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LASER BEACON STUDIES

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Attention: M-P and C-CA

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TABLE OF CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

The program carried out at Electro-Optical Systems under Contract No. NAS 8-2459 has been concerned with a feasibility study of using a laser beacon for daylight optical tracking; the scope of the work to include:

A. To determine whether or not an airborne laser light source is practical if used as a pulsed beacon for daylight optical tracking.

B. The beacon is to be used with a BC-4 Ballistic Camera and meet the following requirements:

   1. Range detection of 500 nautical miles in daylight.
   2. Frequency of flash, once every 10 seconds.
   3. Minimum of 100 flashes.
   4. Flash beacon width to be as wide as practical (180° ideal).
   5. The weight and power required should be held as low as feasible.
   6. The spectral output of the laser to be compatible to available narrow band pass optical filters.

The initiation of this program has been based on the desire of tracking in daylight the Saturn booster by means of a pattern of BC-4 cameras. The necessity of tracking in daylight is not only governed by convenience but of other considerations which are not pertinent here.

The purpose of using a laser output over other light sources, e.g. flash tubes, stems from its high power output within a narrow frequency region. Standard light sources are inherently broadbanded.

This implies that the power output at any given frequency interval is only a small percentage of the total output. The laser is able to convert a large percentage of light of all frequencies into one small frequency band and so is inherently able to give higher outputs in this small band. This advantage can only be utilized, however, if the receiver is narrow band also. Unfortunately, no known filters can be found with transmission bandwidths which are nearly as narrow as the laser output; less than 0.1 Å. The best that can be found in the optical region have bandwidths of about 1 Angström unit. In the beacon application, this means that a much larger bandwidth of noise gets into the receiver than is optimum. However, as will be shown below, the difficulty in using the laser as a beacon lies not in the signal-to-noise ratio so much as in the amount of light energy necessary to expose a photographic film. Therefore, although one is not able to utilize the laser to its best advantage, one is still able to use it successfully as a beacon. One is helped in this in that the output of most lasers available today have frequencies in the red and near infra-red region of the spectrum where the intensity of the sky light background approaches a minimum.

The best filters available for use in our receivers are of an interference type. The transmission through such a filter depends very strongly upon the angle of incidence of the light upon its surface. Thus, in order to maintain a transmission at a given frequency, one must maintain a constant angle of incidence, usually normal incidence, from the laser beacon. This necessitates a tracking mechanism to keep the normal to the filter always pointed towards the beacon. This tracking can be quite loose, however, just to keep the transmission through the filter high. Since the flight path of the missile is already predetermined, the tracking can be preprogrammed or, alternatively, information can be given for tracking from a ground radar tracking station.

In order that the background light be kept to a minimum, a shutter will have to be designed which can be opened when the laser beacon flashes and is within the correct range. Thus a program will also be necessary for a shutter which opens and shuts as close to the speed of the beacon flash as is possible and which only opens for a certain of the beacon flashes, i.e. the ones whose image falls upon and will give some darkening on the film. Furthermore, in order to better distinguish between flashes and to present backgrounds from accumulating from one flash to the next, a collimator should be used. This collimator need only be as good as the tracking for the filters.

One of the characteristics of the laser, useful for other purposes, cannot be used here. This is its very well collimated beam. In order to project the light to several cameras, spread widely on the ground, some type of beam diverger must be used. The actual divergence, of course, depends upon the separation of the cameras from each other and the distance from the flight path. Since no information is yet available on these parameters, all calculations have been made on the assumption of 180° beam spread.

Another characteristic of lasers is that they operate more efficiently at lower temperatures. Thus, a lighter weight beacon package is to be anticipated by operating at lower temperatures. This, of course, requires a low temperature dewar. However, the reduction in power requirements for optically pumping the laser is such that the overall package is lower in weight.

2. LASER BEACON SYSTEMS PROPOSAL

A block diagram of all the essential elements of a laser beacon system is shown in Fig. 2.1. The laser beacon proper is shown on the lefthand side of the figure while the detection apparatus is shown on the right. A general description of the operation of the system is as follows:

A suitable laser material is fabricated for optimum pumping and lasering output. The excess heat is carried away from the laser into a cooling bath. Pump power is supplied to the laser material by discharging a charged energy storage capacitor through a flashtube. The storage capacitor is charged to several kilovolts by a DC power supply. Normally, the flashtube will not conduct at this voltage. Conduction will take place only when a suitable trigger pulse is supplied to an electrode located close to the wall of the flashtube. The timing of these pulses can be controlled, e.g., through the use of a timer. Figure 2.2 depicts a proposed power supply and flashtube assembly with provision for triggering.

A beam spreader, consisting of optical parts, is used to transform the parallel output beam of the laser into a divergent beam of suitable angular spread.

The laser signal is to be received basically by the BC-4 camera. However, auxiliary equipment will be necessary to assure a good signal-to-noise ratio as well as maintaining exact synchronization between laser flash and shutter opening. Regarding the signal-to-noise qualification, a narrow-band interference filter is to be located in front of the BC-4 lens. Furthermore, as the shutter is to be opened several times, a collimator is also anticipated which

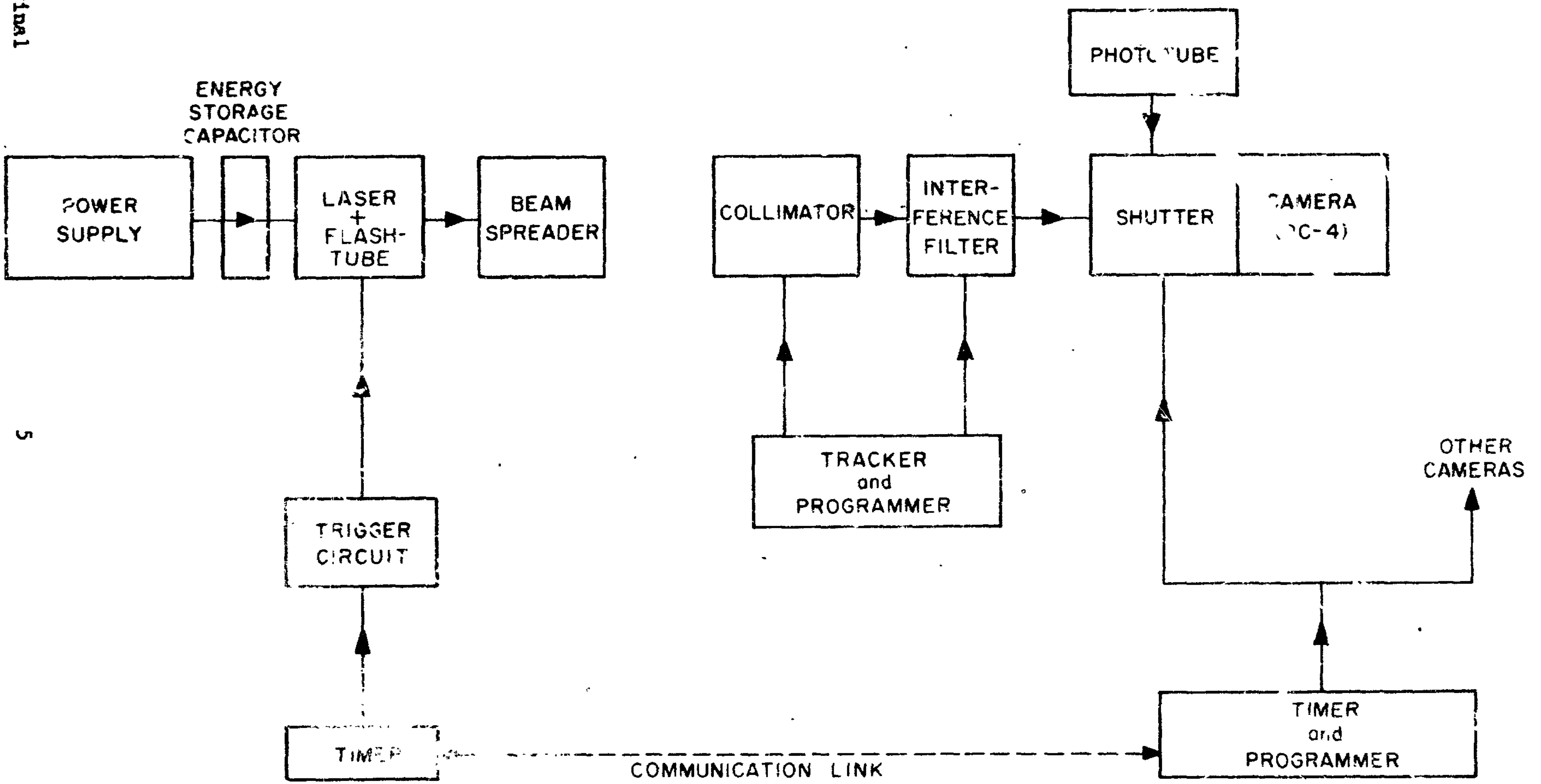


FIG. 2.1 BLOCK DIAGRAM OF OVER-ALL LASER BEACON SYSTEM

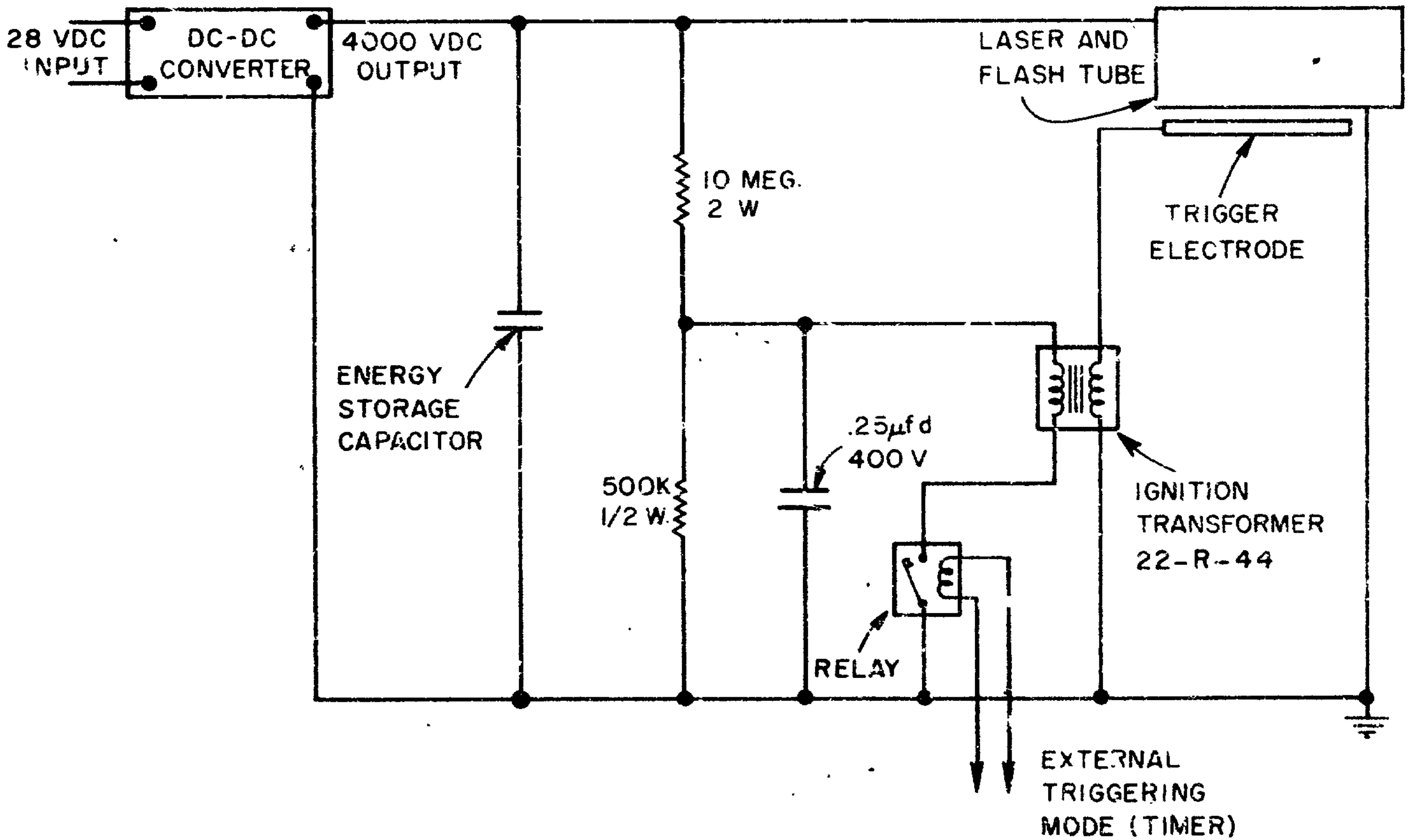


FIG. 2.2 PROPOSED POWER SUPPLY PLUS FLASH TUBE ASSEMBLY

will prevent multiple exposures of the sky background at any given point on the photographic film. Both the collimator and the interference filter must always remain normal to the signal direction, and this could be accomplished by programming.

Means will have to be provided for preventing exposures in a line-of-sight of the sun. This could be accomplished by monitoring the lens opening with an auxiliary phototube which closes the shutter for large exposures.

3. DESCRIPTION OF COMPONENTS

3.1 Laser

The heart of the laser beacon system is the laser itself. The number of different lasers is increasing monthly. The threshold power, i.e. the minimum necessary electrical power to cause lasering, is being lowered by choice of new materials and by design and polishing techniques. Thus efficiencies, power outputs, frequency stability, reliability, etc., are continually improving. However, no laser material has been as thoroughly investigated as the ruby laser, i.e. chromium doped aluminum oxide. For this reason, all calculations for this report are based on these characteristics:

Peak power out	20 kilowatt
Duration of light out	1 millisecond
Frequency of output	6940 Angstrom units
Efficiency	1.0 percent

It is to be understood that these are the characteristics of an existing laser. The improvements will not only reduce the necessary weight but increase the power output. In future, one may easily see efficiencies up to 50 percent and power outputs above one megawatt.

A list of the presently known laser materials is shown in Table I together with the wavelengths at which lasering action takes place.

TABLE I

KNOWN LASER MATERIALS

MATERIAL	STATED INPUT REQUIREMENTS	OUTPUT	WAVELENGTH OF EMITTED LIGHT
Pink Ruby (~0.07 percent Cr^{+++})	200 joules	20 Kw.	6,943 Å (at room temperature) 6,934 Å (at liquid helium temperatures)
Red Ruby (~0.7 percent Cr^{+++})			7,009 Å 7,041 Å
CaF_2 (0.07 percent Sm^{++})	20 watts		7,080 Å (at liquid helium temperatures)
CaF_2 (u^{+++})	6 joules		2.5μ
CaW (Nd)	5 joules (threshold)		10,600 Å (at room temperature)
He - Ne		15 mw. (C.W.)	11,180 Å; 11,530 Å; 11,600 Å; 11,990 Å; 12,070 Å
Gas Laser at Berkeley			5μ
CaF_2 (Eu)			~6,100 Å
SrF_2 (Sm^{++})			6,500 Å

3.2 Dewar

A liquid helium dewar assembly has been designed for cooling the laser materials and performing experiments with laser materials at liquid helium temperatures. It is anticipated that the total weight requirements for a cooled system will be considerably less than an uncooled system as the power requirements will be greatly reduced. A diagram of the liquid helium dewar assembly is shown in Fig. 3.2. The unique features of this assembly are as follows:

1. It can be operated in any orientation.
2. It has a thermal insulator surrounding the nitrogen chamber which is porous to allow precooling with escaping nitrogen gases.
3. It has a sapphire shell intimately contacted to the ruby laser crystal to allow rapid cooling during and after operation.

3.3 Flashtube

Flashtubes are made in a wide variety of shapes and sizes, as well as with varying specifications. There are two shapes that have been used in laser applications: the helical and linear. The latter is especially suited with cylindrical mirrors of elliptic cross-section for coupling the light output to the laser material. In this configuration, the flashtube and laser material are situated along the 'focal axes' of the elliptical cylinder, as shown in Fig. 3.1. The energy required per pulse for laser action in ruby is quoted for such a configuration (see Section 3.1), and a suitable flashtube is, e.g., the FX-38, manufactured by Edgerton, Germeshausen and Grier, Inc.

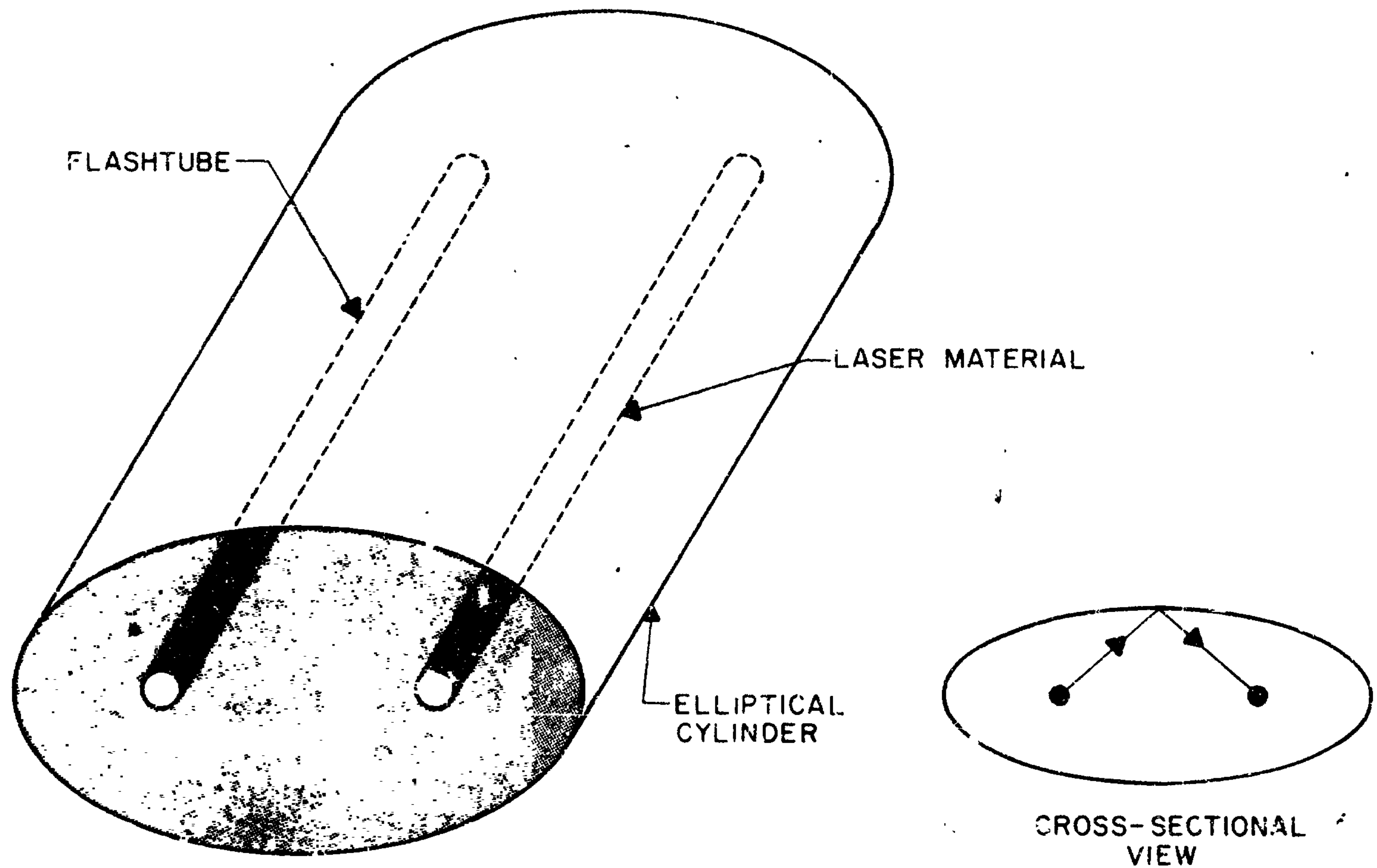


FIG. 3.1 GEOMETRICAL ARRANGEMENT FOR IRRADIATING LASER MATERIAL

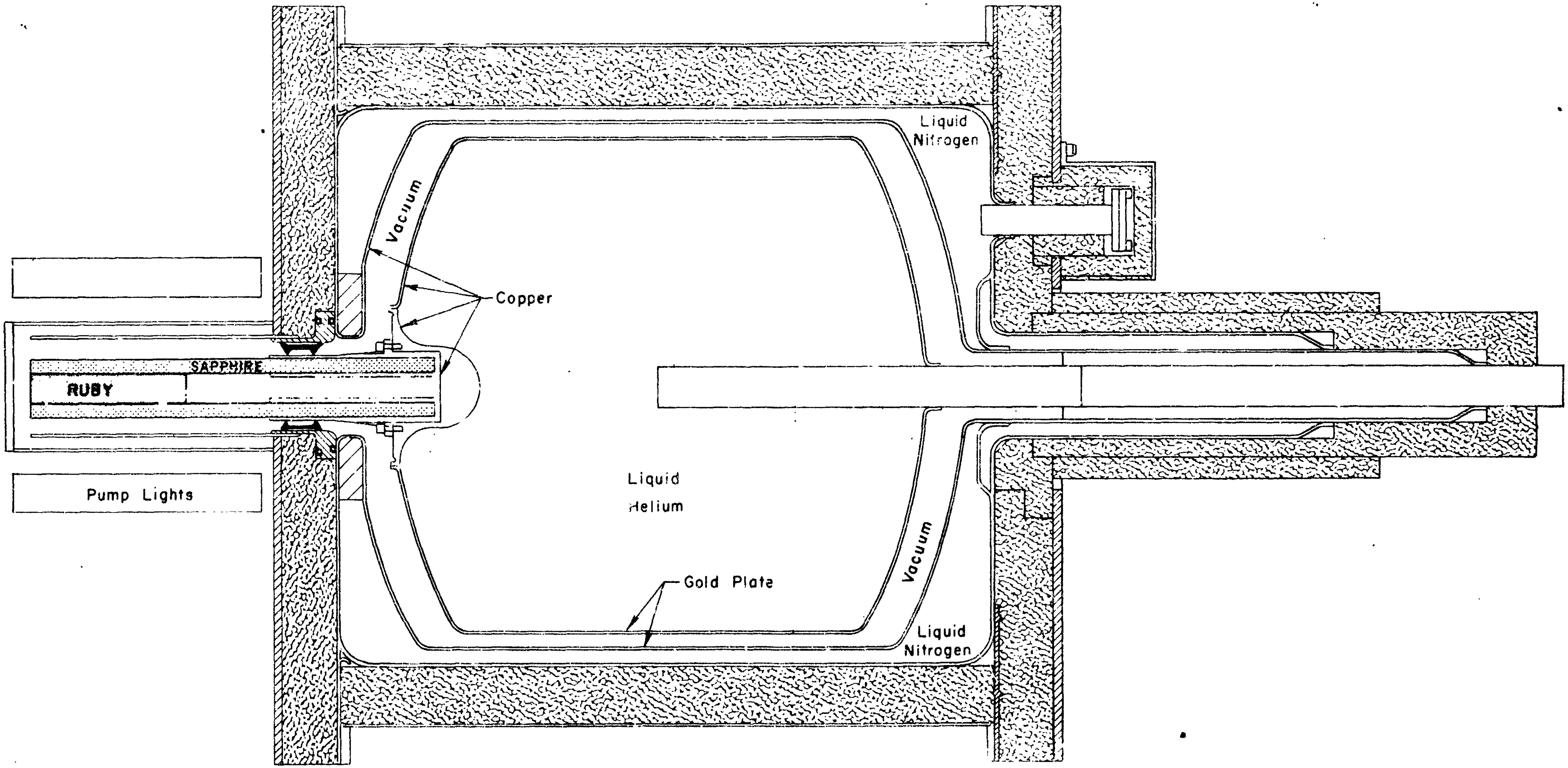


FIG. 3.2 LIQUID HELIUM DEWAR ASSEMBLY

3.4 Power Supply

The design of a power supply depends on the energy required per flash to produce laser action. In the present design, attention has been focused on the presently known information on the uncooled ruby laser.

For a ruby laser in the elliptical configuration, approximately 200 joules per pulse are required. At 4 KV, an energy storage capacitor of 24 μf is needed. The average current drawn for a pulsing rate of once every ten seconds is about 10 mA. Sorensen and Co., Inc., make DC-to-DC converters with a nominal output voltage of 1000 volts rated at 25 mA and requires a 28 VDC input. Four of these inverters can be placed in series to obtain the necessary 4000 V. Each unit weighs two pounds, and the cross-sectional dimensions are $3\frac{9}{16}$" x $3\frac{1}{16}$". There are no vacuum tubes used in these units. A diagram of a converter can be seen in Fig. 3.3.

It appears that 28 volts power source will be available from the Saturn vehicle if power requirements are not above 20 watts. Should additional power be required, it could be obtained from, say, NiCd cells. Cells of 1.25 volts nominal are available from Gould National Batteries, Inc., with ratings of 2.3 ampere-hours, and a weight of 3 ounces each. A stack of 23 such cells can be connected in series to give the desired 28 V and easily last for 100 pulses. The total weight of the cells would be about four pounds and the dimensions: L = 35", D = 1.3".

3.5 Energy Storage Capacitor

It was mentioned in a previous section that a capacitance of approximately 25 μf will be needed for the energy storage capacitor in the case of the ruby laser. The Sprague Electric Company

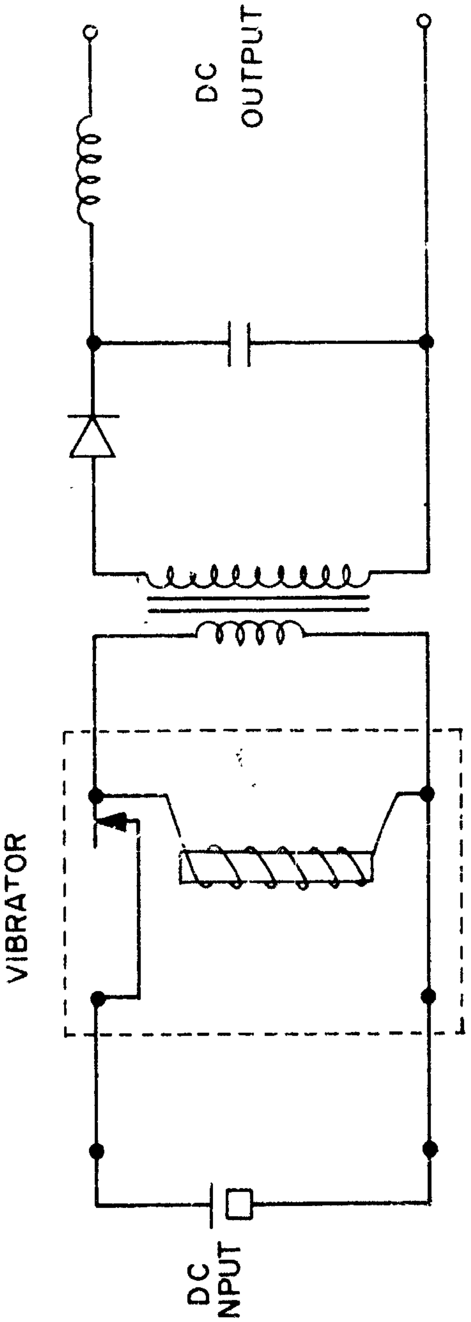


FIG. 3.3 DC-TO-DC CONVERTER

manufactures photoflash capacitors of 25 μfd rated at 4000 V. The weight is $7\frac{1}{4}$ pounds and has dimensions of $4\frac{9}{16}'' \times 3\frac{3}{4}'' \times 9\frac{1}{4}''$. This unit is designed for long life, however, and it might be advantageous to use capacitors with a short life and lighter weight.

3.6 Trigger Circuit

A method of triggering the flashtube is shown in Fig. 2.2. It meets the requirement that no vacuum tubes be employed. The description of the circuit is as follows:

A bleeder circuit is placed across the output of the DC-to-DC converter providing 200 volts to which a 25 μfd capacitor is charged. The flashtube is triggered whenever the charged capacitor is electrically connected to the primary coil of the ignition transformer (Thordarson 22-R-44). The electrical connection can be made by e.g., the contacts of a relay, which in turn can be controlled, say, by a timer. The weight of the circuitry beyond the storage capacitor, including the flashtube and laser material, would be about two to three pounds.

3.7 Beam Divergers

Beam divergers can be classified generally into two categories: 180° beam divergence, and less than 180° beam divergence. The two methods for 180° beam divergence that have been considered were the cassegrain mirror plus lens system, and the fiber optics bundle. The simpler of the two, and having more flexibility, is the fiber optics bundle. It has been suggested, however, (from discussions held between Dr. P. C. Fletcher and Mr. P. Button of Electro-Optical Systems, Inc., and Messrs. Rainbolt, Taylor and Simpson of M.S.F.C.) that the beam divergence may be less than 180° and a simple lens system would be the most suitable.

3.8 Interference Filter

Various types of filters were considered as a means of reducing the sky background exposure: they were the glass color, birefringent, and interference filters.

The glass color filter has the advantage that the transmission region is independent of the angle of incidence of the radiation. However, the transmission bandwidth is much too great, and the resulting signal-to-noise would correspondingly be too low. Another disadvantage is that the reflection off the front face is dependent on the angle of incidence.

The birefringent filter can, in principle, be made to give half-bandwidths down to 1 Å. Similar to the interference filter, it suffers the disadvantage that light must be incident normal to the front face, but the construction of the filter is such that relatively large dimensions are involved (See Fig. 3.4, L is of the order of millimeter), and the location of the wavelength for peak transmission can be given to a higher precision than, say, interference filters (see below). However, there are a multitude of related wavelengths which show peak transmission and an interference or glass-color filter must be used in tandem for isolating one wavelength.

The investigation of the interference filter has proven to be the most fruitful. Baird-Atomic, Inc., makes such filters with half-bandwidths down to 0.1 percent or 7 Å at peak transmission around 7000 Å. The tolerance in locating the peak transmission wavelength is as much as 10 Å, which could be a serious disadvantage. The peak transmission is about 40 percent for the 7 Å half-bandwidths. If greater half-bandwidths can be tolerated, e.g., 1 percent or 70 Å, the peak transmission would be about 65 percent.

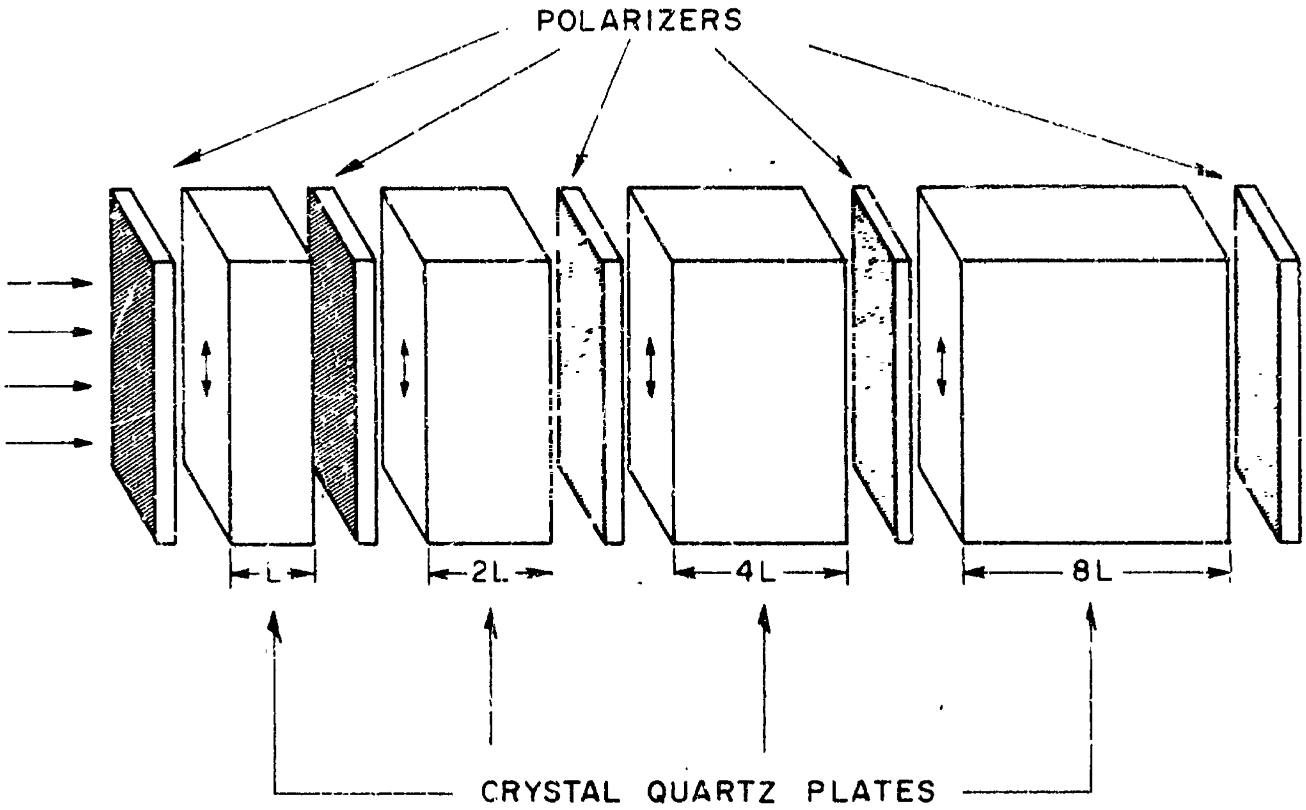


FIG. 3.4 COMPONENTS OF A BIREFRINGENT FILTER

Another manufacturer of interference filters is Librascope, Inc.; their filters have a peak transmission of 75 percent and half-bandwidths of 1 percent at any λ.

As stated above, an interference filter suffers the disadvantage of having to keep its plane perpendicular to the line-of-sight of the laser signal. This could be accomplished through programming of the filter mount. The effect of misalignment is such that an angle of incidence of 5° will cut down the transmission and consequently, the signal-to-noise ratio, to 50 percent of maximum. Baird-Atomic, Inc. manufactures filters up to 6" in diameter and, upon special request, will make any desirable size and shape. The price quotations for single units of 1 percent bandwidth filters are as follows: 1" square, $65; 2" square, $100; 4" square, about $425; and a 6" square, about $500. Lower prices prevail for orders of six or more filters.

3.9 <u>Collimator</u>

As a number of exposures will be taken by any one camera, the total background exposure would degrade the signal-to-noise ratio for a single exposure if no modifications are made. Basically, what is needed is a collimator which will reduce the size of the sky image to an extent where non-overlapping of adjacent images occur.

In order to determine suitable dimensions for the collimator, reference is made to Fig. 3.5. The following symbols are utilized:

- a - the diameter of the collimator
- b - the length of the collimator
- θ - the angle collimator makes with the normal to the lens
- β - the angle that a diagonal of the collimator makes with its length
- f - focal length of the lens.

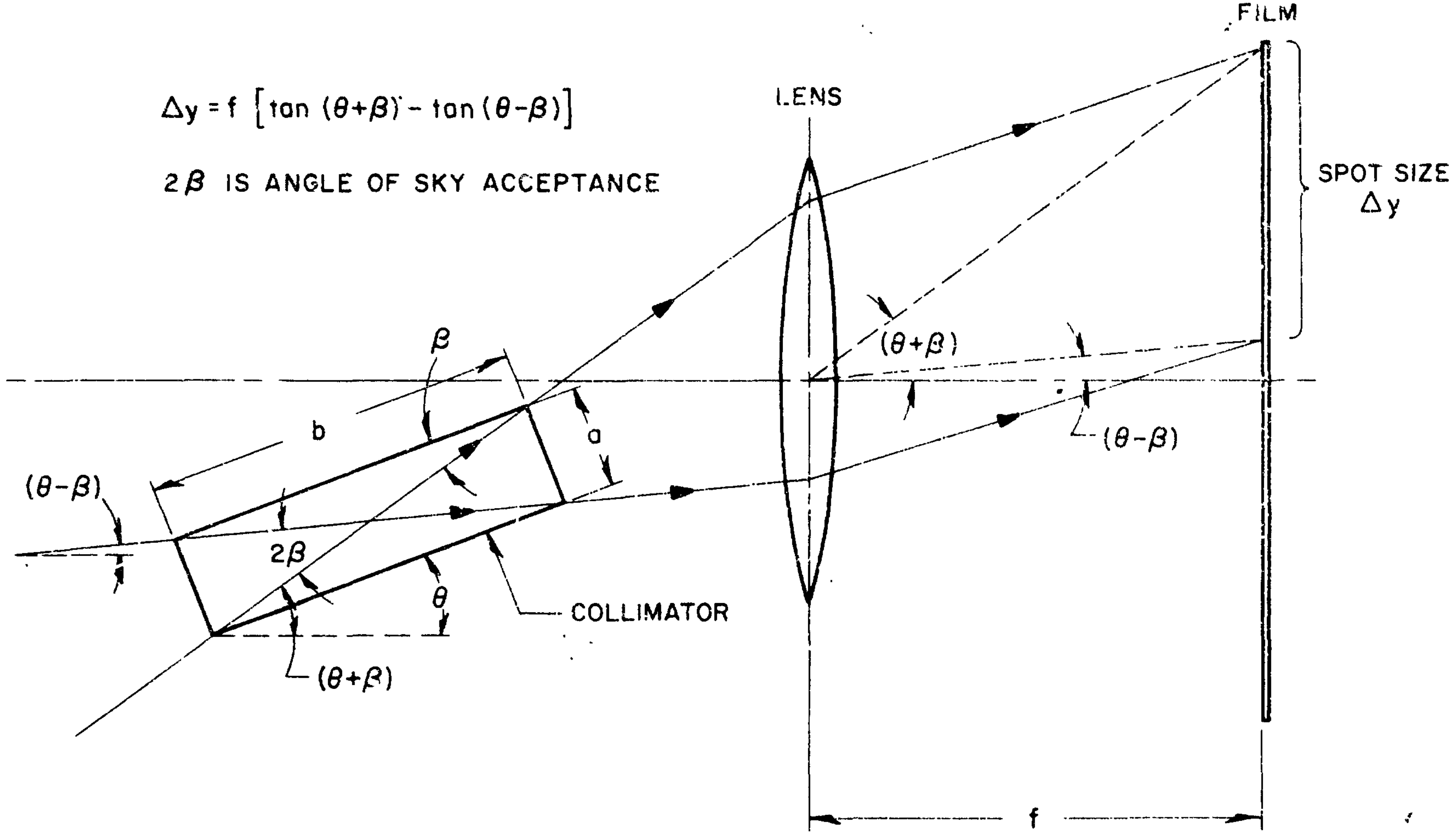


FIG. 3.5 RELATIONSHIP BETWEEN COLLIMATOR DIMENSIONS AND SPOT SIZE

From Fig. 3.5, it is seen that the spot size, Δy, can be given by:

$$\Delta y = f \left[\tan(\theta + \beta) - \tan(\theta - \beta) \right] \qquad (1)$$

Assuming vehicle speeds of roughly 6000 m.p.h, a focal length of 30.5 cm (for the " Astrotar" lens), and a slant range of 500 nautical miles, the image separation for successive flashes 10 seconds apart becomes about 1 cm. Therefore, for non-overlapping of sky images, the spot size should be no larger than 1 cm. From the above equation, this is realized when $\theta = 16^{\circ}$ (image near edge of plate) and $\beta = 1^{\circ}$. Since $\tan \beta = \frac{b}{a}$, the length of the collimator must be about 60 times its diameter. A collimator that completely encloses the " Astrotar" lens (aperture = $4 \frac{5}{8}''$) would be about 23 feet long. This length is impractically long.

A honeycomb pattern (see Fig. 3.8) can be used, however, with some sacrifice in signal strength. As an example, one can choose the length of the honeycomb to be about 15" , the cross-section of a slot $\frac{1}{4}'' \times \frac{1}{4}''$, and wall thickness 4 mils. Under these conditions, the light signal lost by a reduction in the effective lens area would be about 3 percent. The inner walls will not be 100 percent absorbing, and wall reflections will raise the background somewhat.

For maximum transmission through the collimator, it must have its normal remain parallel to the incident laser signal. Any misalignment will result in signal loss. In order to study the extent of signal reduction on misalignment, reference is made to Fig. 3.6. We assume an angle of incidence, ϕ, with respect to the collimator normal. x represents the effective width of the incident beam that will be transmitted through one slot. We have

$$x = D \sin(\beta - \phi)$$

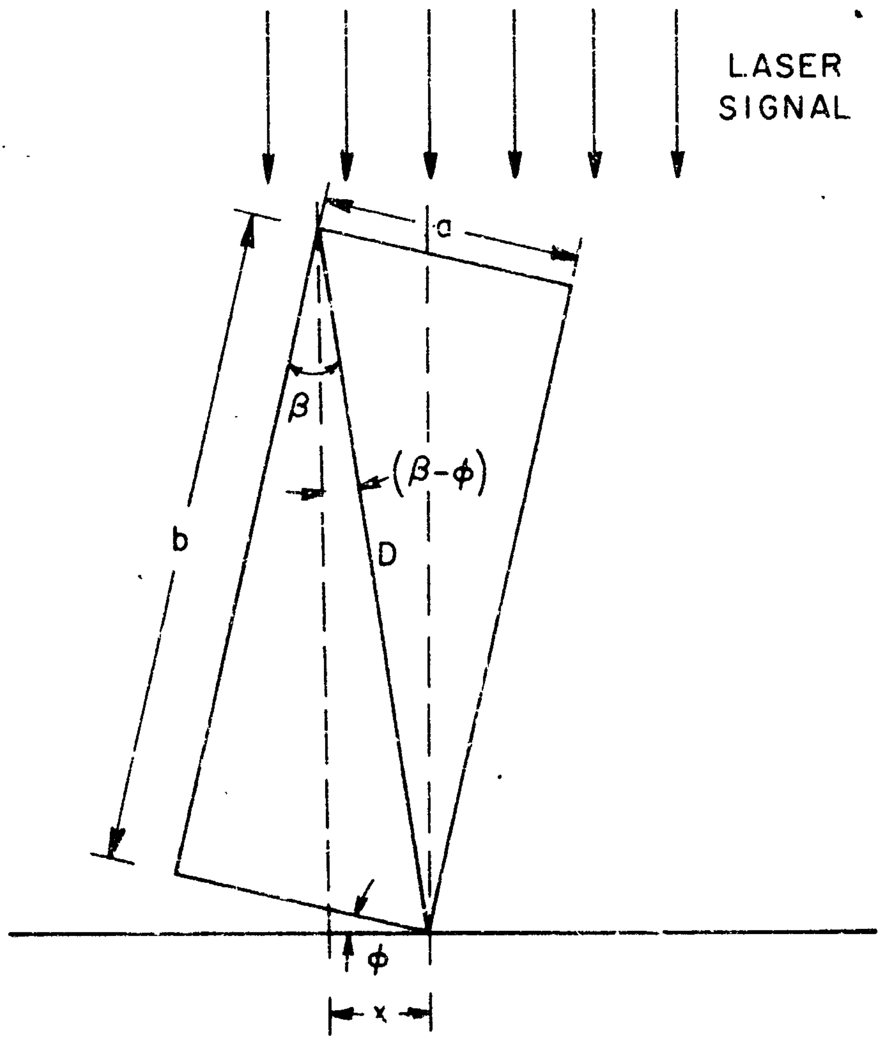


FIG. 3.6 EFFECT OF MISALIGNMENT OF RELATIVE SIGNAL TRANSMITTED

and the fraction transmitted upon misalignment is

$$\frac{x}{a} = \frac{D}{a} \sin (\beta - \phi) = \frac{\sin (\beta - \phi)}{\sin \beta} \tag{2}$$

If there is a 1° misalignment, then β must be as large as, say, 4° for a 75 percent transmission. This means, of course, that over-lapping of sky images will be necessary, but, as pointed out below, some pre-fogging may be necessary, and the over-lapping might be used for this purpose.

3.10 Shutter

An ideal shutter would be one that has a rectangular response, is synchronized precisely with the laser flash, and has its "open" time equal to the flash duration. A limitation is placed on the speed of the shutter by the large dimensions involved; of the order of five inches in diameter. Three types of shutters that have been considered are: the louvre, electro-optic, and stress plate. The most promising one is the louvre type, which has been commercially built for a 12 inch camera aperture having an opening and closing time of 2 milliseconds [Missiles and Rockets, 9, 32 (1961)]. This would degrade the signal-to-noise ratio by a factor of two (assuming laser outputs of 1 millisecond duration). However, as is pointed out below and mentioned above, some pre-fogging may be necessary and the shutter opening might be used, in part, for this purpose.

3.11 Programmer, Communication Link, and Trackers

In addition to programming requirements associated with the tracking of the collimator and the interference filter mentioned above, a program will be necessary for triggering a predetermined sequence of camera shutters for all the cameras on the range of the vehicle's flight. The transit time of the light signal from the beacon to a camera site will have to be taken into account. It would take light about 3 milliseconds to travel 500 nautical miles, and this time is of the order of the lens " open" time.

Methods for synchronizing shutter opening with the laser flash have been looked into. At present, there are two systems under consideration: one is to telementer the flash trigger pulse to the laser with one of the other communication links to the vehicle. The second method is to operate the shutter and laser with separate timers which are synchronized to one millisecond; these timers would have to be accurate to 1 part in 10^6. The relative desirability of these two systems depends upon the availability of a communication link to the vehicle.

A preliminary schematic of the tracking system is shown in Figs. 3.7 and 3.8.

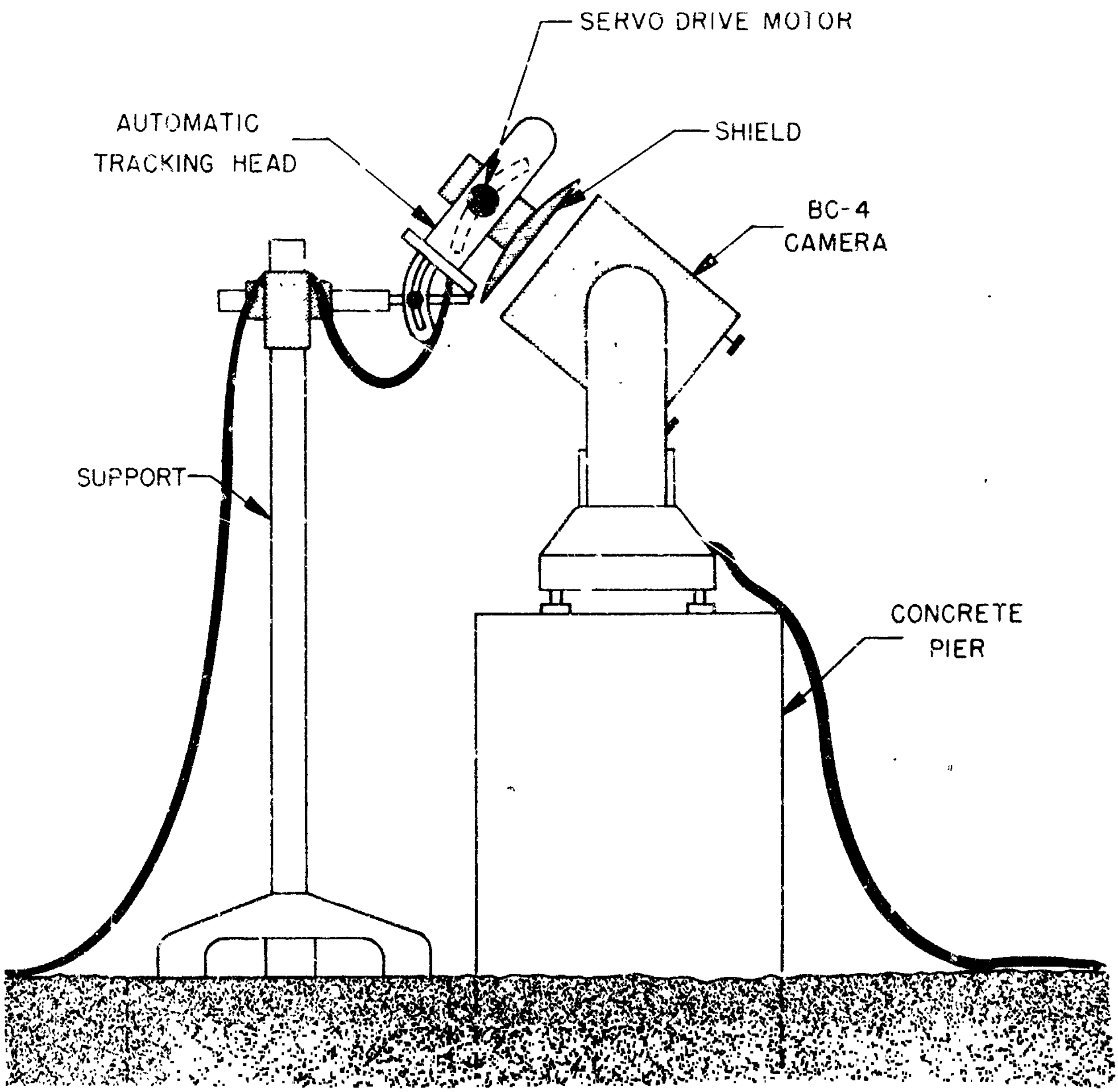
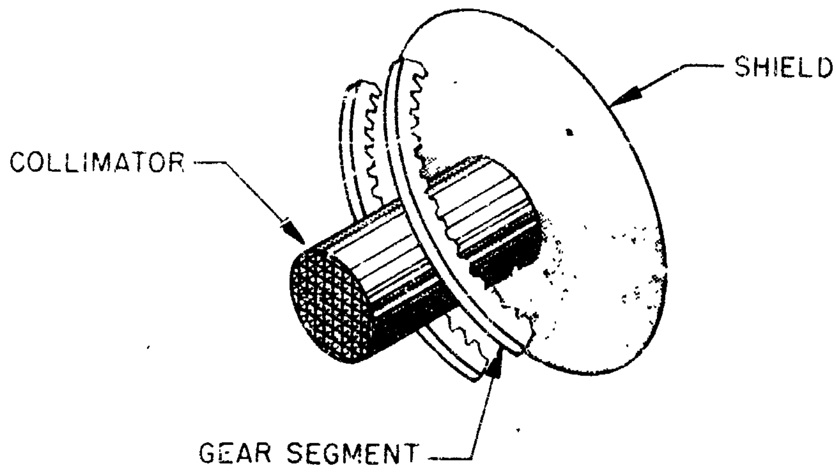
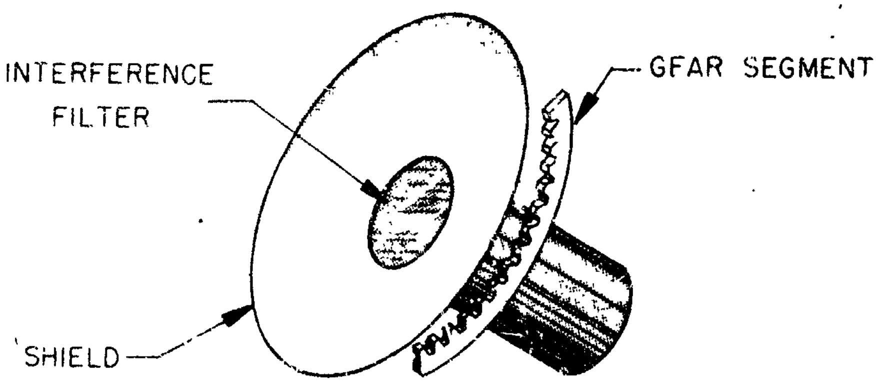


FIG. 3.7 LASER BEACON FILTER-COLLIMATOR TRACKING ASSEMBLY FOR BC-4 CAMERA



FRONT VIEW



REAR VIEW

FIG. 3.8 LASER BEACON FILTER AND COLLIMATOR ASSEMBLY FOR BC-4 CAMERA

4. SIGNAL-TO-NOISE CALCULATIONS

The signal strength, and hence the signal-to-noise ratio, received at the BC-4 camera depends on many factors, the major ones being: laser output, beamspread, atmospheric condition, and zenith distance.[1] The remaining sources of signal degradation, such as losses through the collimator, interference filter, and lens system, are omitted in this section as the signal and noise are attenuated equally. They will be discussed, however, in Section 5.

If the power transmitted by the ruby laser is P_T and the beamspread is 180^o, then the power received/area a distance R away is:

$$P_R = \frac{P_T \cdot T}{2\pi R^2} \qquad (3)$$

where T is the transmission of the atmosphere.

The presently known output of the ruby laser is approximately 20Kw. Then, for a slant range of 500 nautical miles the unattenuated power/area received is 34.4×10^{-11} watts/ft^2. The curves of Fig. 4.1 show the atmospheric transmission as a function of both the zenith distance and "haze".[1] These curves will be utilized below in signal-to-noise calculations.

---

[1] The zenith distance is an angular co-ordinate measuring from the zenith. Other angular co-ordinates used in this section are the azimuth and the altitude. These three co-ordinates are depicted in Fig. 4.2. The sum of the altitude and the zenith distance is always equal to 90^o. The term "haze" is used here in the sense of atmospheric condition, i.e., very clear, clear, light haze, etc.

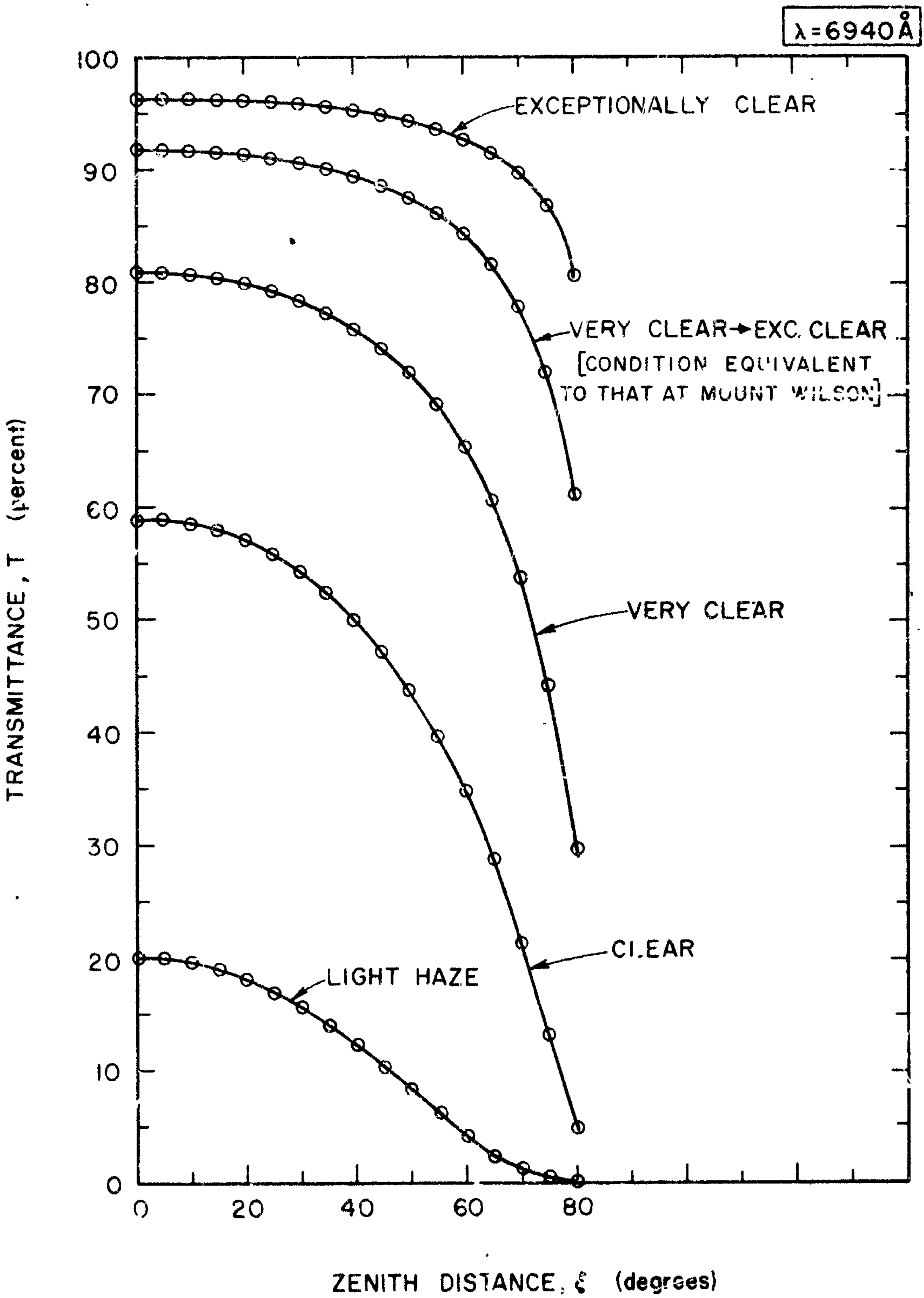


FIG. 4.1 ATMOSPHERIC TRANSMITTANCE CURVES

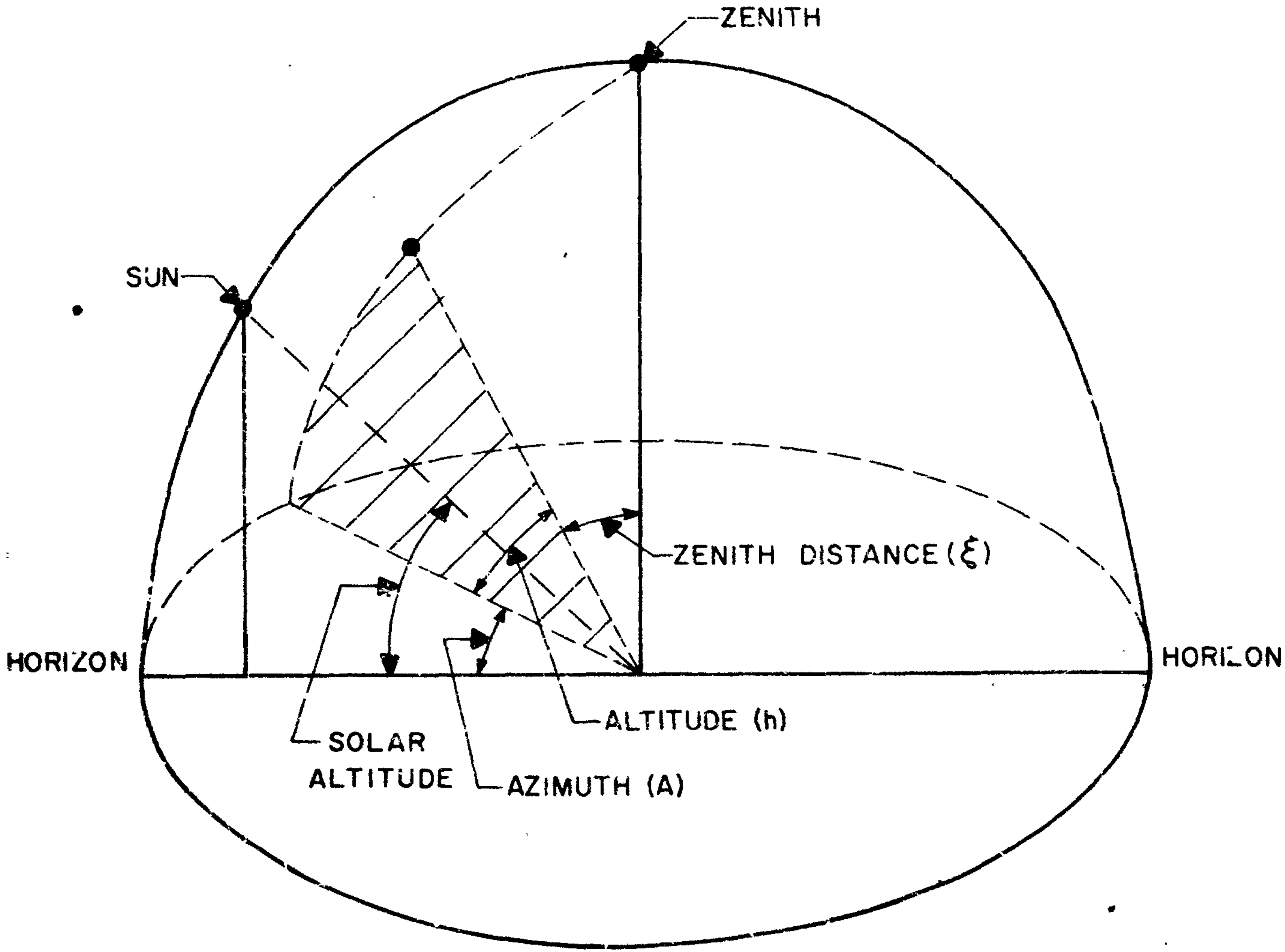


FIG. 4.2 CELESTIAL SPHERE INDICATING PERTINENT CO-ORDINATES

An extensive search of the literature was undertaken to accumulate all available data on the spectral irradiation from the sky. Ideally, the sky data demanded is the spectral distribution as a function of altitude and azimuth for various solar altitudes (see Fig. 4.2). In those references where the spectral distribution is given, there is no knowledge of the sky co-ordinates nor the sun's altitude [L. G. Mundie, et. al., J. Opt. Soc. Am. 50, 1187 (1960); E. E. Bell, et. al., J. Opt. Soc. Am. 50, 1313 (1960)]. In another reference [Jones and Conduit, J. Opt. Soc. Am. 38, 123 (1948)] the background irradiation from the sky is given, in photometric units, as a function of azimuth, altitude, and sun's location; however, there is lack of knowledge of the spectral distribution. The Smithsonian Astrophysical Tables (8th revised edition, Table 777, page 611) give the spectral distribution in relative units for a zenith distance of about 50°.

The desired information was extrapolated from the data of Jones and Conduit by the following outline: The relation between the luminous flux in photometric units and the spectral distribution in physical units is given by [see Astrophysical Quantities, C. W. Allen (the Athlone Press, London, 1955) page 103]

$$F_V = 680 \int_0^{\infty} K_\lambda F_\lambda \, d\lambda \tag{4}$$

where F_V is the luminous flux in lumens,

K_λ is the relative luminous efficiency factor,

and F_λ is the spectral power per unit wavelength in watts/Å.

In order to determine F_λ one must know its relative spectral distribution. F_λ can be represented by:

$$F_\lambda = a e^{-b\lambda} \tag{5}$$

which is a good approximation for the values from the Smithsonian tables.

The empirical curve for K_λ can be approximated by a Gaussian shape, and thus we can write

$$K_\lambda = e^{-\alpha (\lambda - \lambda_o)^2} \qquad (6)$$

Substituting equations (5) and (6) into equation (4) yields:

$$F_v = 680\, a \int_o^\infty e^{-\left[b\lambda + \alpha (\lambda - \lambda_o)^2\right]} d\lambda$$

$$= 680\, a\, e^{-b \left(\lambda_o - \frac{b}{4\alpha}\right)} \sqrt{\frac{\pi}{\alpha}}$$

or,

$$a = 1.47 \times 10^{-3} \sqrt{\frac{\alpha}{\pi}}\; e^{b \left(\lambda_o - \frac{b}{4\alpha}\right)} F_v \qquad (7)$$

The constant b is deduced from the slope of a plot of the logarithm of the relative power as a function of wavelength, which, from the Smithsonian tables, yields: $b = 3.62 \times 10^{-4}$ Å^{-1}. The constants α and λ_o are deduced from that Gaussian curve which best fits the luminous efficiency curve; obtaining $\alpha = 2.75 \times 10^{-6}$ Å^{-2}, and $\lambda_o = 5600$ Å.

The data of Jones and Conduit give the sky luminence values in ft-lamberts. This can be converted to illuminance values by:

$$I_s = \omega \frac{B_s}{\pi} \cos\theta \qquad (8)$$

or

$$I_s/\omega = \frac{B_s}{\pi} \cos$$

where I_s is the sky illuminance in lumens/ft^2

ω is the solid angle of the sky element considered

B_s is the luminance of the sky in ft-lamberts

and θ is the angle that the sky element makes with the normal to the illuminated plane.

Equation (8) yields the sky illuminance in lumens/ft^2 · steradian. If these values are substituted for F_v in equation (7), and the resulting value of a substituted into equation (5), then the resulting value of F_λ, the spectral distribution of the background sky, will be in units of watts/ft^2 - steradian - Å.

Ruby lasers at a wavelength of 6943 Å; on substituting this value for λ into equation (5) one can obtain the background noise at the wavelength of the ruby output. The final noise values obtained from the data of Jones and Conduit lie in the range $(0.58 \times 10^{-4} \rightarrow 28.2 \times 10^{-4})$ w/ft^2 - steradian - Å. The data of Mundie, et al., yield 2.3×10^{-4} w/ft^2 - steradian - Å, while the data of Bell, et al., yield 0.65×10^{-4} w/ft^2 - steradian - Å. It is thus seen that the converted data of Jones and Conduit encompass the other data.

The signal-to-noise exposure ratios are deduced from the following considerations. Suppose the area of the lens is A_L, of the photographic film A_p, and the spot size A_g (see Fig. 4.3). Then the image exposure (H_I), i.e., the energy emitted by the laser passing through the camera lens per unit area of spot size is given by:

$$H_I = \frac{\text{Power Received x time of exposure}}{\text{Area of Spot size}} \qquad (9)$$

The power received by the photographic film (P_F) is given by:

$$P_F = P_R A_L \tau \qquad (10)$$

where P_R is given by equation (3), and τ is the total transmittance of the filter, collimator, and camera lens system. Combining equations (9) and (10) gives:

$$H_I = \frac{P_R A_L t \tau}{A_g} \qquad (11)$$

where t is the time of exposure.

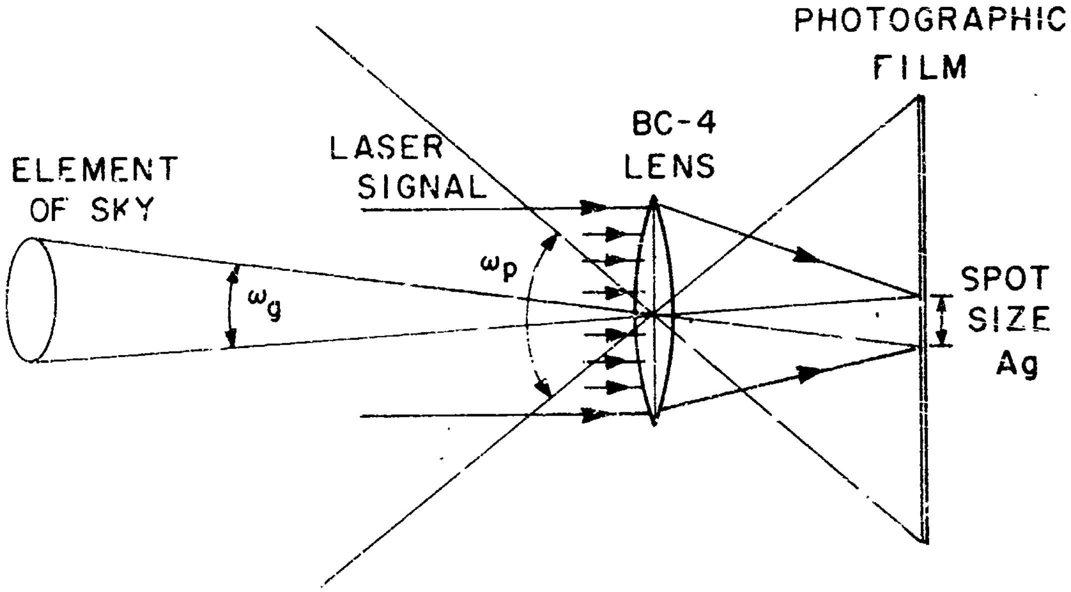


FIG. 4.3 DIAGRAM ILLUSTRATING ELEMENT OF SKY WHICH EXPOSED SAME AREA AS LASER IMAGE

The exposure due to the background sky (H_B) is:

$$H_B = \frac{NB\omega_p A_L t\tau}{A_p} \qquad (12)$$

$$\approx \frac{NBA_L t}{A_p} \frac{A_p}{f^2} = \frac{NBA_L t}{f^2} = NBA_L t\tau \frac{\omega_g}{A_g}$$

where, ω_p and ω_g are the solid angles that the plate and spot size subtend at the center of the lens, respectively

N is the sky background irradiance (watts/ft^2 - steradian - Å),

B is the bandwidth of the filter,

and f is the focal length of the lens.

Dividing equation (8) by (9) yields

$$\frac{H_I}{H_B} = \frac{P_R}{NB\omega_g} \qquad (13)$$

It is assumed that the background exposure time is the same as the image exposure time, which will be guaranteed by th collimator.

It is seen from equation (13) that in order to determine the signal-to-noise exposure one must know the image spot size. The resolution of the "astrotar" lens is about 35 microns. Then, with a focal length of 30.5 cm., and an aperture of $4\frac{5}{8}$'', ω_g is calculated to be 1.03×10^{-8} steradians.

Values for N for different sun azimuths and laser positions have been substituted into equation (13) and sets of curves deduced for an atmospheric condition termed as "very clear" (see G. P. Kuiper (ed.) - <u>The Atmospheres of the Earth and Planets</u>, The University of Chicago Press, Chicago, p. 52) and a filter bandwidth of 10 Å. These curves are shown in Figs. 4.4 and 4.5. The signal-to-noise exposures are plotted against the altitude and for various azimuths, measuring from the sun's azimuth. Each family of curves is for a given solar altitude. The signal-to-noise ratios are seen to vary from about 0.9:1 when the laser is within about 10° of the sun to 45:1 when the laser lies in the opposite sky to the sun and with sun's altitude low and laser's altitude high. As the laser's altitude dips below 15°, the signal-to-noise ratio rapidly approaches 1:1.

In order to examine the effects of atmospheric condition, curves have been plotted for signal-to-noise as a function of zenith distance for various atmospheric conditions. The curves averaged over the various solar altitudes are shown in Fig. 4.6. The ones for individual solar altitudes are shown in Figs. 4.7 through 4.10. All curves are based on an azimuth of 90°.

From photographic contrast considerations, the film density resulting from signal plus background exposure must be at least 0.05 density units above that due to the background alone [O. Oldenberg, J. Opt. Soc. Am. 46, 300 (1956)]. A typical film exposure curve is shown in Fig. 4.11. We can write:

$$D_T = \gamma \log_{10} (H_I + H_B) + \text{const.}$$

$$D_B = \gamma \log_{10} H_B + \text{const.}$$

$$\therefore \log_{10} \left(1 + \frac{H_I}{H_B}\right) = \frac{D_T - D_B}{\gamma}$$

When $H_I \ll H_B$ this gives:

$$H_I/H_B \approx 2.3 \frac{D_T - D_B}{\gamma} \qquad (14)$$

where: D_T is the density resulting from exposure of signal plus sky
D_B is the density resulting from sky alone
and γ is a characteristic for a photographic film.

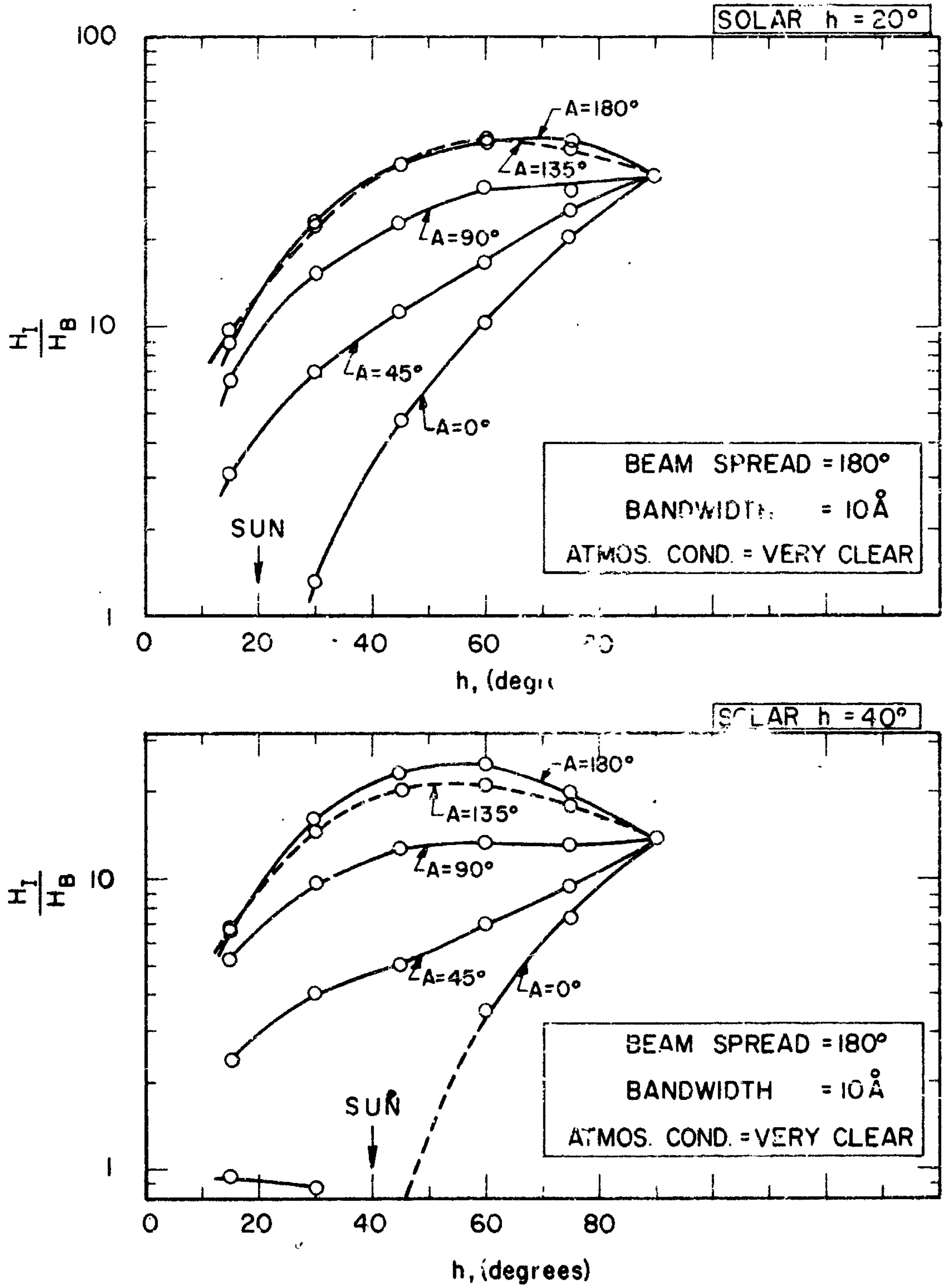


FIG. 4.4 SIGNAL-TO-NOI^E EXPOSURE RATIO VS ALTITUDE

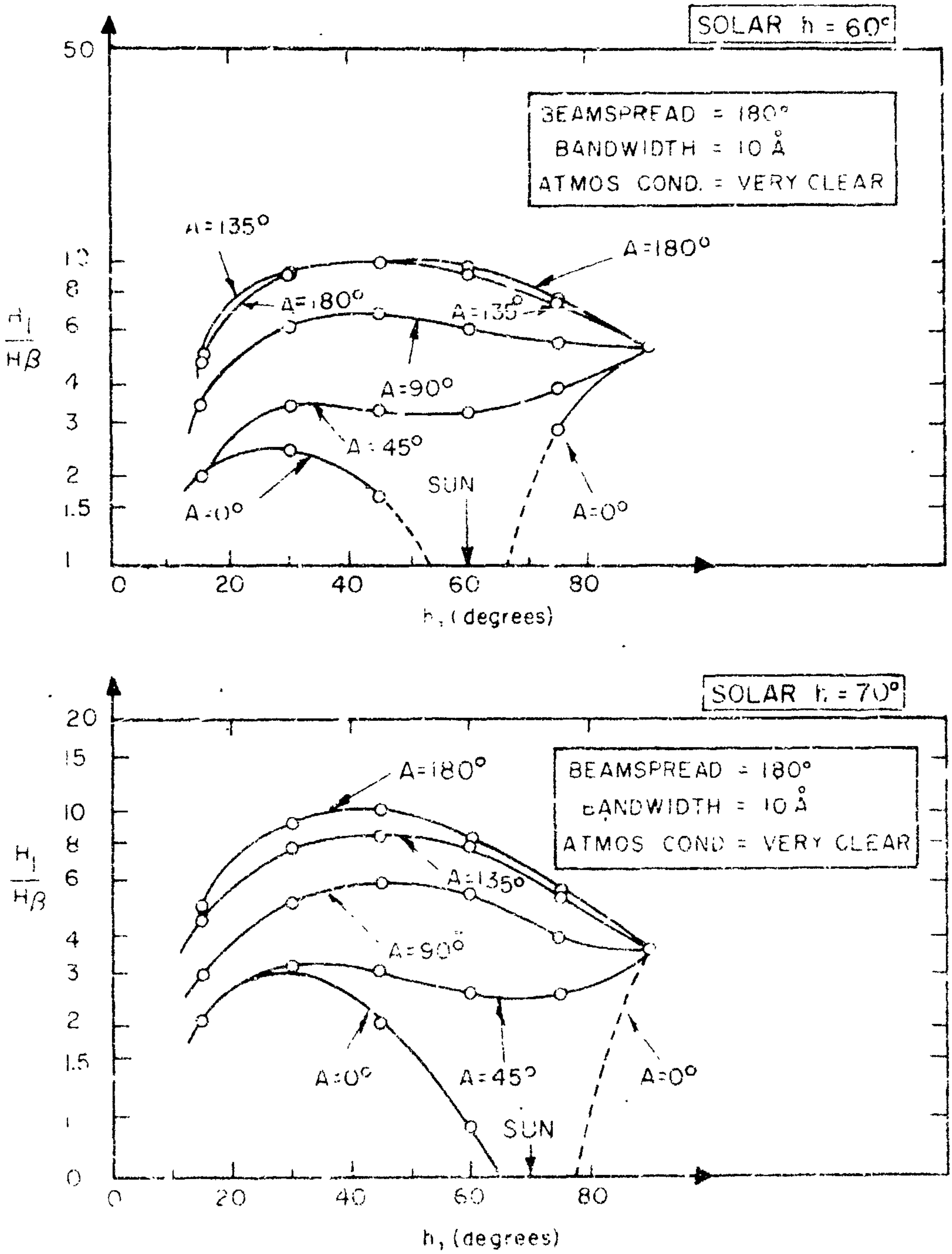
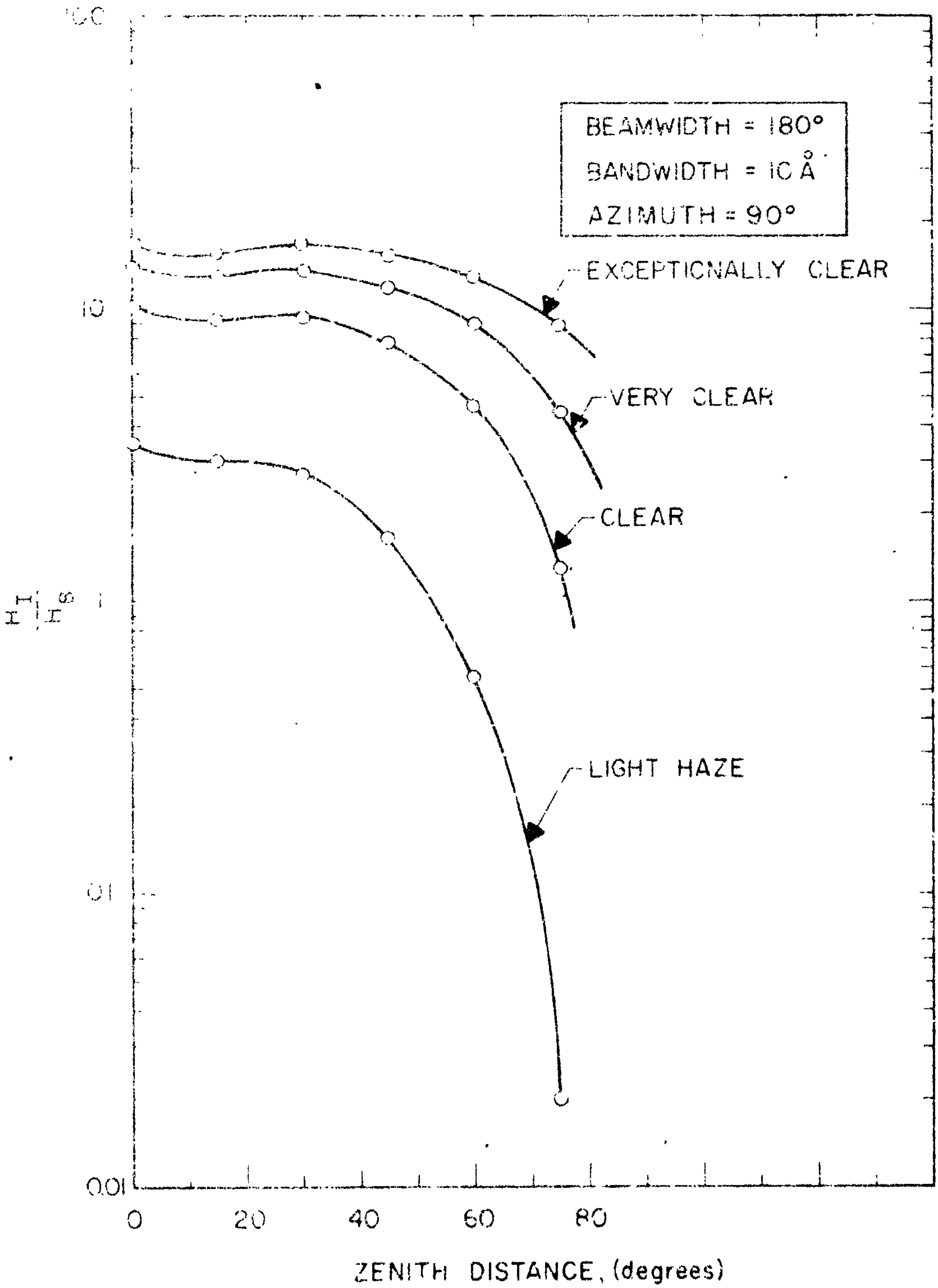


FIG. 4.5 SIGNAL-TO-NOISE EXPOSURE RATIO VS ALTITUDE



1920-Final

FIG. 4.6 AVERAGE SIGNAL-TO-NOISE EXPOSURE VS ZENITH DISTANCE

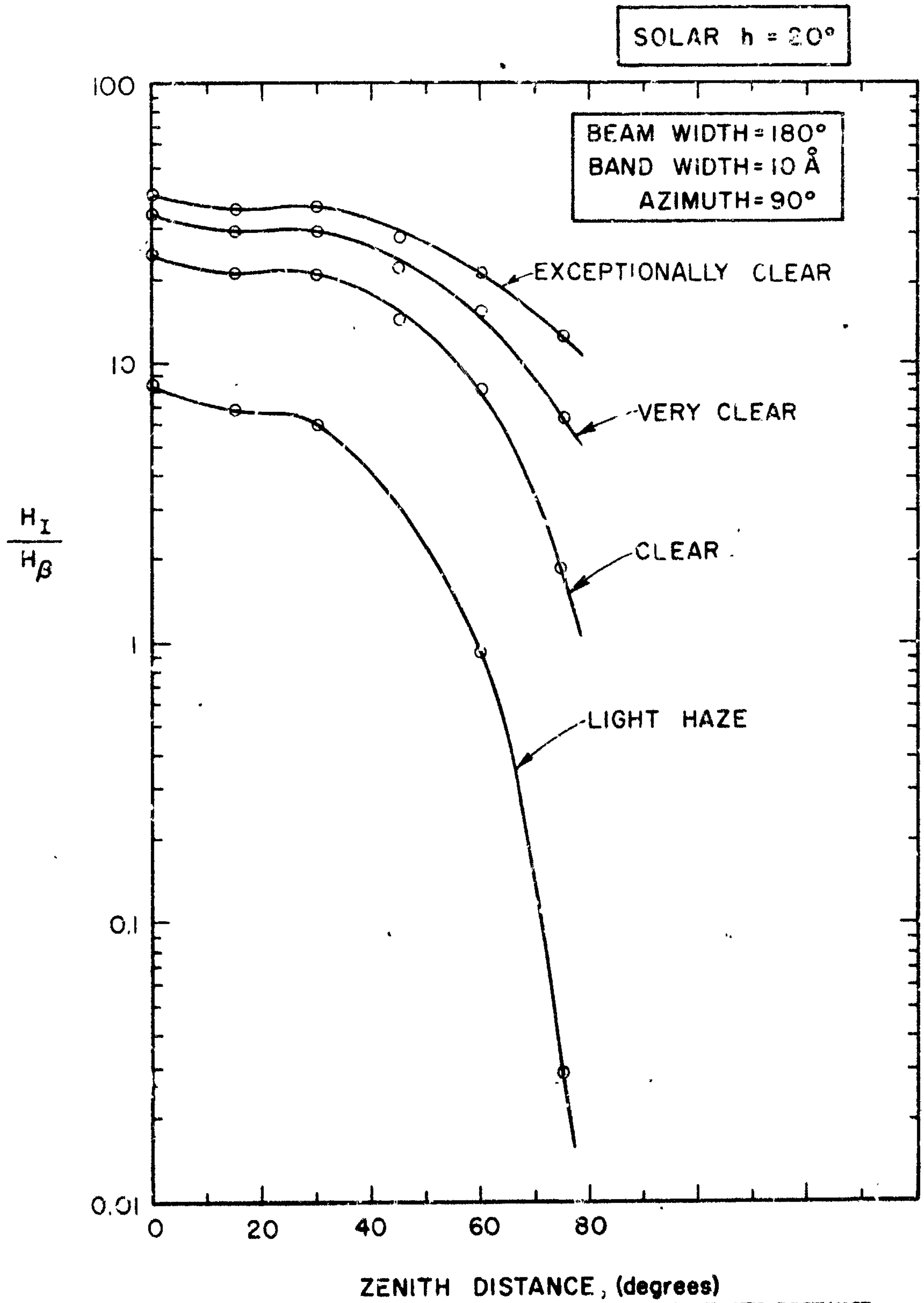
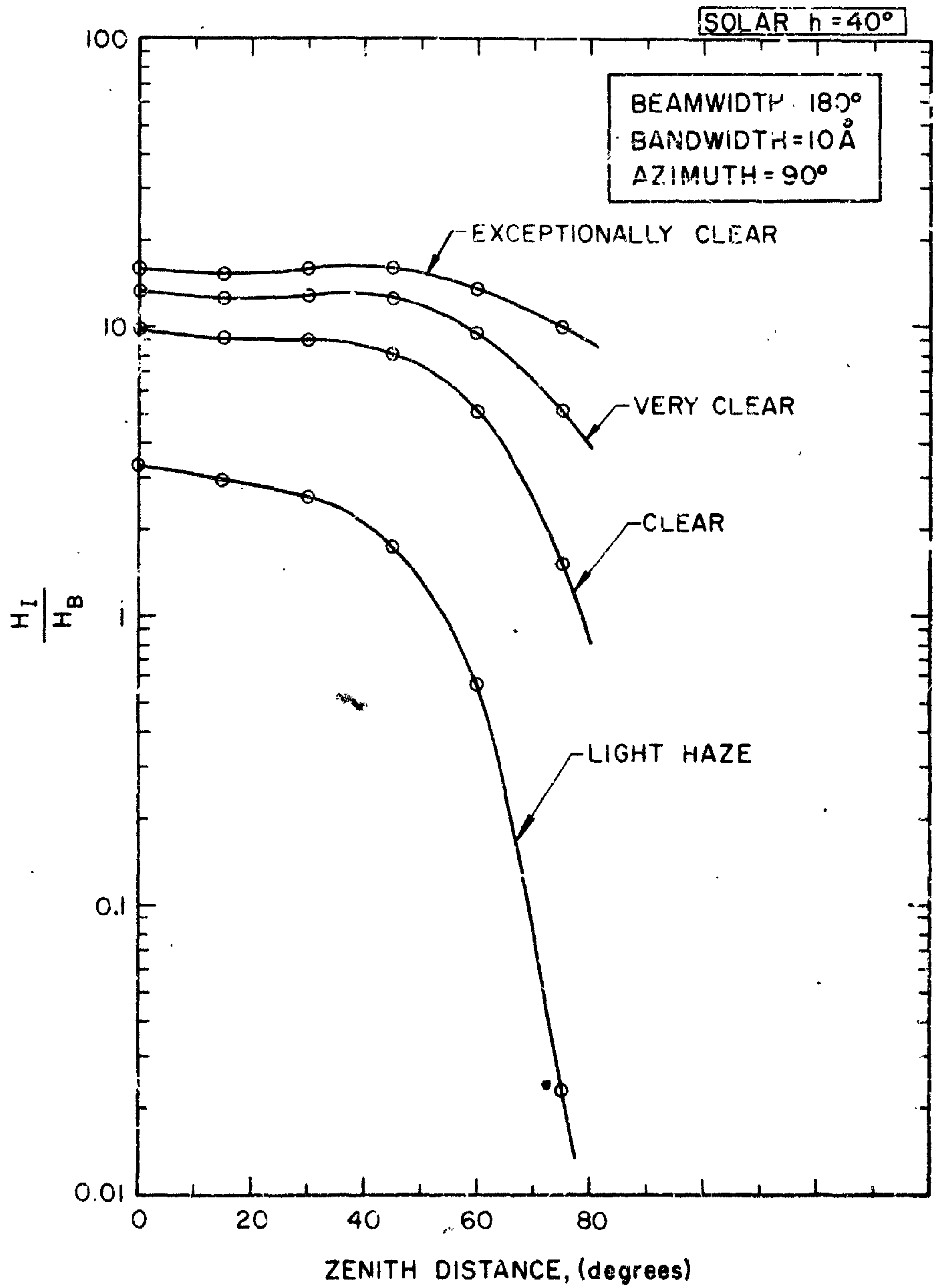


FIG. 4.7 SIGNAL-TO-NOISE EXPOSURE RATIO VS ZENITH DISTANCE



1920-Final FIG. 4.8 SIGNAL-TO-NOISE EXPOSURE RATIO VS ZENITH DISTANCE

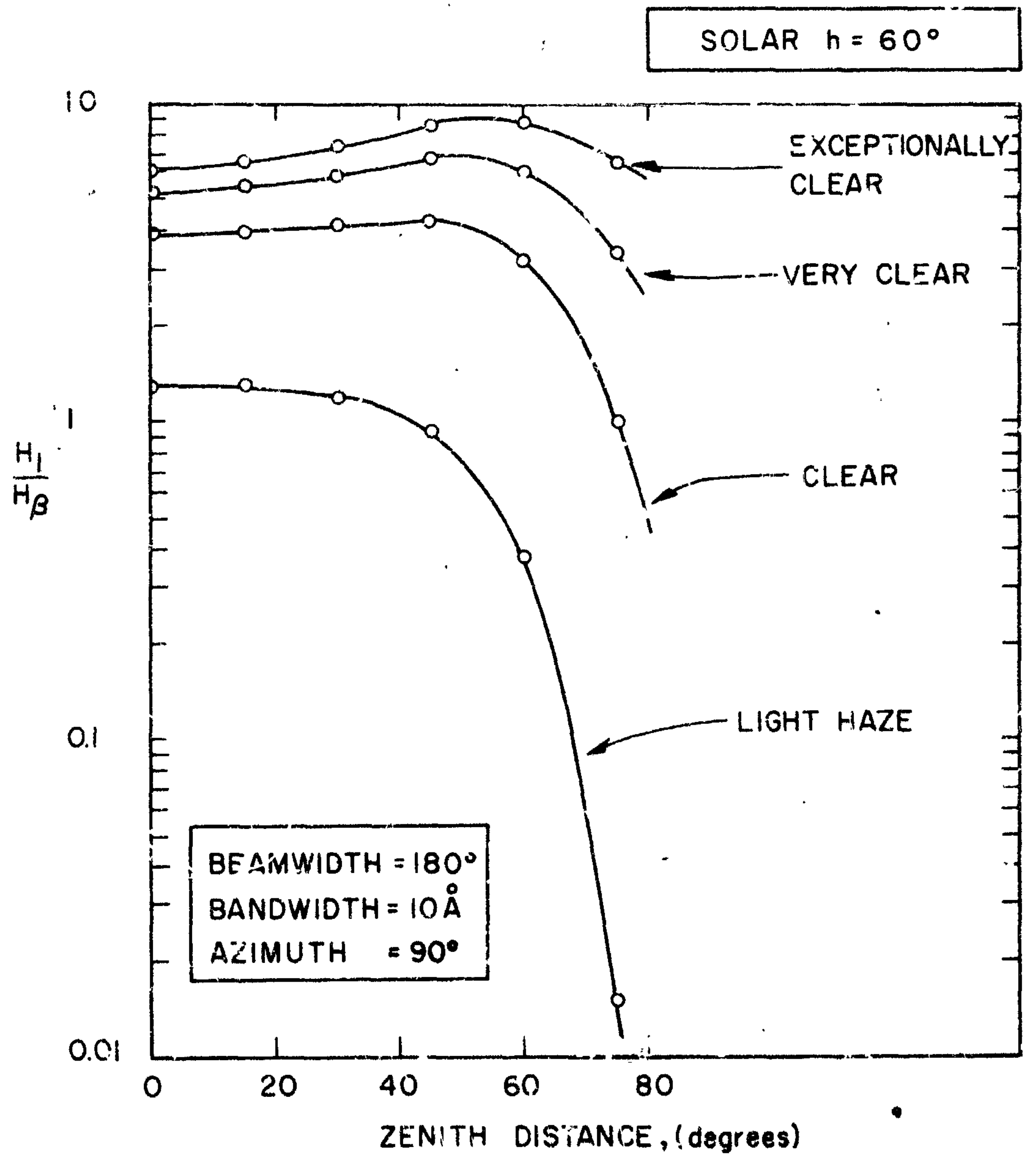


FIG. 4.9 SIGNAL-TO-NOISE EXPOSURE RATIO VS ZENITH DISTANCE

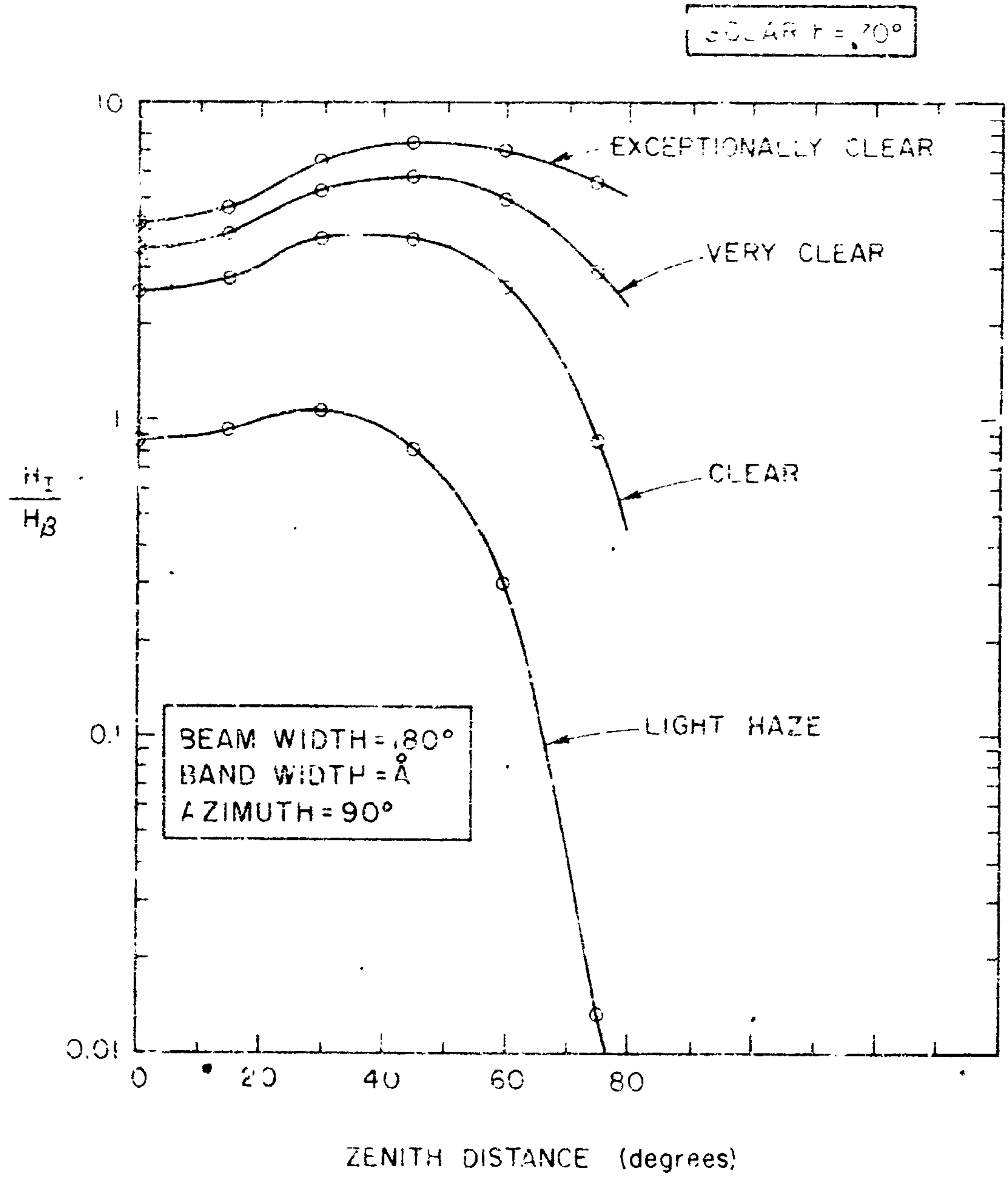


FIG. 4.10 SIGNAL-TO-NOISE EXPOSURE RATIO VS ZENITH DISTANCE

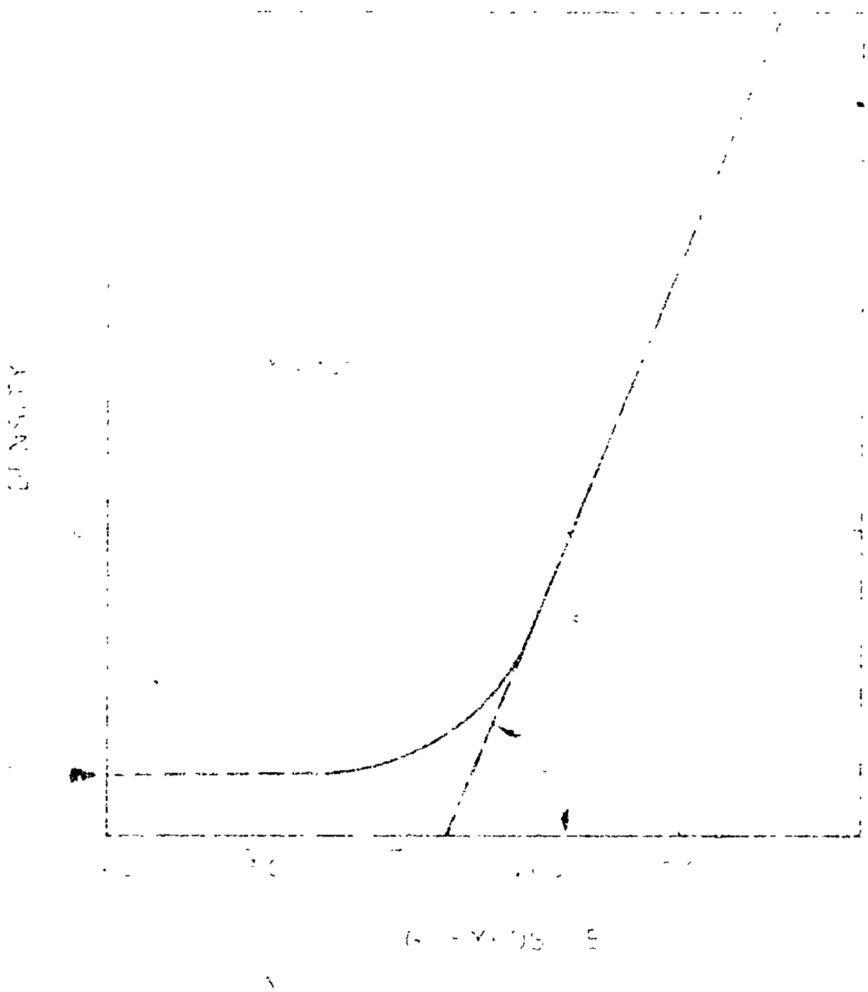


FIG. 4.11 A TYPICAL FILM EXPOSURE CURVE

Thus, for the Kodak 103a - F film, with $\gamma = 2$, we see that the minimum signal-to-noise ratio is 0.056:1, or that the background can be as much as 17 times the signal. It is seen, therefore, that the above signal-to-noise ratios encountered are more than adequate, as long as the beacon does not come within about 10° of the sun and remains at least 15° above the horizon.

5. SIGNAL SENSITIVITY

The minimum signal required is, of course, dictated by the film used. The Kodak 103a - U film, e.g., requires 0.05 erg/cm^2 to produce a density which lies 0.6 units above the fog level [Kodak Photographic Films and Plates For Scientific and Technical Use, 8th Edition, 1960; pages 20 and 24]: the criteria generally taken for film sensitivities.

The laser signal is degraded in at least three areas: transmission through the atmosphere, filter absorption, and losses through the collimator and lens system. For a very clear day and a zenith distance of 45° the transmittance of the atmosphere (λ = 6940 Å) is about 74 percent. A 1 percent (70 Å) bandwidth filter would have a transmittance of about 75 percent.* In Section 3.8, it was stated that the collimator would give an additional 3 percent loss. Thus, the over-all transmittance would be about 54 percent. The image exposure is given by equation (11). Substituting in appropriate values, one gets for H_I a value of 0.023 ergs/cm^2. The signal-to-noise ratio using the above filter would be at least 1:1 over most of the sky, and the total exposure would be at least 0.046 ergs/cm^2. This is seen to be approximately what is required. A number of avenues of approach could be taken to improve the situation. One method is to pre-fog the film,

*It should be mentioned that the cost for a given size interference filter rises rapidly for bandwidths less than 1 percent, e.g., the prices for a 2" x 2" filter manufactured by Baird-Atomic, Inc. are as follows: a 0.1 percent bandwidth costs $375; a 0.7 percent bandwidth costs $150; 1 percent - $100; and 20 percent - $70. In addition, the transmittance increases slightly above a 1 percent bandwidth, but drops off significantly toward the 0.1 percent bandwidth.

or, what amounts to the same thing, larger background noise levels can be tolerated. as the signal-to-noise ratio is much more than needed. Pre-fogging can be achieved in several ways: one method is to expose the photographic film beforehand by a known amount; one can use a wider bandwidth filter with corresponding increase in signal strength; one can use a longer shutter speed; or one can allow overlapping of sky images by a suitably designed collimator. In particular, if the noise is increased 10-fold by, say, using interference filters with 10 percent bandwidths, the total exposure would be at least 0.23 $ergs/cm^2$. Another improvement would be to decrease the angular beam spread of the laser output from 180° to 60°. This will result in a signal improvement of a factor of 8. With weight permitting, one can use two or more lasers which again would double the signal strength.

6. SUMMARY N65-23285

In this report, a description has been given of the various components of a laser beacon together with the problems that will be encountered. The weight of the beacon proper for an uncooled system, excluding components for synchronization, is estimated to be about 22 pounds, and the volume about 650 cu. in.

Author