during on-going aircraft-type control tasks.

This evaluation is being carried out in the Dunlap laboratory, and the primary task will make use of an adaptive loop simulator. The test apparatus is shown in Figure 29. The controller uses a stiff stick to perform compensatory tracking for errors in pitch and roll. The primary display for these variables is a scope positioned directly in front of the controller, and as far from him as feasible, so that he will view a somewhat distant display. The controller attempts to null the input errors and, as he decreases the error, the adaptive loop increases the disturbance so that a constant error is maintained.

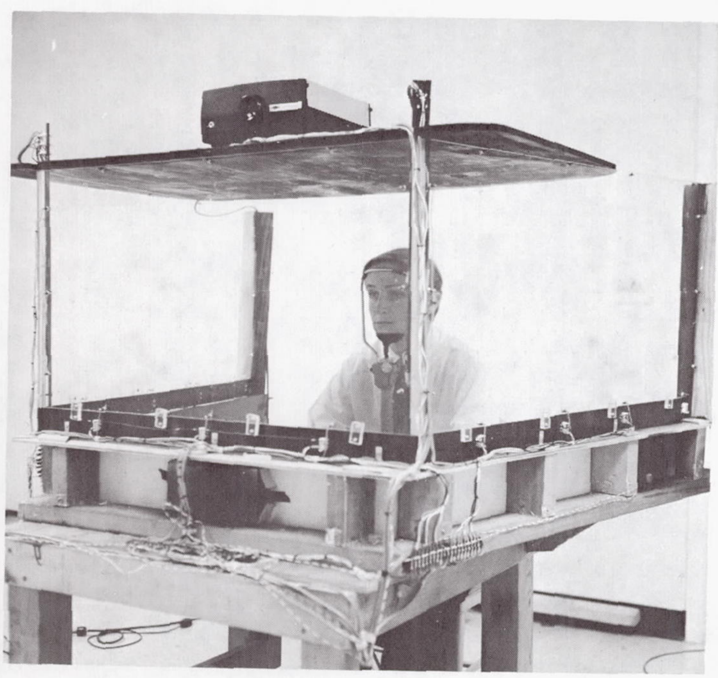

Figure 29. - Plastic windshield setup used to test both display forms at Dunlap and Associates

In the case of the embedded matrix display, hopefully the time lag will decrease because the search of the pilot, once alerted, will be confined to a small area. Hopefully, also, time lost in visually switching from near to far, successively, will be less than if the display were one among many instruments in the cockpit panel.

In the case of the HEDGE display, hopefully the time lag will decrease because no time will be lost in visual switching (ref. 68). The problem of the trade-off between time necessary for discriminating the point of intersection on the x-y axes of the flashing peripheral lights and time necessary for visual switching remains to be determined. A series of directional peripheral lights seem desirable, since collision signals may occur at the extreme periphery where motion is detectable but where forms cannot be identified (refs. 69-71).

A simplification of the HEDGE display to the horizontal element alone may prove more efficient than the two-axis model. This depends on which is greater: the time to detect a signal on the low horizontal axis, plus time to search the vertical column thus indicated, or the time to detect two signals, one on each axis, plus the time to resolve their projected intersections, plus the time to search the relatively small area of intersection. In considering simplification of warning displays, it may be noted that results of most vigilance experiments show that over a period of monitoring, the decrement in performance is less for the relatively more complex displays (ref. 72).

In the case of the DAD display, hopefully the use of a completely auditory device will enhance the warning alert. Also, the warning device is not affected by extreme variation in ambient illumination, e.g., flying into the sun, glare, and reflections. An auditory system would probably be less expensive, adaptable to a greater number of aircraft cockpits, and require less maintenance than a visual display system.

The display of range information has not been considered here, but a saturable amplifier could stretch the pulses of strong signals. This would result in a very economical range sorter. Ultimately, if required, this mechanism or others could be adapted to provide adequate range indication.

In terms of installation ease, the embedded matrix could be manufactured as part of every new aircraft. For retrofit, it might be possible to cement a thin embedded matrix in existing cockpits. The HEDGE unit is readily adaptable to retrofit aircraft and can be manufactured for each installation as an accessory. Installation of the DAD unit would perhaps be the simplest, given the crowded format of the instrument panel. In any event, the test criterion of a PWI display is the significant decrease in collisions for PWI-equipped aircraft. The laboratory tests now being conducted will indicate the optimal direction in which to pursue such display designs.

VIII. OPTICAL SIMULATOR FACILITY

An optical simulator test facility has been designed as a potential base for technical evaluation of PWI receiving systems or their components and subassemblies. The following discussion will present plans and expected capability of the modest simulator under consideration. First, the overall design concept for the simulator will be discussed indicating those capabilities to be provided initially, and pointing out directions in which these capabilities could readily be extended.

Fundamental Capabilities and Uses

The fundamental capability sought in this facility is that of presenting optical signals to the optics and detector package of an experimental PWI receiver, which will simulate flashing xenon beacons on intruder aircraft. Such an optics-detector package may, in fact, be connected to a complete PWI receiving system, including post-detector signal processing electronics and a display, so that the total system response can be observed for various simulated flight environment situations. At least initially, it is not planned to include cockpit simulation, nor the dynamic capabilities which would make this facility a flight simulator in the usual sense. Rather, the initial facility will be more of a three-dimensional optical bench, with specialized capabilities for supplying calibrated optical signals adjustable to simulate intruder aircraft at various ranges and in various directions, plus a variety of background and false target signals. It is expected that initial emphasis will be placed upon measurements made with laboratory instrumentation to determine the characteristics of optics-detector packages, and to analyze the behavior of post-detector signal processing electronics and discrimination logic. The intent is to couple simulator testing actively to the process of design and development of components and subsystems, rather than merely to evaluate the usefulness of completed results. However, it is conceivable that in a later phase of the work, the display portion of a PWI system could be removed to a separate cockpit simulator, and provision could be made for dynamic computer control of both the optical simulator and the cockpit simulator so as to simulate actual flights, with collision threat encounters, pilot reactions, evasive maneuvers, and the like. This sort of growth is anticipated.

Design Concepts

The design concept adopted for the simulator is illustrated in Figure 30. The source-pointing framework and mechanism will support collimated sources directed toward the center of a sphere where the PWI system optical receiver is to be located. The collimated source will be fed with pulsed xenon light by means of

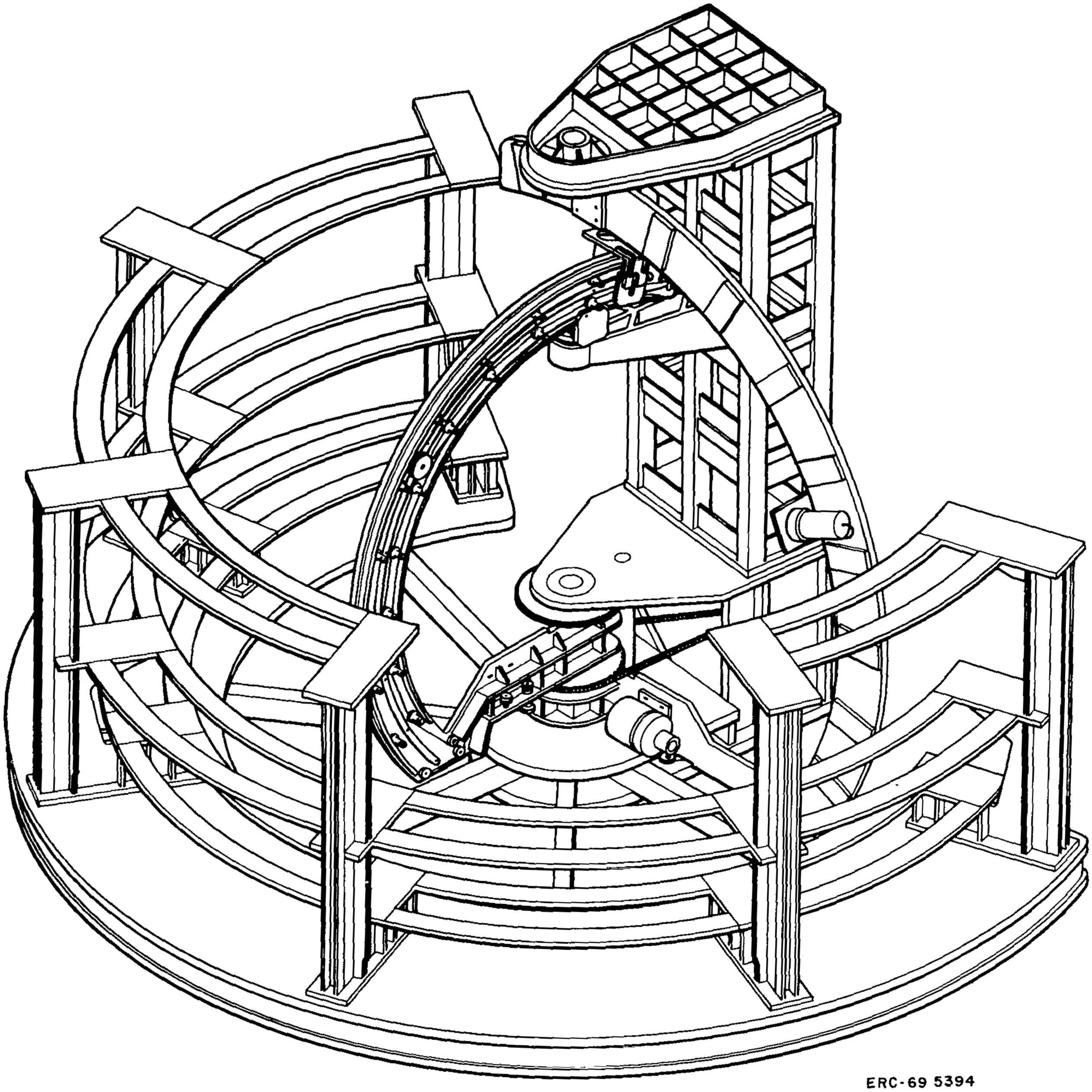

Figure 30. - Preliminary design concept of optical simulator

fiber optics light pipes from a control box or console. Calibrated variable neutral density filters in the optical path between the xenon flash lamps and the fiber optics inputs will permit the input light to be attenuated to simulate changes in range or atmospheric transmission. All structural members in the source-positioning mechanism and framework will be designed to present a minimum cross-sectional area normal to radii of the sphere, i.e., when viewed edge-on from the position of the detector optics package at the center. Background flux can then be supplied to the detector by surrounding the source-positioning mechanism with a spherical shell of panel lighting fixtures aimed toward the center.

Source-Pointing Mechanism

In the source-pointing mechanism (Figures 30 and 31) collimator carriages ride up and down in elevation on concentric meridian sector arms. These arms are pivoted about the polar axis of the simulator to provide for motion in bearing. The meridian sector arms rotate one inside the other, with radial clearance to permit them to pass. Either arm can thus swing through the entire 230-deg bearing range of the simulator. The elevation range will be from -30 to +100 deg, the upper ends of the arms being extended past the zenith and connected to the upper axial pivot point by offset bearing supports. Remotely controlled variable-speed motors will drive these two carriages at bearing and elevation rates up to 10 deg/sec. The vertical drive will be accomplished through a pulley and cable arrangement from motors riding on the lower radial members of the swinging arms. The fiber optics light pipes will be kept taut within the clearance allotted to each arm by means of an arrangement of pulleys and counterweights.

For the three circular rails at fixed elevation angles, collimator bases will be designed with kinematic mountings, so that wherever they are placed on such a rail, they will automatically be pointed toward the center with the proper declination angle. Finer degrees of elevation selection will be provided by constructing a variety of bases with various offsets. Thus more detailed coverage can be provided for the elevation range from -5 to +5 deg, critical for determination of safe altitude separation. A detailed design for the pointing mechanism has been made at the Varitek Engineering Company of Woburn, Mass., under contract to the Research Engineering Branch at NASA/ERC.

It is planned ultimately to provide a gimbal or goniometer mount for the detector optics package at the center of the pointing mechanism. Hopefully, this can be a dynamic mount suitable for simulating aircraft angular motions. To adapt the pointing mechanism further to dynamic simulation of flight encounters, the bearing and elevation scanning motors would be replaced with servomotors, or digitally controlled stepping motors.

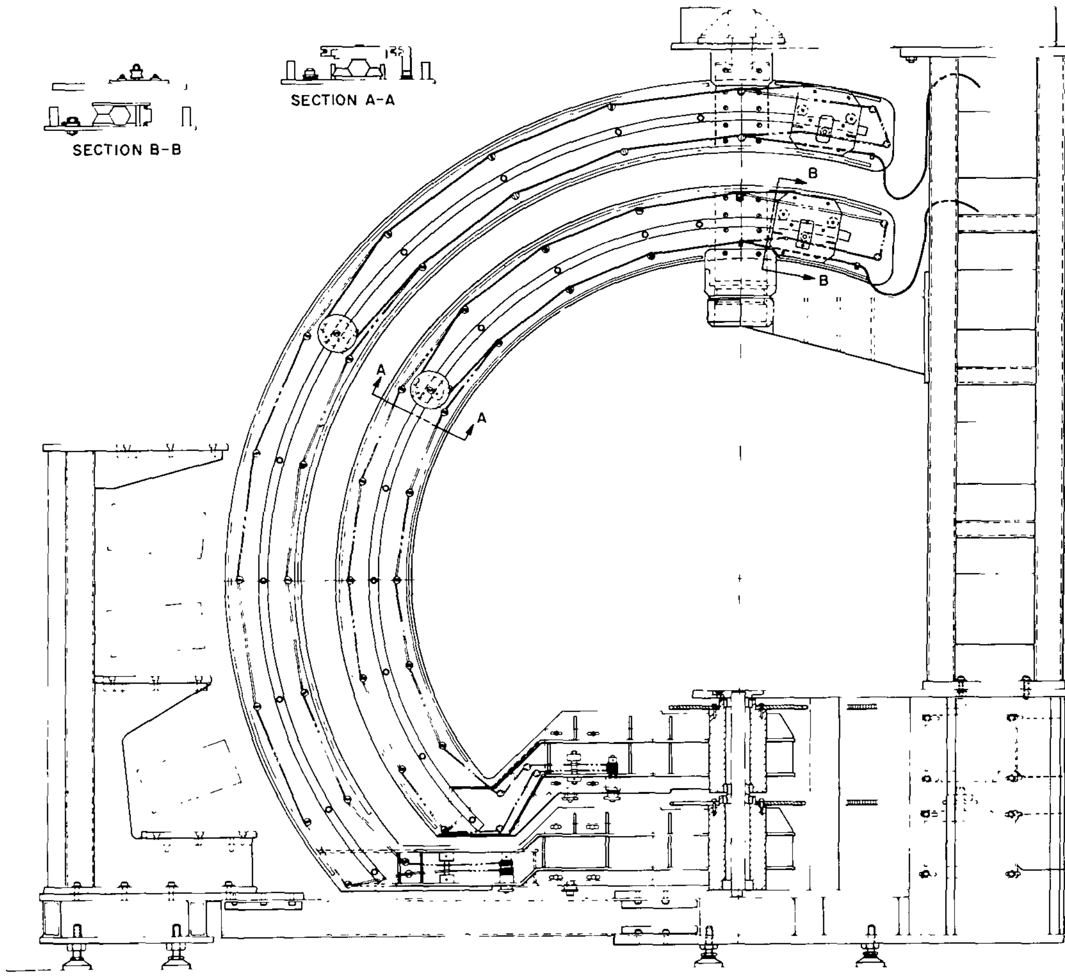

Figure 31. - Source-pointing mechanism and frame

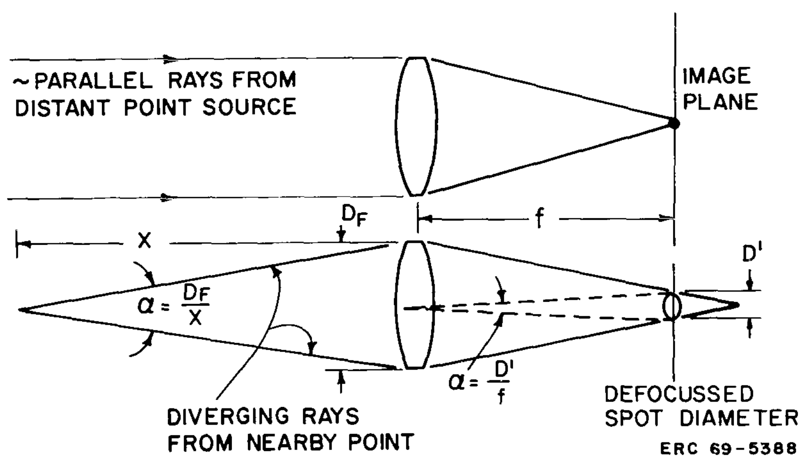

Figure 32. - Defocussing limit to angular resolution for "point sources" at finite distances

The general nature of the simulator, as described above, is dictated in part by the desire to have a high degree of optical realism within the confines of conventional laboratory space, so that the simulator work can be closely coupled with other kinds of laboratory experimentation. Collimated sources are necessary to achieve any appreciable degree of angular resolution within a small instrument, as may be seen from the simple geometrical optics considerations illustrated in Figure 32. Presumably the optical system of any PWI system of the type considered will be designed to work with sources which are effectively point sources at infinity. While there may be some special reasons why particular systems may be deliberately defocussed, it is necessary to be able to test all possible reasonable systems, which certainly may include ones which are focussed at infinity. In this case, light from a distant point source will enter the optical system as essentially parallel rays and be brought to a small spot on the image plane, as limited by aberrations, imperfections, and diffraction effects. For a nearby source, however, even if indefinitely small, the rays entering the receiver will have a finite angle of divergence α, given by the angle which the receiver collector subtends as seen from a nearby source. This light is spread over a defocussed spot subtending this same angle when seen from the lens, and is undistinguishable from the image of a distant object of the same angular size. The seriousness of this limitation depends, of course, on the diameter of the collector, but in designing a simulator to test all possible plausible systems, it must be assumed that some systems designers may employ a sizable receiving collector. For a collector aperture 4 inches in diameter, a working distance of about 20 feet is required to achieve resolution better than 1 deg, and at distances of 4 feet, the resolution is only 4.8 deg. With a collimated source the angular divergence can be reduced indefinitely, by reducing the source size, to the limits imposed by aberrations and diffraction. However, the apparent source produced by the collimator must match the real source in apparent intensity, i.e., the total flux collected by the receiver must be the same in both cases. Since real sources have a finite radiance, the size of the pinhole aperture at the end of the fiber optics light pipe will determine the total flux. Once all of the collection efficiencies and optical transmission factors in the fiber optics and filter system are accurately known, this pinhole size can be chosen to set the flux magnitude to correspond to the desired range interval to be simulated. Estimates indicate that apparent source diameters of a few tenths of a degree will still provide sufficient flux.

A planetarium approach to the simulator was considered, but was abandoned, principally because of the angular resolution problem as described above. To achieve reasonable angular resolution, a planetarium would have to be of generous size, beyond what could reasonably be accommodated within ordinary laboratory space. In addition, the structure itself would be quite expensive, and the problem of flooding its interior with anything approaching the background level required to simulate daylight sky would be an extremely formidable problem. (As will be discussed in more detail below, this problem is formidable enough already with the present design, which requires background illumination to be distributed over the interior of about a 6-foot radius spherical shell.)

Since this line of reasoning leads to collimated sources and to the large-scale source-positioning and pointing mechanism thus far described, alternative possibilities have been considered. Clearly, if one were concerned only with evaluating his own experimental apparatus, he could use uncollimated sources at short distances and merely refocus the optical system being tested. However, it is desired that the simulator be capable of testing arbitrary systems which may be presented by contractors or commercial developers in the future, and some systems might be incapable of refocussing, even if one were willing to so perturb the object being tested. The possibility of fitting auxiliary optics to the detector optics in the manner of eyeglasses has also been raised. However, the design of such "spectacles" for any of the very wide field-of-view systems being considered would be formidable, to say the least, and a universal design suitable for all possible systems would appear to be unrealizable in principle. Even if special supplementary optics could be designed for any given system, this approach would sacrifice a desired capability for quick response in evaluating new systems and new ideas, since the supplementary optics could not be designed in advance.

The use of fiber optic light pipes to supply light to the collimators will facilitate remote control of the characteristics of the light from an operator's console position. The input end of a fiber optic feed line will be connected to the exit aperture of the circular variable filter in Figure 33. On one of two shafts, a circular variable neutral density filter, having a range of 3.75 density units, will be employed to introduce optical attenuation equivalent to a change in simulated range by a factor of 74 to 1 (less in the absence of atmospheric absorption and scattering). Optical attenuation introduced in this way will not affect the spectral distribution nor the angular and spatial distribution of the light from the collimator. Atmospheric scintillation can be simulated by installing a second neutral density filter on the second shaft, and rotating it at an irregular rate, so as to present random attenuation values at the moments of flash input. Filtering at this point could also be used to correct for any changes in the light spectrum inadvertently introduced in the simulator optics, or to improve the simulation of particular beacon source spectra, or to modify the spectrum in the manner produced by atmospheric transmission.

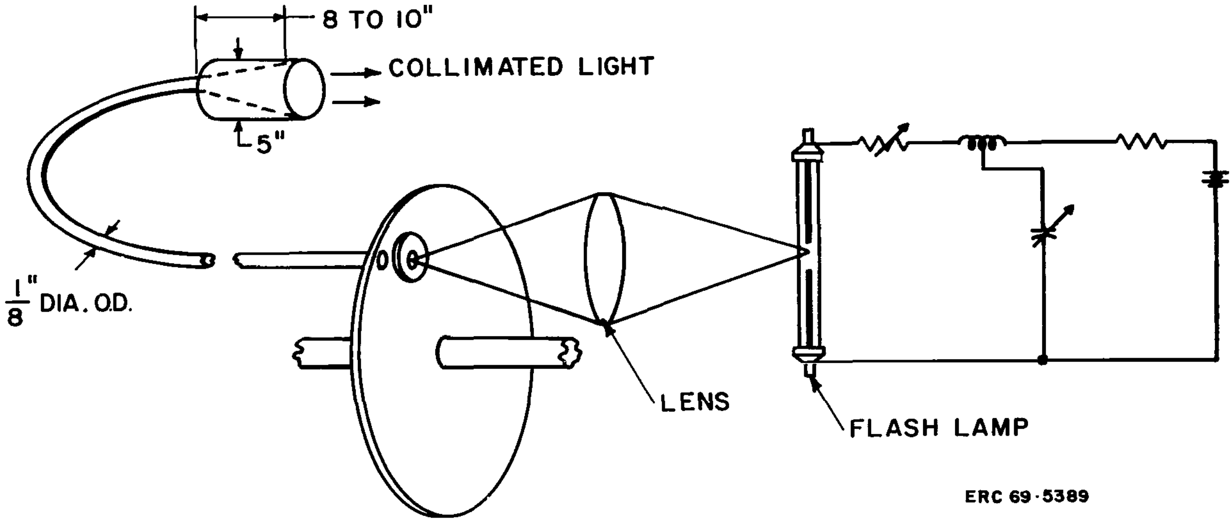

Figure 33. - Simulated intruder source optics

For simulating distant xenon beacons, the light input to the variable attenuator filter boxes will be from low-power xenon flash lamps (about 1 joule electrical input). Triggerable pulse driver units, capable of repetition rates up to 1.5/sec, with switch selection of L and C values, will be employed to produce various pulse widths in the range 200 to 2000 microseconds. It will, of course, be possible to adapt other primary light sources for the optical input to the filter box and fiber optic light conduits.

For example, GaAs injection diodes will provide a source with great flexibility in time characteristics, since their light output is essentially linear with current input. Such sources could readily be used to investigate any ideas involving information coding on the optical pulse, and so forth. To be sure, the spectral output is narrowly centered at about 0.9 micron, but this should not vitiate studies of system time response. Input from a continuously running lamp, with provision for chopping and/or pulsing by means of a mechanical shutter, will probably also be provided to take advantage of the stability and precision of calibration available for such sources.

Backgrounds and Bogies*

The technical practicality of a PWI system of the type considered is essentially a question of its performance as to detection probabilities and false alarm rates. It is clear from the section on receiver analysis that the signal-to-noise factors

*The term "bogies" is preferred here rather than the frequently used term "false targets" in view of the benign and peaceful intent of PWI detection.

which determine this performance will depend crucially on the characteristics of the radiation background and the nature of spurious optical signals incident upon the receiver. The effects of interfering radiation will depend in a complicated way on its intensity, its spectral distribution, its angular distribution, its spatial distribution over the collecting aperture, and its time variation. Clearly, to duplicate in the laboratory all background radiation fluxes with strict fidelity to all of these characteristics would be ideal, but prohibitively expensive. A more reasonable alternative is to duplicate only those characteristics which are essential to the investigation of particular attributes of the particular PWI system under test. It will always be necessary to remain aware of those characteristics of the incident radiation which are not perfectly duplicated, and to confirm that they are not essential for the purposes at hand. This point of view with regard to the use of collimators in simulating distant point sources has already been adopted. To match the total incident flux using a laboratory source which has no higher radiance than the original distant source, a larger angular divergence must be utilized. The apparent source will be larger, but if its resulting image is still comparable to the aberration and diffraction limit for a true point source, or otherwise negligible in relation to the instrument resolution, the approximation will be acceptable.

One of the principal effects desirable of simulation is the generation of shot noise caused by sky background radiation. As stated in the section on receiver analysis, this shot noise is proportional to, among other things, the background radiance integrated over the field of view of the detector, and to the product of the background spectrum, detector responsivity, and the optical filter transmission integrated over wavelength. Clearly, if one could match the spectral distribution of the background radiation exactly, valid experiments could be performed with various optical filters introduced to improve the signal-to-background ratio.

Ordinary tungsten sources have radiant power spectral distributions characteristic of blackbodies at temperatures of about 2000° to 3000°K, and are quite deficient in the blue end of the spectrum in comparison to solar radiation, for which the color temperature is about 6000°K. A fair spectral match in the blue end of the spectrum can be obtained by using high pressure xenon arc sources with corrective filters. However, such sources and their accompanying power supplies become quite expensive when the number of units required to provide uniform coverage over the total field of view is considered. For the present, the additional expense is regarded as unjustified, since it is expected that PWI receiver systems will incorporate a filter shutting out the blue portion of the spectrum. The efficiency of such filtration may have to be tested, perhaps with a laboratory monochromator or a single xenon arc source, but this testing can be separate and apart from the problem of supplying background shot noise. For the purpose of simulating background-induced shot noise, a spectral match may be foregone, and tungsten sources used, provided their intensity is adjusted as necessary to give the proper value for the spectral product integral appearing in the equation for $\langle V^2_{sh} \rangle$ on page 55. On this basis, a rough estimate of the lamp power required may be made.

ERC computer results for spectrum product integrals show that the incident solar flux (see section on Backgrounds) is equivalent to 26 mW/cm^2 at 0.9 micron, so far as the silicon detector response is concerned. For a white cloud of albedo 0.80 and Lambertian reflectivity, this flux corresponds to an effective radiance of 6.67×10^{-3} W/cm^2-sr, equivalent to 0.667 lm/cm^2-sr of 2870°K blackbody radiation for typical silicon detectors. If this luminance is obtained from a collection of panel fixtures having Lambertian directional characteristics, their emittance must be 2.1 lm/cm^2. If these are distributed over the inner surface of a shell of 6-foot radius covering the 8.06-sr field of view of the simulator, and if we take a lamp efficiency of 8 lm/W, the total electrical input power required is about 72 kW. This corresponds to placing 7200 10-watt bulbs 2.4 inches apart over the interior surface. If the panel radiators can be highly directive, like spotlights aimed at the detector, efficiency can be raised and the power requirements decreased in proportion to the ratio of the solid angles involved. For example, if half of the light from each source can be confined to a 15-deg cone, the power requirement comes down to a reasonable 2.5 kW.

Background requirements can also be met by use of bare bulbs mounted very close to the receiver optics. The photometric analysis must be carefully done, however, since the light which enters the receiver is completely out of focus, and one must analyze the detector optics to determine what fraction of it strikes the detector element in any given situation. If all of the light collected is effective, background requirements for a 4-inch receiver having a 30-deg conical field of view can be satisfied by a 75-watt bulb placed about 8 inches away.

A solar simulator for this facility would consist essentially of a bright source illuminating a small pinhole at the focal point of a collimator large enough to cover the aperture of the PWI receiver. As in the case of the collimators simulating distant xenon beacons, the size of the pinhole would determine both the apparent angular size and the irradiance for a primary source of given radiance. To demonstrate noise swamping caused by background when the solar image falls on a detector element would require only that the total flux effective for the silicon detector had the proper value. Neither a proper spectral distribution, nor holding the angular divergence to the 32 seconds of arc, which characterizes the real sun, would be necessary.

However, a quiet source would be needed, lest fluctuations in source output introduce excess noise within the pass-band of expected PWI post-detection electronics. To test whether the detector element in a given optical system would be damaged by the solar image, a realistic concentration of the flux into an image of the proper size is important. Apparent source size, as determined by angular divergence, would also affect the sharpness of the step transient occurring as the sun image was brought onto a detector element by own-craft motion. Proper spectral distribution would be needed for a direct test of the efficacy of any filters introduced into the system to defend against solar damage and/or solar background noise. With reasonable filtration, both carbon arcs and high-pressure xenon arc lamps could be adjusted to a fair match to the spectrum of solar radiation as filtered by the atmosphere. The radiance of carbon arcs is roughly half that of the sun, while in small regions of high current concentration, the radiance of high-power xenon arcs can exceed that of the sun by a margin sufficient to allow for losses in an optical system. Thus, the total flux value, spectral power distribution, and proper apparent angular size can all be attained with xenon sources. Carbon arc sources, having lower radiance, would require a modest increase in the angular divergence to get the right total flux. Both of these sources as yet require further investigation of their noise and stability characteristics in relation to this application. Tungsten sources, particularly in highly evacuated bulbs, are known to be quiet, but are short on radiance, particularly toward the blue end of the spectrum. Thus, it appears that precise simulation of all relevant aspects of solar radiation is a decidedly formidable problem. However, it is also clear that much can be done in the way of device and system testing by simulating one or more attributes at a time, and the selection and/or specification of one or more solar simulators for this facility presently remains an active area of investigation.

Various kinds of "bogies," or sources of spurious signals likely to generate false alarms, have been suggested. Clearly the pulse-detection filtering introduced to pick out the flash pulse from steady-state background noise should discriminate against any fixed lights, except insofar as they contribute to the background radiation shot noise level. However, there is a possibility that transient signals will be produced when the image of such a source is swept into the field of view of a detector element by own-craft motion. Valid testing of this effect will require that the fixed light come from a collimated source, because otherwise the sharpness of the transient will be degraded by defocussing. The necessary scanning motion can be produced by mounting such a fixed source on one of the movable arm collimator carriages, or by rotating the detector in its gimbal mount to scan fixed sources across the field of view. A motor-driven tilting mirror could also be used for this purpose. It is worth noting in this context that the possible generation of such signals by sweeping the edge of sunlit clouds into or out of the field of view cannot readily be simulated by energizing only a portion of the panel illumination planned for the outer shell, since the background panels will not be in sharp focus. However, in terms of the total sudden change in flux on a detector element, this effect should be adequately simulated by the use of fixed collimated sources of small angular subtense. Neon signs, fluorescent lamps, and some forms of street lamps appear to be likely bogies, since they exhibit strong modulation at power line frequencies. It appears feasible to simulate all of these at a distance by supplying light of the appropriate character to the fiber optic conduits of the standard source collimators. The principal difficulty will be in calibrating the levels of such simulated sources.

Testing Techniques

Though some of the possibilities for testing have been discussed in describing the capabilities of the system, a few other considerations should be noted. While the pointing mechanism is clearly capable of bringing two, or even three, sources to the same angular coordinates, it is evident the inner ones will then block the others. To test angular resolution of two or more targets so closely spaced as to occult each other, a beam-splitting mirror can be set up at the center of the simulator and the detector optics moved back to make room for it. The mirror image of one source can then be brought arbitrarily close to, or made to coincide with, a second actual source, while the calibrated neutral density filters are reset to compensate for the losses in the beam splitter.

There are a number of ways in which the position-scannable sources can be used to evaluate the angular sensing capabilities of a detector-receiver system. The separate fields of view of individual sectors can readily be mapped by scanning or searching in bearing and elevation for various settings of the source intensity, thus determining the detection threshold range as a function of angle. It may prove that sector fields-of-view are not sharply defined, but depend perhaps on signal and background levels. It will be of interest to check the sector-to-sector crossover characteristics. Sectors could possibly fail to overlap, leaving dead zones in between, or if they did overlap, then one could investigate the angular field in which indications are obtained on both sectors, under various signal and background conditions. By use of two sources set at various intensity levels, one could readily test the ability of a system to detect additional targets in sectors already occupied by stronger ones. Such tests could include variations in the pulse repetition rates and/or phases. In the case of position-sensing detectors employing analog processing, it should be possible to determine the accuracy of angular calibration constants and examine the linearity and degree of field distortion by scanning in elevation and bearing while making recordings on an x-y plotter.

Finally, it should be possible to do a certain amount of system optimization by experimenting with various variable parameters in a receiver system while under test on the simulator. Perhaps a small laboratory analog computer could be used for rapid set-up of alternative post-detection filters, and to search for optimum parameter values. Similarly, in a predominantly digital logic-oriented system, it might be profitable to vary some of the threshold settings. Control of background illumination and of intruder signal strengths will make it possible to check the functioning of any sensitivity adjustments provided to control the detection range, to change the operating parameters for night use, and so forth.

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