AN ELECTRO-OPTICAL

TRACKING SYSTEM

by

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ABSTRACT

An electro-optical tracking system for determining the velocity and absolute location of a target and the relative locations of multiple targets is evaluated for resolution, field of view, time tagging, and light level, in order to determine the requirements for a TV camera tube. The ability of three camera tubes to meet the requirements of the system is determined by using dynamic limiting resolution, square wave response, and spectral response.

CHAPTER 1

INTRODUCTION

The problem posed is to evaluate the accuracy and performance of an optical tracking system for determining a target's velocity and absolute location and the relative locations of multiple objects. Although the analysis performed is valid for a large variety of targets, the particular target being tracked is a Minuteman III missile, which has three propulsion stages, accompanying body sections, and cone-shaped projectiles on the reentry vehicle. The reentry vehicle is covered with a shroud during the early stages of flight. The shape of the entire object can be approximated by cylinders and cones.

The target is to be tracked from the launch point, on the California coast, throughout its flight over the Pacific Ocean. The target reaches a maximum range of about 4000 miles from the launch point. The most critical time for tracking is at, and just after, the third stage cutoff. This occurs at about T+185 sec, where T is the time of launch, and at a range of about 200 miles. In general, the path that the target follows is directly away from California-based tracking stations. The missile is therefore seen end on for most of the flight. It is desirable that the target be launched and tracked at any time of day or night, and in any kind of weather. The ability of a system to track with the required accuracies is, however, limited by atmospheric conditions and quantity of the light from the target reaching the detector. During the

propulsion part of the missile's trajectory, the rockets are fired and the plume is clearly visible. Since the plume is the most luminous object in the sky save for the sun, it is tracked rather than the missile itself. The light reflected from the missile is not detected during this time.

After the rockets burn out it becomes necessary to use reflected sunlight to track the missile. The missile is assumed to be a specular reflector having a 10 to 50% reflectance. Because of the amount of light involved, tracking cannot be done during the day, and, in fact, is limited to certain nighttime hours when the missile is illuminated properly. By this time the target is only the reentry vehicle with the projectiles exposed, which appears to travel almost directly in the line of sight of a tracking station. The target is a cylinder of about 8 feet in length and 4 feet in diameter. At the front end are one, two, or more cones, 6 feet in length and 2 feet in diameter. It is likely that the missile will be aligned with only an end toward the tracking station; therefore only the end of a 4-foot-diameter cylinder will be seen, and later, after separation, only the ends of the 2-foot-diameter cones will be seen.

The actual tracking problem is complicated by the high accuracy required. The desired goal of ±1 foot accuracy of the target requires a small field of view. To further complicate the problem, the projectiles are separated from the nose cone and follow different trajectories. Each of these smaller cones must be tracked. This indicates that there is a need for a system having more than one field of view.

The total system consists of conventional radar, tracking the target and aiming a telescope at the position of the radar located target. This must be done so that only the missile and not the jettisoned stages are followed. The location of the target, determined on the TV camera tube of the telescope may then be used (after T+185 sec) to direct another telescope, with a smaller field of view. Each telescope assembly will consist of an optical part (the optical components are not evaluated here) and a TV camera tube, with its photocathode at the image plane. All three telescopes will be tracking at the same time.

During the tracking the target is moving away from the detector sites, and, therefore, the range increases. The more distant the target becomes, the more atmospheric turbulence and absorption affect the system accuracy. The path of the target is such that the angle between the horizon and the detector to target line of sight decreases with time, which also increases the amount of the atmosphere through which the system must perform.

CHAPTER 2

AN ELECTRO-OPTICAL TRACKING SYSTEM

A careful evaluation of the required characteristics of the tracking system must be made to determine its parameters. There are two cases to be considered, tracking before and after the third stage cutoff. These will be discussed separately.

Resolution

The resolution of the system is a measure of its ability to show two object points as two separate points in the image. The desired resolution for this system is one foot on the object. That is to say, two points in the object one foot apart are just distinguishable. Assume that 250 by 250 feet in the object space are imaged into 1 inch on the detector photocathode. One foot of the object corresponds to 2 TV lines (TVL) on the image, where there are 500 TV lines/raster height.

The typical daylight atmospheric seeing might be expected to be as good as 1 arc second. A 1-foot object-space resolution at a range of 250 n.mi., 1.5×10^6 feet, implies an angular resolution of 0.6 μrad, or 0.14 arc second. This means that 1-foot object-space resolution is approximately 10 times greater than the atmospheric seeing limit. It is obvious that ±1 foot of resolution will not be possible to achieve.

A more realistic figure would be obtained by using resolution only half the atmospheric seeing limit. This is equal to 5 feet at the object, which corresponds to 2 TV lines for 100 TV lines/raster height resolution across the detector.

Field of View

The object field imaged by a system is called the field of view (FOV). The FOV is a property of a telescope and is the full angle subtended by the object at the telescope aperture. In order to keep the entire plume in the image, a region of 250 by 250 feet is required at a range of 250 n.mi. For small angles, θ equals tan θ, which equals the object height divided by the object-to-telescope distance. This means that for an image height of 250 feet at a range of 250 n.mi., a FOV of 34 arc seconds is required.

After T+185 sec the problem changes. The plume is no longer visible, and the original target divides into as many as three separate targets. In order to keep all the targets in the same field, the required FOV is between 18 arc-min and 6°. To get the best resolution possible, a 34 arc-sec FOV is still necessary. Therefore a cascaded system, employing three separate telescopes with three different FOV's is proposed. Each FOV is associated with a telescope and the three telescopes, 6°, 18 arc-min, and 34 arc-sec, work at the same time. This will enable one camera to keep all targets in the field, (6° telescope) locating the position of a particular target so that the smaller field-of-view system (34 arc-min telescope) can obtain the accuracy required.

Photometric Evaluation

Basically what is required of a detector is that it be able to resolve the image of the target against the sky background. This is dependent upon the illuminance at the focal plane of the optical system.

The first step in the procedure is finding the illuminance, E, due to a source. The total illuminance at the telescope due to the source, E_{Tel}, is, from the definition of illuminance (RCA, 1974) the amount of luminous flux per area. Knowing that the total luminance, L, due to a source is the amount of luminous flux per area-steradian, which is a function of wavelength, gives the total illuminance at the telescope aperture as

$$E_{Tel} = L\, T_A\, \frac{A_T\, A_o}{d^2\, A_T} = \text{lumens/area} \; . \qquad (1)$$

In this equation T_A is the transmission of the atmosphere, A_o is the area of the source, A_T is the area of the telescope aperture, and d is the distance from the source to the telescope, which is the object distance (Fig. 1).

The total illuminance, E, at the image plane of the telescope is the illuminance of the telescope pupil, times the transmission of the telescope, times the ratio of the areas of telescope and image

$$E = E_{Tel}\, T_T\, \frac{A_T}{A_I} \; . \qquad (2)$$

Here T_T is the transmission of the telescope and A_I is the area of the image. The magnification squared, of a telescope, is the area of the image divided by the area of the object. It is also equal to the square

of the image distance, f, divided by the object distance, d

$$\frac{A_I}{A_o} = \frac{f^2}{d^2} . \qquad (3)$$

When Eq. (3) in terms of A_o, f and d, and Eq. (1) are put into Eq. (2), terms cancel to give the final result that

$$E = L\, T_A\, T_T \frac{A_T}{f^2} . \qquad (4)$$

It is important to note that the illuminance due to a source depends only upon the luminance of the source, the F/number of the telescope, and the transmissions.

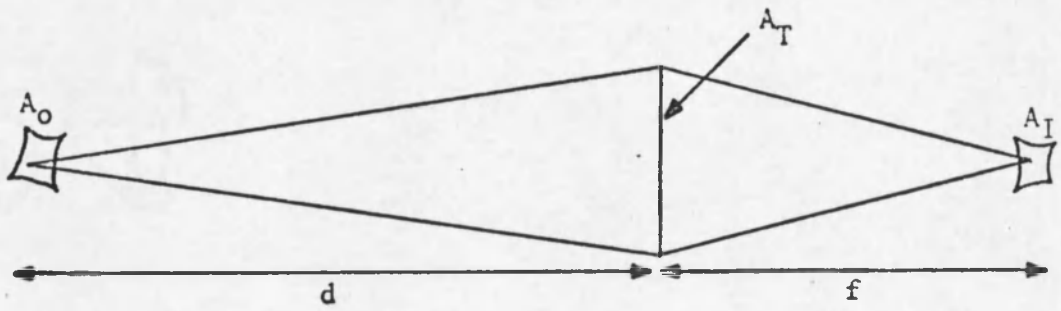


Fig. 1. Photometric Evaluation: Diagram Showing the Parameters Used in Determining the Total Illuminance.

Sky Source

For the case where the source is the sky, on a clear day, the value of luminance for the daylight sky near the horizon is 10^4 lumens/m^2-sr, and for the half hour after sunset, it is 10^{-1} lumens/m^2-sr, also for the sky near the horizon (Table 1).

Table 1. Approximate Values of the Luminance of the Sky near the Horizon under Various Conditions (RCA, 1974, p. 70).

Sky Condition	Approx. Values of Luminance-- (lumens/m^2-sr)
Clear Day*	10^4
Overcast day	10^3
Heavily overcast day	10^2
Sunset, overcast day	10
1/4 hour after sunset, clear	1
1/2 hour after sunset, clear	10^{-1}
Fairly bright moonlight	10^{-2}
Moonless, clear night sky	10^{-3}
Moonless, overcast night sky	10^{-4}

*The upper surface of a fog or cloud in sunshine may also have this value.

If these values are called L_s, where $L_s = L\ T_A$ is the luminance of the sky, at the focal plane the value of the illuminance, E_s, due to the sky, is given by

$$E_s = L_s\ T_T \frac{A_T}{f^2} . \qquad (5)$$

Therefore E_s for a clear day is $E_s(\text{day}) = 0.8 \times 10^4 \frac{A_T}{f^2}$, and for a half hour after sunset, $E_s(\text{night}) = 0.8 \times 10^{-1} \frac{A_T}{f^2}$, where the transmission of the telescope, T_T is approximately 80%.

Plume Source

Before T+185 sec the target is the plume, which can be approximated by a blackbody radiator of absolute temperature of 2000°K. The radiance of the plume, L_λ, is dependent upon the wavelength of a radiometric source and can be converted to photometric units. The total power for the black or graybody is $\varepsilon\sigma T^4$, where ε is the emissivity of the graybody, T is the absolute color temperature of the source, and σ is the Stefan-Boltzmann constant, 5.6686×10^{-8} W/m^2-deg^4. Assuming that the source is a Lambertian surface, L_λ is the total power divided by π. That is,

$$L = \frac{\varepsilon\sigma T^4}{\pi} . \tag{6}$$

Assuming ε to be one, the value of L used here is 2.891×10^5 W/m^2-sr. The total radiance, L_λ, is then multiplied by 1.8 lumens/Watt, the luminous efficacy for a 2000°K blackbody. Luminous efficacy is the ratio of the total luminous flux to the total radiant flux. It is therefore used to convert flux in watts to flux in lumens. The value of luminous efficacy used here is obtained from Fig. 2. The final calculated value for the luminance of the plume, L_p, which is 5.2×10^5 lumens/m^2-sr, is used in Eq. (4). The value of the illuminance from the plume, on the focal plane, E_p, is

$$E_p = L_p \, T_A \, T_T \frac{A_T}{f^2} = 2.5 \times 10^5 \frac{A_T}{f^2} \tag{7}$$

where T_T is 0.8 and the value for T_A can be obtained from Fig. 3.

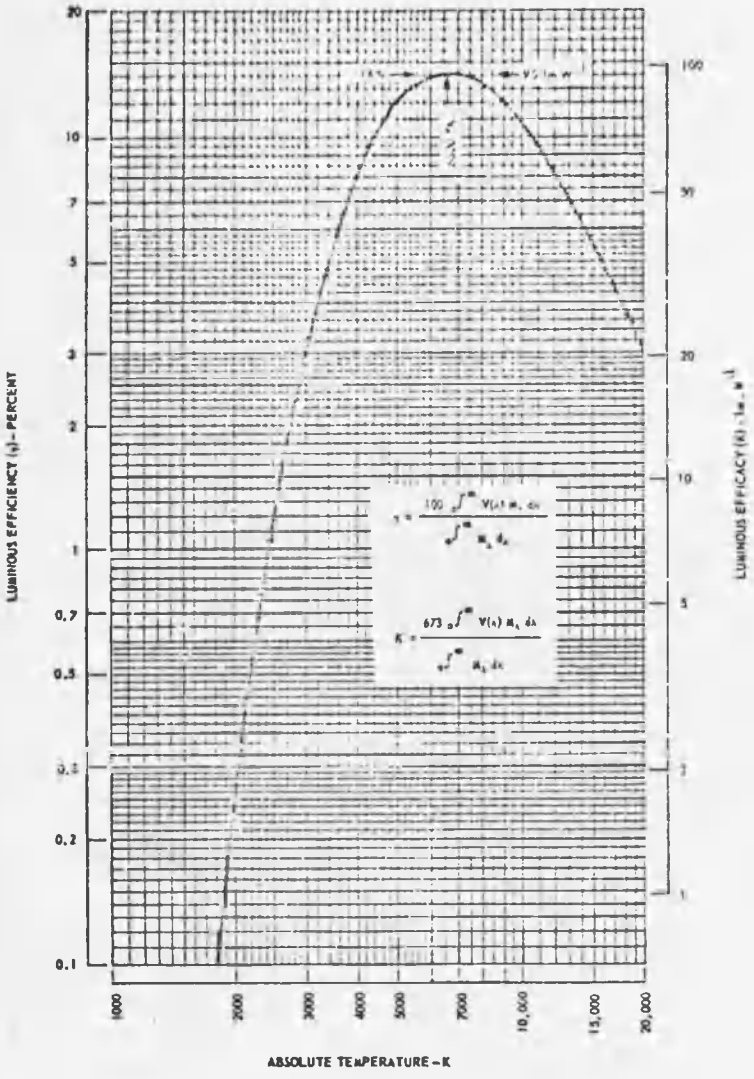


Fig. 2. Luminous Efficacy K of Blackbody: as a Function of its Absolute Temperature where M_λ is the Spectral Radiant Exitance of the Blackbody and V_λ is the Relative Spectral Response of the Average Human Eye (RCA, 1974,p. 41).

An approximation for the transmittance value for the atmosphere on a day with excellent visibility (greater than 50 mi.), and a zenith angle of 60°, is 60%.

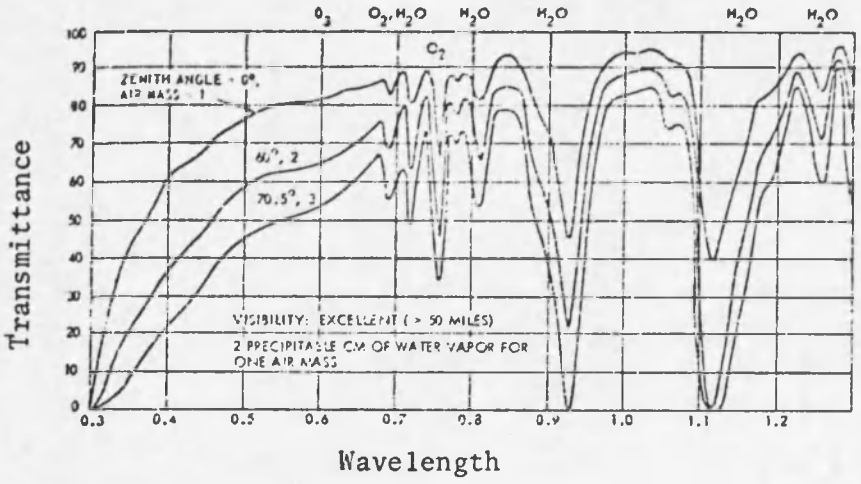


Fig. 3. Spectral Transmission of the Earth's Atmosphere for Varying Optical Air Masses (RCA, 1974, p. 83).

The ratio of E_p to E_s for the case before T+185 sec is,

$$\frac{E_p}{E_s(\text{day})} = 3.1 \times 10$$

$$\frac{E_p}{E_s(\text{night})} = 3.1 \times 10^6 \ .$$

Contrast Enhancement

At night there is sufficient target-to-sky contrast to track the 2000°K source. Based on assumptions previously discussed, the contrast ratio, E_p/E_s, is better than 10:1, during the day also. Since these are assumptions, there may be times when the final system may still need enhancement. Two possible ways are using a red filter and using a polarizer.

The spectral distribution of day skylight can be approximated by a blackbody between 20,000°K and 25,000°K (RCA,1974,p.70). The relative

spectral distribution of sky light in the longer wavelengths, as compared to the spectral distribution of a 2000°K source is 240% and for the skylight it is 50%, of their radiances at 560 nm, for a ratio of (4.8:1) about 5 to 1 (Fig. 4).

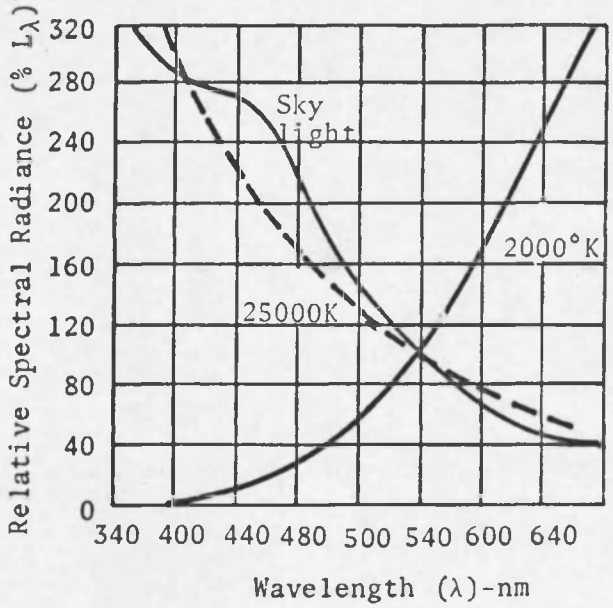


Fig. 4. Spectral Distribution of Sky Light on a Clear Day.

Dashed curve shows the spectral distribution of radiation from a blackbody at 25,000°K. Spectral distribution of a 2000°K source is also included. 100% spectral radiance is assumed at 560 nm (RCA, 1974, p. 71).

Day sky light is polarized, and a polarizer will therefore seem to aid contrast enhancement. The amount of this enhancement is hard to determine because for different times of day and different positions of the target (different portions of the sky and different viewing angles) the background polarization varies in percentage. The relative angles for the situation being considered, with the target to the west, indicate that a polarizer will not improve the contrast.

When observed transversly there is no component of sunlight in the direction the light is traveling (longitudinal)(Fig. 5).

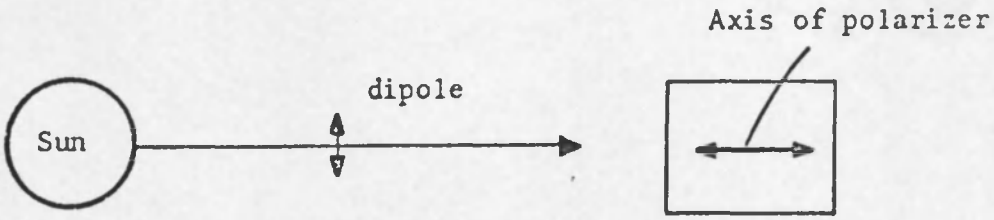


Fig. 5. Polarization of Sunlight.

Result is no light through the polarizer.

The situation for total polarization can only exist at an angle of 90° to the sun. This total polarization of light will happen only at noon, because the target is generally in the west and in other situations the sky light will not be seen transversly, but at some angle. Therefore, sun light will be partially polarized and the light from the plume will be non-polarized.

In Gehrels' article (162, p. 1164), "the blue sky was observed near 90° from the sun, in the vertical plane through the direction of the sun, with the sun above and just below the horizon. For a normal clear sky...with the sun 11°.5 above the horizon, 75% polarization was found at 5500Å." Other values for the polarization of the sky can be found in the article by Gehrels and in Table 2, which was taken from it. At best, the polarization of the sun light will not be more than 75% and probably an average of 63% [number calculated from Gehrels (1962, Table 2)]. This indicates that using a polarizer will not appreciably improve the illuminance contrast ratio.

Table 2. Averages of Percentage Polarization; Normalized to 61.1% at $1/\lambda$=1.89 (Gehrels, 1962, p. 1169).

Conditions	Average polarization at $1/\lambda$					
	1.06	1.26	1.46	2.29	2.82	3.08
	%	%	%	%	%	%
Sun below horizon	64.8	62.7	---	---	52.3	---
Sun above horizon	50.7	55.3	---	---	52.3	---
Clear sky	45.8:	55.2:	58.1:	59.2:	53.3	48.6:
Sky not perfectly clear	42.3	---	55.6	61.7	54.1	52.4
Infrared polarization high	59.0	60.7	---	---	51.9	---
Infrared polarization low	42.2	51.8	55.3	59.7	53.7	49.8

$1/\lambda$ = 1.89 corresponds to λ = 5290Å
= 1.46 corresponds to λ = 6850Å
= 2.29 corresponds to λ = 4370Å

Time Tagging Before T+185 Sec

The total amount of energy incident upon the image plane of the telescope, is proportional to the amount of time involved. If the photocathode of a TV camera with standard integration time is placed in the image plane of a telescope the frame rate is 30 frames per sec, or a 1/30 sec exposure.

One of the requirements of the system to be designed is that "time tagging" be included, which means a very short picture exposure time. For example, for a 10 μsec time resolution the total amount of effective illuminance will be reduced by 10^5, as compared to a 1 sec exposure.

The final values for illumination levels before T+185 sec are shown in Table 3.

Table 3. Focal Plane Source and Background Illumination Levels: Including Time Tagging, Before T+185 sec, A_T is 6.3 ft^2 and f is 691.7 ft.

FOV	Bright Sky E_s (day) lumens/m^2)	Dark Sky E_s (night) (lumens/m^2)	2000°K Source E (lumens/m^2)
34"	1.1×10^{-6}	1.1×10^{-11}	3.3×10^{-5}

Target Source

After T+185 seconds the target is not a source of light. It can, however, reflect light from the sun. The illumination due to the sky background is the same as previously evaluated. The following section closely follows the Appendix of the Optical Tracking System Interim Report, Optical Sciences Center (1975).

A Fortran IV program was written to calculate the ground illuminance, EG, at the optical site due to reflected sunlight from the target. The value for EG obtained versus target range and various sun positions is then used to calculate the focal plane illumination due to the target, ET, as a function of the optical system f-number.

In the computer program latitude and longitude of the optical site are converted to earth-center-fixed (ECF) coordinates (Fig. 6). Luminous intensity (JTOTAL) is the effective luminous intensity (lumen/sr) of the target, treating it as a point source. The comment cards in the program listing describe the required input information and the output (see Appendix). Figures 6 through 10 describe the

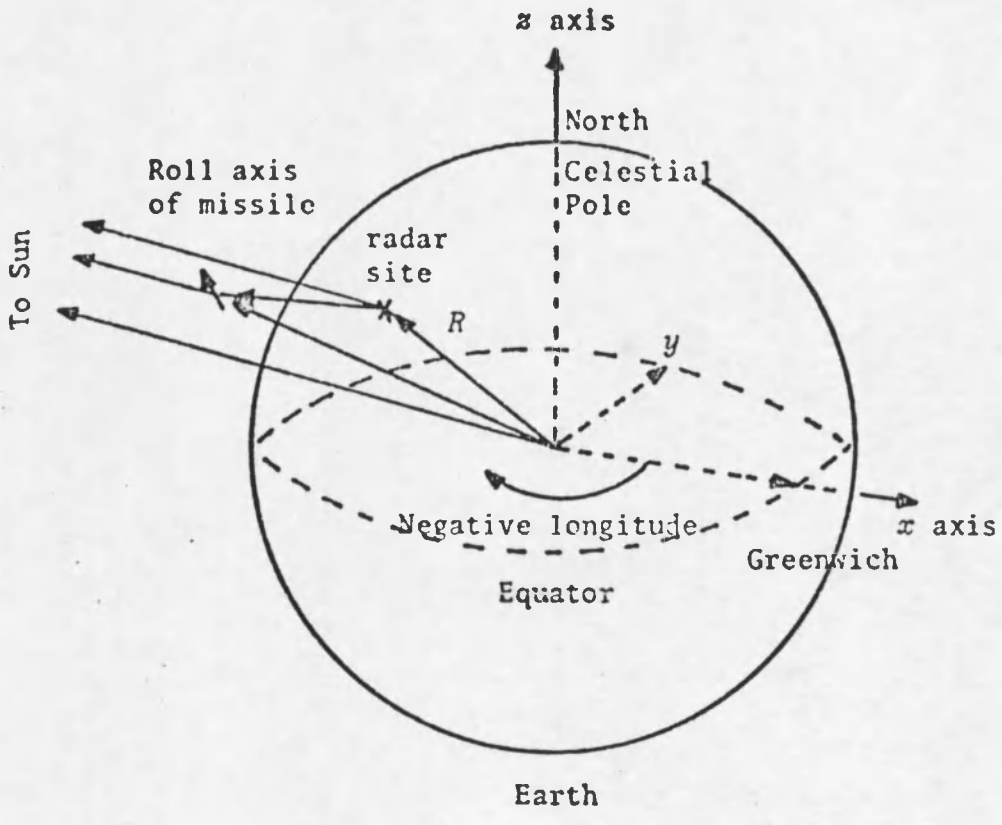


Fig. 6. Description of ECF Coordinate System.

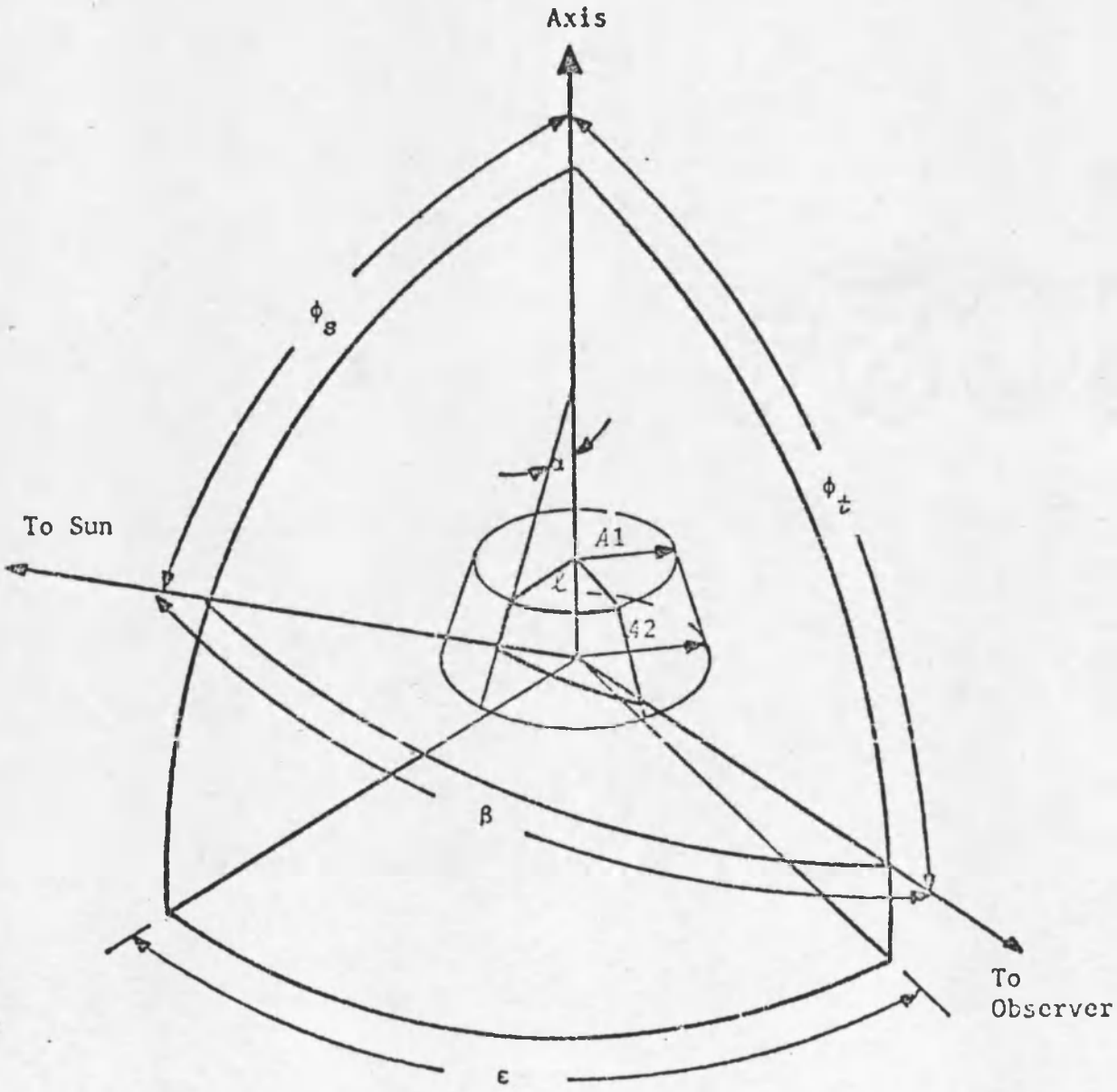


Fig. 7. Diffuse Reflecting Cone Variables
(Scott et al., 1960, p.13).

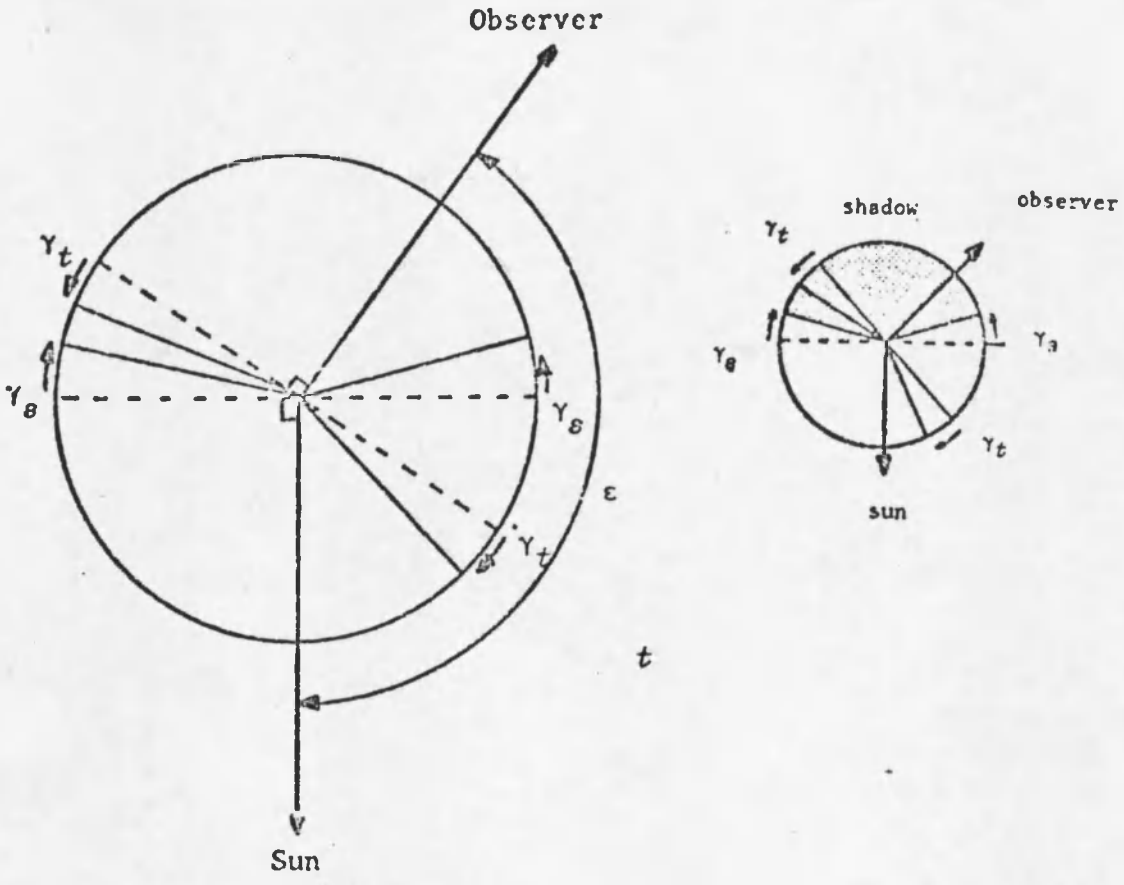


Fig. 8. Base of Cone: Angles Used in Subfunction FRUST.

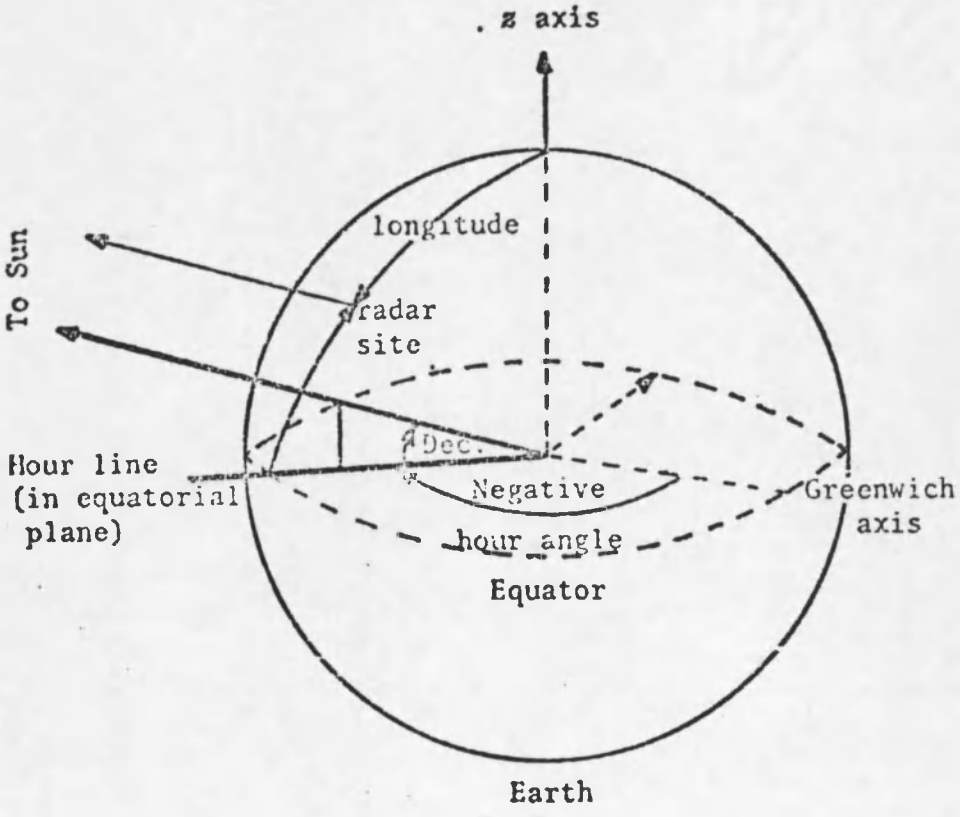


Fig. 9. Conversion of Solar Hour Angle and Declination to ECF.

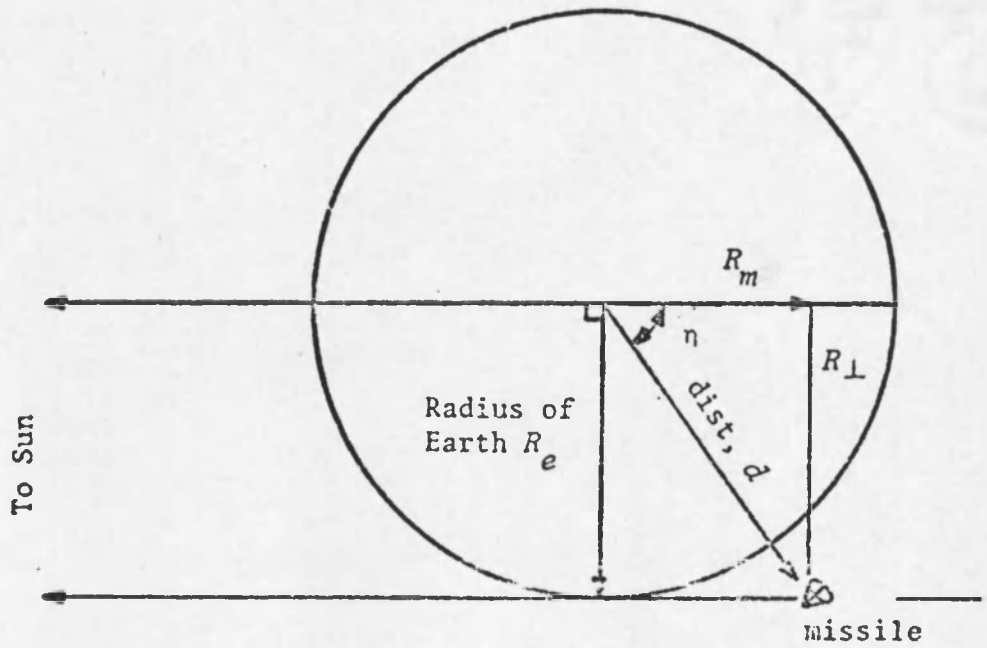


Fig. 10. Describing Subfunction LIGHT.

various parameters used in calculating the ground illuminance and focal plane illumination.

In the calculations, the shape of the missile is described in terms of cylinders and cones (Fig. 11). It can be shown (Scott et al., 1960) that the apparent radiant intensity, J, of a diffusely reflecting cylinder is given by

$$J_{cylinder} = \frac{\rho}{\pi} H_s \frac{a\ell}{2} \{[(\pi-\varepsilon)\cos\varepsilon+\sin\varepsilon]\sin\phi_s \sin\phi_t\} \tag{8}$$

where H_s is the illuminance from the sun, ρ is the spectral reflectance, a is the radius, ℓ is the length of the cylinder, ϕ_s and ϕ_t are the angles from the cylinder axis to the direction of irradiance and to the direction of observation, respectively, and

$$\cos\varepsilon = \frac{\cos\beta - \cos\phi_s\cos\phi_t}{\sin\phi_s\sin\phi_t} \tag{9}$$

The case for the diffusely reflecting cone, and by implication the frustum as well, is given by Eqs. (10) below, which are corrected versions of the results given in Scott et al. (1960). Figure 7, page 17, shows the relations between the variables. Equations (10) must each be multiplied by

$$\frac{\rho}{\pi} H_s \frac{(a_1 + a_2)\ \ell \cos\alpha}{4}$$

to obtain the apparent intensity of the object.

Case 1: The entire surface of the object is both seen and irradiated (object head-on or nearly so):

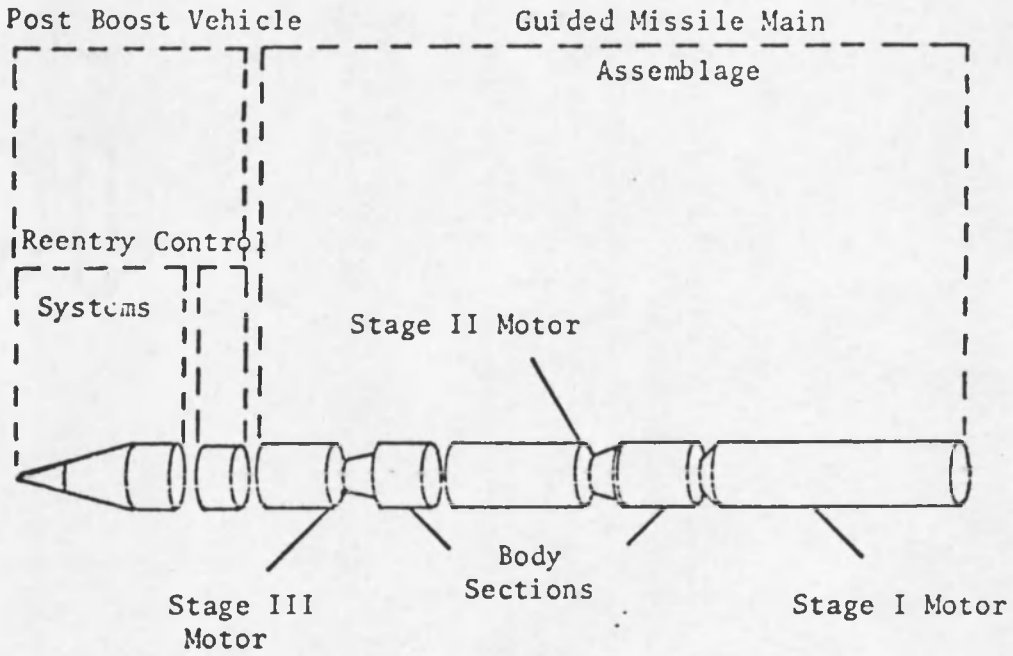


Fig. 11. Minuteman III PRD, Shape.

$$\phi_s \leq \alpha,\ \phi_t \leq \alpha$$

$$2\pi\ (2\ \cos\phi_s\ \cos\phi_t\ \tan^2\alpha + \cos\varepsilon\ \sin\phi_s\ \sin\phi_t). \qquad (10a)$$

Case 2: The entire surface of the object is seen but not fully irradiated:

$$\phi_s \leq \alpha,\ \phi_t \geq \alpha$$

$$2\ (\pi + 2\gamma_t)\ \cos\phi_s\ \cos\phi_t\ \tan^2\alpha$$
$$+ 4\ \cos\gamma_t\ \cos\phi_s\ \sin\phi_t\ \tan\alpha$$
$$+ 4\ \cos\varepsilon\ \cos\gamma_t\ \sin\phi_s\ \cos\phi_t\ \tan\alpha$$
$$+ [(\pi + 2\gamma_t) - 2\ \sin\gamma_t\ \cos\gamma_t]$$
$$\cdot\cos\varepsilon\ \sin\phi_s\ \sin\phi_t. \qquad (10b)$$

Case 3: The entire surface of the object is irradiated but not fully seen:

$$\phi_s \geq \alpha,\ \phi_t \leq \alpha$$

$$2\ (\pi + 2\gamma_s)\ \cos\phi_s\ \cos\phi_t\ \tan^2\alpha$$
$$+ 4\ \cos\varepsilon\ \cos\gamma_s\ \cos\phi_s\ \sin\phi_t\ \tan\alpha$$
$$+ 4\ \cos\gamma_s\ \sin\phi_s\ \cos\phi_t\ \tan\alpha$$
$$+ [(\pi + 2\gamma_s) - 2\ \sin\gamma_s\ \cos\gamma_s]$$
$$\cdot\cos\varepsilon\ \sin\phi_s\ \sin\phi_t. \qquad (10c)$$

Case 4: The entire surface of the object is neither fully seen nor fully irradiated; two bands of irradiation apparent:

$$\phi_s \geq \alpha,\ \phi_t \geq \alpha,\ \gamma_s \leq 0,\ \gamma_s + \gamma_t \geq \pi - \varepsilon$$

$$4\ (\gamma_s + \gamma_t)\ \cos\phi_s\ \cos\phi_t\ \tan^2\alpha$$
$$+ 4\ (\cos\gamma_t + \cos\varepsilon\ \cos\gamma_s)\ \cos\phi_s\ \sin\phi_t\ \tan\alpha$$
$$+ 4\ (\cos\gamma_s + \cos\varepsilon\ \cos\gamma_t)\ \sin\phi_s\ \cos\phi_t\ \tan\alpha$$
$$+ 2\ [(\gamma_s + \gamma_t) - \sin\gamma_s\ \cos\gamma_s - \sin\gamma_t\ \cos\gamma_t]$$
$$\cdot \cos\varepsilon\ \sin\phi_s\ \sin\phi_t. \qquad (10d)$$

Case 5: The entire surface of the object is neither fully seen nor fully irradiated; one band of irradiation apparent:

$\phi_s \leq \alpha,\ \phi_t \geq \alpha$, for γ_s & γ_t both positive; $\gamma_s + \gamma_t \leq \pi - \varepsilon$,

for γ_s or γ_t negative, or both; $\varepsilon - \pi \leq \gamma_s + \gamma_t$

$$2\ [(\pi - \varepsilon) + (\gamma_s + \gamma_t)]\ \cos\phi_s\ \sin\phi_t\ \tan^2\alpha$$
$$+ 2\ [\cos(\varepsilon - \gamma_s) + \cos\gamma_t]\ \cos\phi_s\ \sin\phi_t\ \tan\alpha$$
$$+ 2\ [\cos\gamma_s + \cos(\varepsilon - \gamma_t)]\ \sin\phi_s\ \cos\phi_t\ \tan\alpha$$
$$+ [\{(\pi - \varepsilon) + (\gamma_s + \gamma_t) - \sin\gamma_s\ \cos\gamma_s$$
$$+ \sin(\varepsilon - \gamma_t)\ \cos(\varepsilon - \gamma_t)\}$$
$$\cdot \cos\varepsilon + \{\cos^2\gamma_s - \cos^2(\varepsilon - \gamma_t)\}\ \sin\varepsilon]$$
$$\cdot \sin\phi_s\ \sin\phi_t. \qquad (10e)$$

In all cases,

$$\cos\varepsilon = \frac{\cos\beta - \cos\phi_s \cos\phi_t}{\sin\phi_s \sin\phi_t}$$

$$\sin\gamma_s = \frac{\tan\alpha}{\tan\phi_s}$$

$$\sin\gamma_t = \frac{\tan\alpha}{\tan\phi_t},$$

where

α = generating angle of cone

β = angle between direction of irradiation and direction of observation

ϕ_s = angle between cone axis and direction of irradiation

ϕ_t = angle between cone axis and direction of observation

ε = dihedral angle between planes of ϕ_s and ϕ_t

$\frac{\pi}{2} + \gamma_s$ = (terminator for the solar illumination) limiting angle of irradiation in plane of ε

$\frac{\pi}{2} + \gamma_t$ = (terminator for the observer) limiting angle of observation in plane of ε.

These equations are used in subfunction FRUST (Fig. 8, page 18). When sunlight hits the cone at any angle not in the plane of the cone's base ($\phi_s \neq 90°$) the part of the cone lit will not be equal to half the cone. The two extreme cases are:

1. $\phi_s = 0°$ where the sun is seen head-on and the entire cone is lit, and

2. ϕ_s just greater than α (where α is the cone angle of the cone) where the sun barely hits the surface and only a small area is lit.

The same situation occurs for the observer where the area involved is that viewed. γ_s and γ_t are the angles, on the cone base, that are the angular difference from the direction lit or viewed. They define the area that is actually seen [see Eqs. (10)]. A band of irradiation appears to be just that. Because of the angle of illumination and viewing, only part of the lit cone is seen, i.e., a band of light.

The computer program converts latitude and longitude of the optical site into ECF, earth center fixed, coordinates (Fig. 6, page 16). Position of the radar site, initially in longitude, latitude, and R, the range, are converted to an x,y,z coordinate system. The position of the sun is given by its hour angle and converted to a direction vector. ϕ_t is found by the scalar dot product of the missile roll axis and the vector from the radar site to the rocket. The sun is effectively at infinity and the direction of the sun is constant over the surface of the earth. (Longitude is measured counterclockwise from x to y axis, i.e., California is -120° longitude.) The hour angle for the sun (Fig. 9, page 19) is determined by deciding how many hours before or after noon, at a specific longitude, are desired. Multiplying that by 15° per hour (-15° for after noon) and adding that amount to the longitude determines the degrees from noon at Greenwich. A nautical almanac will give a declination angle for the sun for a given day of the year (and hour after Greenwich noon).

Subfunction LIGHT (Fig. 10, page 20) determines whether or not the missile is either in sunlight or in shadow. The Earth is in the plane of solar incidence and the missile. X_m, Y_m, and Z_m are ECF for the missile. AL, BE, and GA are the ECF direction cosines for the sun, and

$$d = (AL \times X_m) + (BE \times Y_m) + GA \times Z_m)$$

$$R_m = (X_m^2 + Y_m^2 + Z_m^2)^{\frac{1}{2}}$$

$$R_\perp = (d^2 - R_m^2)^{\frac{1}{2}}$$

If η is greater than 90° the missile is in light. If η is less than 90° but the perpendicular distance is greater than the radius of the Earth, the missile is in light. (R_m is the component of distance in the direction of the sun. The perpendicular distance is found by the Pythagorean theorem).

The computer solution of the expected focal plane illumination for the half hour before sunrise, the half hour after sunset and 1 and 2 hours after sunset, for the case where $\rho = 0.1$, and $H_s = 1.27 \times 10^4$ lumens/ft^2 (illuminance from the sun), is shown in Table 4 for 260 n.mi. range. To convert these numbers to lumens/m^2 multiply by 10.76. There are additional factors of T_A and T_T that are assumed equal to 0.6 and 0.8, respectively. Therefore, the focal plane illumination due to the plume E_t

$$E_t = ET\ T_A\ T_T\ (10.76) = ET\ (5.16). \qquad (11)$$

For $\rho = 0.5$, E_t is a factor of 5 larger and

$$E_t = ET\ (25.8). \qquad (12)$$

Table 4. Focal Plane Illuminations (lumens/ft^2) Due to Target at a Range of 260 n.mi.

	Illuminations (ET) ρ=0.1 (lumens/ft^2)			
F/Number	½ hr before sunrise	½ hr after sunset	1 hr after sunset	2 hr after sunset
1	8.2×10^{-1}	1.1	1.1	9.9×10^{-1}
11	6.8×10^{-3}	9.0×10^{-3}	9.1×10^{-3}	8.2×10^{-3}
232	1.5×10^{-5}	2.0×10^{-5}	2.0×10^{-5}	1.8×10^{-5}

Launch Window

The situation where light reflected from the target is greater than the background light is when the target rises above the shadow of the earth and the detector is in darkness. The launch windows are where this lit-target, dark-detector situation occurs. The launch window is acceptable for two hours after sunset and a half-hour before sunrise.

Time Tagging After T+185 sec

TV cameras with standard integration time will be placed in the image plane of the telescopes. Therefore, there is an exposure time per frame of 1/30 sec, and the total amount of effective illuminance per frame, will be reduced by a factor of 30. The final values for illumination levels after T+185 sec, are shown in Table 5.

Summary

The parameters of the optical system described in this chapter are summarized in Table 6.

Table 5. Focal Plane and Background Illumination Levels, Including Time Tagging, for after T+185 sec (lumens/m^2), and ½ hr after Sunset.

		Reflection from Target E_p (lumens/m^2)					
		R=260 n.mi. $=1.6\times10^6$ ft.		R=1300 n.mi. $=7.8\times10^6$ ft.		R=6617 n.mi. $=39.7\times10^6$ ft.	
FOV	Dark Sky E_s (night) (lumens/m^2)	ρ=0.1	ρ=0.5	ρ=0.1	ρ=0.5	ρ=0.1	ρ=0.5
6°	2.0×10^{-3}	1.9×10^{-1}	9.3×10^{-1}	1.4×10^{-1}	7.1×10^{-1}	3.5×10^{-2}	1.8×10^{-1}
18'	1.6×10^{-5}	1.5×10^{-3}	7.7×10^{-3}	1.2×10^{-3}	5.9×10^{-3}	2.9×10^{-4}	1.5×10^{-3}
34"	3.7×10^{-8}	3.5×10^{-6}	1.7×10^{-5}	2.6×10^{-6}	1.3×10^{-5}	6.6×10^{-7}	3.3×10^{-6}

Table 6. Summary of System Parameters.

	Before T+185 sec	After T+185 sec
Resolution	100 TVL/raster height	100 TVL/raster height
FOV	34"	6°, 18' and 34"
Illuminance Background	$E_s = L_s T_T A_T / f^2$	$E_s = L_s T_T A_T / f^2$
Target	$E_p = L_p T_A T_T A_T / f^2$	$E_t = T_T T_A$ ET (10.76)
Contrast Enhancement	Red filter	
Time Tagging	10^{-5} sec exposure	1/30 sec exposure
Launch Window		½ hr before sunrise and for 2 hrs after sunset. Best is 1 hr after sunset.

CHAPTER 3

TV CAMERA TUBES

The application of a camera tube to the system can be evaluated on the basis of published performance data. Comparison of different tubes also must be based on those same data. Data required include (1) the dynamic limiting resolution of the system (resolution in TV lines/raster height vs. photocathode illumination) in terms of the contrast ratio, which is given by

$$\frac{E_t - E_s}{E_t} \times 100\% \qquad (13)$$

where E_t is the focal plane illumination due to reflection from the target or light from the plume and E_s is the focal plane illumination due to light from the sky, (2) the square wave response (SWR) and (3) the photocathode spectral response. These three items will be discussed in some detail. The type of camera tube required by the suggested system is one that can resolve 100 TV lines/raster height at a target illumination level of 3.3×10^{-5} lumens/m^2 (3.1×10^{-6} lumens/ft^2) with a contrast ratio of 97% (before T+185 sec) and at a target illumination level of 2.6×10^{-6} lumens/m^2 (2.4×10^{-7} lumens/ft^2) with a contrast ratio of 99% (after T+185 sec, at 1300 n.mi., ρ=0.1). The spectral response of the tube should be maximum in the visible region of the spectrum, especially in the red end of that region, to give the best performance when and if a red filter is used.

Resolution is usually measured using a bar chart with 100% contrast. If the contrast is lower than 100%, for example 50%, the resolution, at a given illumination will also be lower. In this case, where the contrast ratios can be approximated as 100% this problem does not occur.

The illumination levels are converted to units of lumens/ft^2, which are equivalent to units of foot candles (fc), because these are the units used by cameratube manufacturers in evaluating their products.

The tubes discussed here were chosen on the basis of information from the manufacturers on TV camera tubes suitable for the low light levels required by this problem.

The tubes chosen for a comparison in this report were an image orthicon (IO) and two silicon intensifier target (SIT) camera tubes (Table 7). The following two paragraphs describe the basic properties of each generic type.

In the image orthicon the photoelectrons from the photocathode are focused by an axial magnetic field onto a thin, moderately insulating target surface. These strike the target, and secondary emission occurs, causing the establishment of net positive charges on the target. "The electron beam scans the charged target pattern, deposits some electrons on the more positively charged areas, and the modulated beam returns to an electron multiplier surrounding the electron gun. The output signal is the amplified anode current of the electron multiplier" (RCA, 1974, p. 182)(see Fig. 12).

Table 7. Three TV Camera Tubes

Camera Tube	Type of Tube	Photo Cathode
GE IO Z-7987	Ruggedized Image Orthicon	(GE) S-25
RCA-C21145	SIT Camera Tube, 40-mm Fiber-Optic Face plate type	S-20 Material NaK-Cs-Sb
Westinghouse WX-32432	32-mm EBS Camera Tube* Developmental Device	S-20

* EBS is the trade name for the generic type tube SIT.

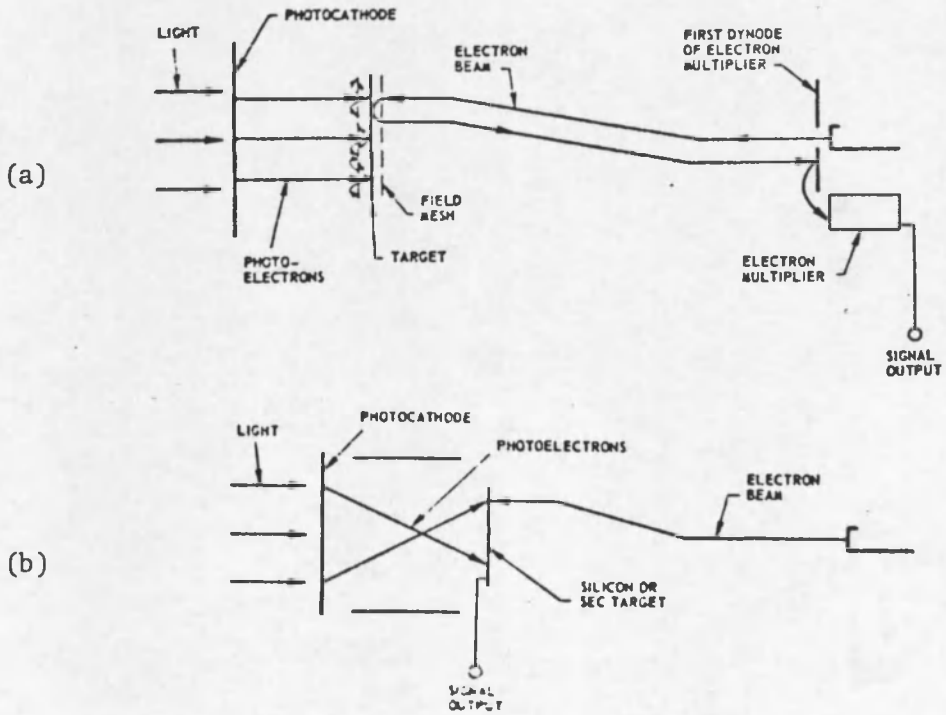


Fig. 12. Schematic Representation of Camera Tubes.

(a) image orthicon camera tube
(b) SIT camera tube (RCA, 1974,pp. 182 and 183).

In the silicon intensifier target camera tube the photoelectrons from the photocathode are focused onto a special target that provides relatively high gain before the scanning operation commences. The target is a very thin silicon wafer upon which a tightly spaced matrix of p-n junction diodes is formed. The photoelectron, from the photocathode, is accelerated to perhaps 10 keV, and inpinges on the target and causes a large quantity of charged particle pairs. The holes are collected at the p-side of the diode where the charge is neutralized by the scanning beam. The signal is read out on the backplate of the target (Fig. 12)(RCA, 1974, p. 183).

Tubes other than the three given in Table 7 were considered but were not included in this comparison because their resolution capabilities did not match the requirements. Though the information on the Westinghouse tube is not as complete as that for either the RCA or GE tubes, the results are comparable and merit consideration in this report.

Teltron, Inc., manufactures a series of special-purpose IO camera tubes. The available information indicates that they are comparable to the tubes in Table 7, but not enough information was available for any real comparison.

Dynamic Limiting Resolution

According to RCA (1974, p. 201):

> Limiting resolution is generally measured with a bar pattern having 100 percent contrast. For image tubes it is usually specified in terms of line-pairs per millimeter; for camera tubes, in terms of the number of TV lines (black and white) that can be resolved in a picture height. One black and white line is equivalent to one line pair...The limiting resolution value corresponds to an MTF of about 3 percent at high light

where picture noise is not a limitation. As the light level is reduced, the number of resolved lines decreases because of the obscuration caused by the noise in the picture. Limiting resolution varies approximately as the square root of the scene luminance at low light levels but is MTF limited at high light levels.

The performance of the GE IO-Z-7987 tube and the RCA-C21145 (Fig. 13) is about equal. Table 8 shows this relationship (illumination vs. TV lines/raster height) more clearly.

Square Wave Response

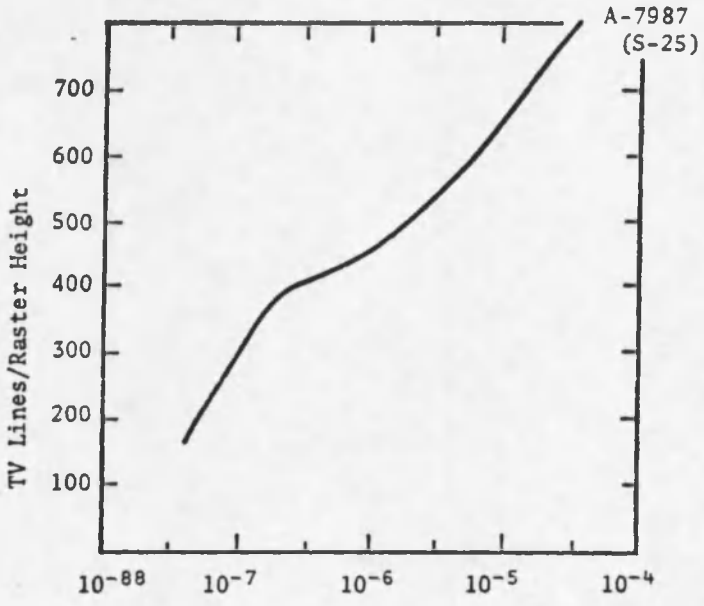
The square wave response (SWR) of a TV camera tube defines the resolution. RCA calls this the contrast transfer function (CTF) and defines it as the spatial-frequency amplitude response. The modulation transfer function (MTF) is the sine-wave spatial-frequency amplitude response. These two types of responses can be converted from one to the other (RCA, 1974, p. 117).

$$\text{MTF} = M(N) = \frac{\pi}{4}\left[C(N) + \frac{C(3N)}{3} - \frac{C(5N)}{5} + \frac{C(7N)}{7} \cdots\right] \qquad (14)$$

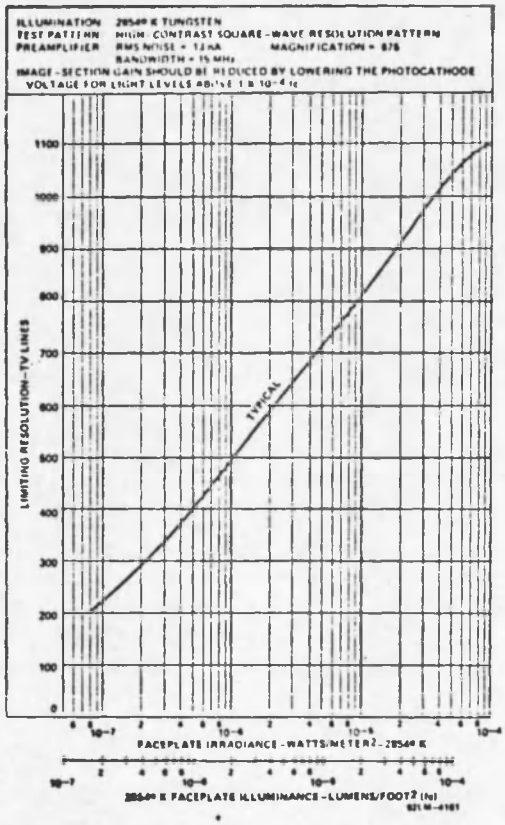
where the term involving C(9N) is omitted because it is zero, or

$$\text{CTF} = C(N) = \frac{4}{\pi}\left[M(N) - \frac{M(3N)}{3} + \frac{M(5N)}{5} - \frac{M(7N)}{7} + \frac{M(9N)}{9} \cdots\right] \qquad (15)$$

The response of the system is usually given by the CTF (hereafter referred to as SWR) because it is easier to measure (RCA, 1974, p. 114). In Fig. 14 the shape of the curves shows that the output signal generated by the camera tube has fallen from its low spatial frequency response. A drop of 50% indicates an effective quantum efficiency reduction of



(a)



(b)

Fig. 13. Resolution Characteristics for (a) GE-IO-Z-7987 (Spalding, 1971, p. 7) and (b) RCA-C21145 Tubes (RCA, 1972, p.8).

Table 8. Resolution.

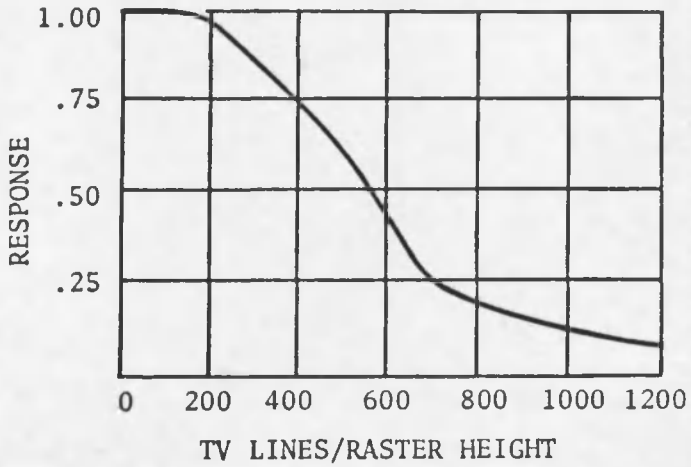
Photocathode illumination (lumens/ft)	(a) GE IO Z-7987 Resolution (TVL/Raster Height)	(b) RCA-C21145 Resolution (TVL/Raster Height)	(c) Westinghouse WX-32432 Resolution (TVL/Target Height)
1×10^{-7}	300	---	---
5×10^{-7}	420	325	200
1×10^{-6}	450	400	---
5×10^{-6}	580	625	---
1×10^{-5}	650	725	---
5×10^{-5}	[850]*	950	---
1×10^{-4}	[900]	1050	---
5×10^{-4}	---	[1100]	800

* Figures in brackets have been extrapolated from graphs.

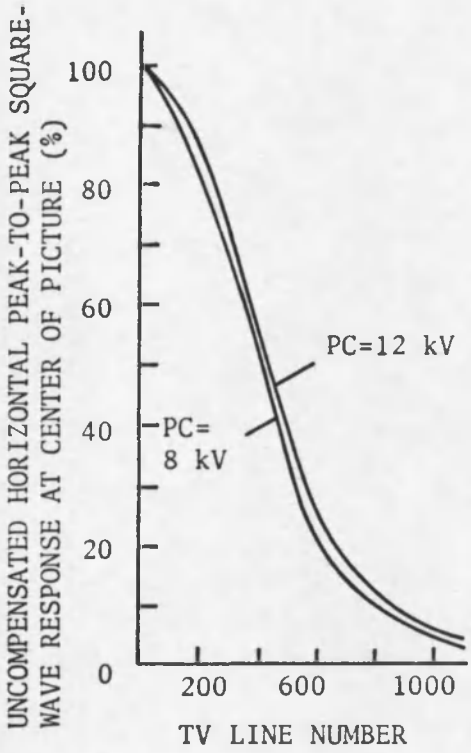
(a) Spalding (1971).

(b) RCA (1972)

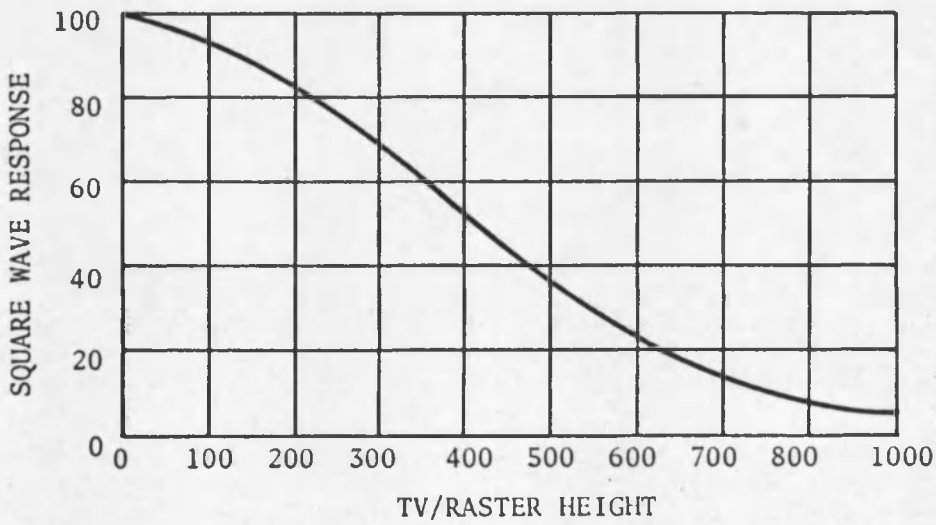
(c) Westinghouse (1974)



(a)



(b)



(c)

Fig. 14. Square Wave Response.

(a) GE IO Z-7987, at 1.5×10^{-3} lumens/ft^2 (Spalding, 1971, p.8).
(b) RCA-C21145, at 500 nA, 1.5×10^{-4} lumens/ft^2 (RCA, 1972, p.7).
(c) Westinghouse, WX-32432, at 800 nA, 3.0×10^{-4} lumens/ft^2 (Westinghouse, 1974, p.5).

2 for the device. Figure 15 shows the same responses for a common illumination of 3 x 10^{-4}lumens/ft^2 and 4 x 10^{-7}lumens/ft^2, respectively.

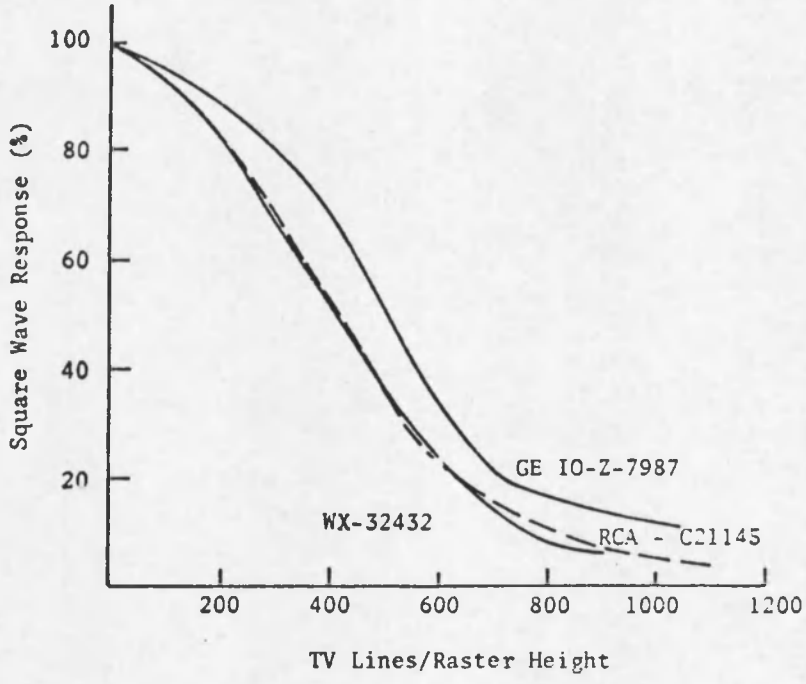
The SWR of the Westinghouse tube was generated at an illumination level of 3 x 10^{-4}lumens/ft^2. The limiting resolutions of the RCA and GE tubes are taken from Fig. 13, page 35. Using these values for the maximum value of TV lines/raster height, the square wave responses for the RCA and GE tubes were transferred onto the same graph. The response of the GE IO unit is higher in both cases, indicating a better quantum efficiency.

Spectral Response

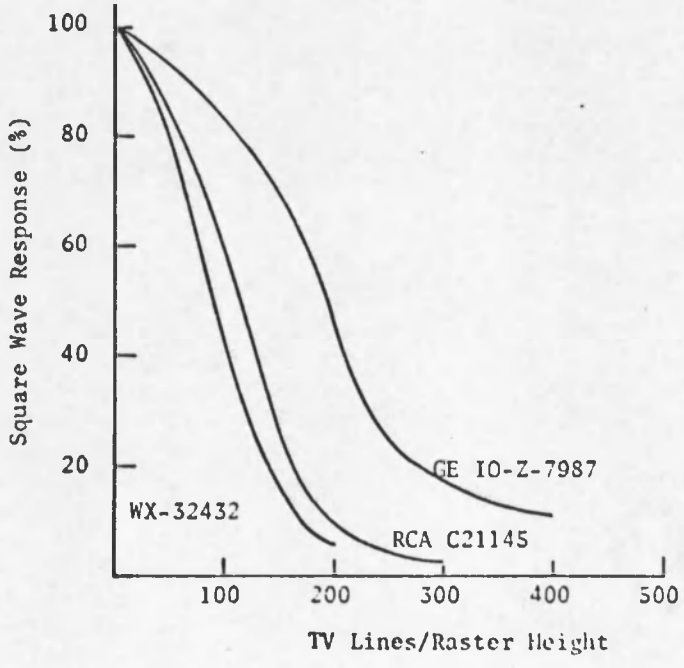
Figure 16 shows the spectral response of several General Electric photocathodes. Their data agree with the response of the photocathodes given by RCA (1974, pp. 152-153). The S-20 and S-25 photocathodes are Na-K-Cs-Sb. The spectral response of the S-25 is greater in magnitude per wavelength for the GE photocathode than for the RCA photocathode.

Other Criteria

When a comparatively bright light is imaged upon the photocathode of a low-light-level camera tube, the apparent diameter of the light is increased. This penomena is called blooming. A factor that must be considered in this application is the effect of a bright object within the same field as the target (such as a star). In an image orthicon the central image is a saturated core surrounded by a black halo (Campana, 1971; p.22,23). A bright light caused no permanent changes



(a)



(b)

Fig. 15. Square Wave Response at (a) 3×10^{-4} fc, and (b) 4×10^{-7} fc (Optical Sciences Center, 1976, p.9).

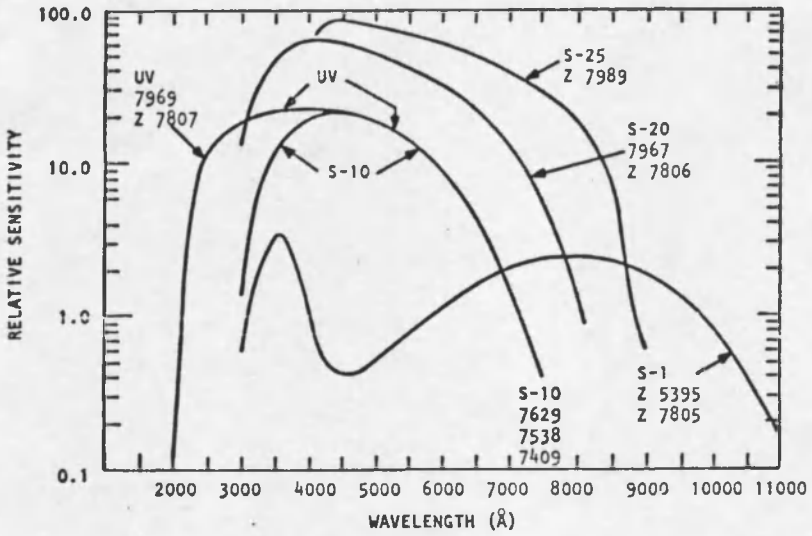


Fig. 16. Spectral Response.

GE photocathode responses for their special purpose orthicons (GE, 1972a, 1972b). The S-20 spectral response is the same as given by RCA for C-21145. Relative sensitivity is equivalent to amperes per watt.

in the target quality, though an after image lasting several minutes did occur. In an SIT the image spreads in a "well defined circle" (Campana, 1971; pp. 23,24). After testing there may be permanent target deterioration.

Comparatively, the picture obscuration due to both IO and SIT tubes is about the same percent, with the Halo in the IO causing most of that obscuration. According to GE Supplement to ET-T1683A (1972a), the S-25 photocathode in the IO Z-7987 does not have a halo and has an obscuration of only 3% at 10^{-4} lumens highlight illumination.

IO units have noise, due to the return beam type of operation, in the dark areas of the image. This will cause the picture to appear grainy. This can be avoided by integrating, but the application

described herein calls for time tagging not integrating. (Integrating is exposing the picture for longer than 1/30 of a second, time tagging exposes it for 1/30 of a second or less.) Actually the grainy picture will not be as serious a problem as the white dots to which SIT units are subject. The operation of the SIT unit generates soft x-rays to which the photocathode is sensitive. The SIT tubes show higher blemish levels than the image orthicon.

"High incident light levels on the photocathode resulting in excessive photocathode current may, over a period of time, result in shortened tube life due to target damage from photoelectrons" (RCA, 1972). The exposure limit for faceplate illumination of 1 lumens/ft^2 is one hour for RCA C-21145. The proposed system must handle illumination at this level. The RCA tube requires a combination of lens stops and filters to limit the light. It is not desirable to filter the already described system because it decreases the resolving capabilities.

To insulate high-voltage TV camera tubes, they should be potted; that is, the high voltage electrodes are encapsulated in a silicon rubber compound. SIT's usually have 15 kV and these will need potting (the RCA C21145 has a photocathode voltage of 3000 to 12000 V). An IO unit usually has, in comparison, 600 V and does not have to be potted (GE IO A-7987 has a photocathode voltage of 600 V). The actual potting operation is difficult, therefore an Intensified SIT (ISIT) camera is usually purchased already potted. The entire ISIT must be exchanged to replace a defective camera tube (resulting in a higher cost), as

opposed to exchanging the IO tube and then recoupling it to the intensifier already in the system (Table 9).

Table 9. Specifications.

	(a) GE IO-Z7987	(b) RCA-C21145	(c) WX-32432
Active photocathode diagonal	1.8 in.	1.58 in.	1.26 in.
Limiting resolution	1200 TVL at 1.5×10^{-3} lumens/ft^2	1100 TVL at 1.5×10^{-4} lumens/ft^2	900 TVL at 3×10^{-4} lumens/ft^2
Operating temperature	of image end 25° to 30°C of target 15° to 55°C	typical 30°C	typical 25°C
Photocathode voltage	600V	typical 3000 to 12000V	Primary voltage 12000 V

(a) GE (1972a), (1972b).

(b) RCA (1972).

(c) Westinghouse (1974).

Summary

The three camera tubes chosen for a comparison were the GE IO Z-7987, RCA-C21145, and Westinghouse WX-32432, where the first is an image orthicon and the other two are silicon intensifier target camera tubes.

Primarily three factors were examined in detail: (1) the dynamic limiting resolution in terms of the contrast, (2) the square wave response, and (3) the photocathode spectral response.

The dynamic limiting resolution (Table 9) shows that all three tubes have acceptable resolutions, with GE IO Z-7987 having the highest TV line/raster height resolution in the very lowest light levels (below 1×10^{-6} lumens/ft^2), and RCA C21145 having higher resolution where there is more photocathode illumination.

The square wave response (Fig. 15, page 39) of the GE IO Z-7987 is higher at both illumination levels graphed. This indicates a better quantum efficiency for that tube.

The relative photocathode spectral response of the S-25 photocathode (GE IO Z-7987) is greater than the S-20 photocathode (RCA-C21145 and WX-32432) in the visible wavelengths of light and notably in the longer, visible wavelengths.

It can be concluded that the GE IO Z-7987 will have fewer problems due to generic types of noise.

The GE IO Z-7987 meets all the criteria of the system. For all the performance data evaluated, it gives equal or superior results. This makes the GE IO Z-7987 the best choice for the proposed system.

CHAPTER 4

CONCLUSION

An electro-optical system is described to track a target through its flight. 100 TV lines/raster height resolution will be required of a TV camera tube.

Because the tracking problem involves tracking a plume and later more than one target, more than one field of view is required. The recommended system is one having three cameras per detection site, and having a FOV of 6°, 18', and 34".

The amounts of light from sky, plume, and target that reach the image plane are calculated to determine the illumination constraints of the camera tubes. These are a target illumination level of 3.3×10^{-5} lumens/m^2 (3.1×10^{-6} lumens/ft^2) with a contrast ratio of 97% (before T+185 sec) and a target illumination level of 2.6×10^{-6} lumens/m^2 (2.4×10^{-7} lumens/ft^2) with a contrast ratio of 99% (after T+185 sec, at 1300 n.mi., ρ=0.1) (Table 3, page 15).

When tracking before T+185 sec a time tagging of 10^5 frames per second is obtainable, and a red filter may be used for contrast enhancement. Tracking after T+185 seconds is possible only for a limited launch window. This window is the half hour before sunrise and two hours after sunset, with the optimum time being one hour after sunset. During this time there is the standard 30 frames per second time tagging due to the camera tube frame time.

TV camera tubes were evaluated for their suitability to the above system, and owing to comparisons of resolution, square wave response, and spectral response, the GE IO Z-7987 was recommended for use.

The GE IO Z-7987 has the highest TV line/raster height resolution (Table 8, page 36) of the compared tubes, at the lowest light levels. Its square wave response is higher at both illumination levels graphed (Fig. 15, page 39), indicating a better quantum efficiency. The relative photocathode spectral response of the S-25 photocathode, in the tube, is greater in the visible wavelengths of light. The GE IO Z-7987 meets all the criteria of the system described above.

APPENDIX

COMPUTER PRINTOUT OF TARGET SOURCE ILLUMINATION

The following is the computer printout of the Fortran computer program described in Chapter 2. Included is a list of the initial data and the output.

```
      PROGRAM  REFLECT   (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                1
C   ***ALL ANGLES IN RADIANS, DISTANCES IN FEET     ,,ROCKET LENGTHS IN FT      2
C   ***LATITUDE AND LONGITUDE WILL BE CONVERTED TO ECF     ***
C*******VARIABLE NAMES *******                                                  5
C     HS        AMOUNT OF DIRECT SOLAR ILLUMINATION(LM/FT**2)                   9
C     RO        SPECTRAL REFLECTANCE , INPUT                                   10
C     JTOTAL    (EG) LUMINOUS INTENSITY      (LM/STER)
C     FRUST SUBFUNCTION, EQUATION (A-3) -LUMINOUS INTENSITY OF CONE(LM/STER)
C     JCYLIN EQUATION A-1  -LUMINOUS INTENSITY OF CYLINDER (LM/STER)
C     FIGURE A-1
C     EPSI      ANGLE DEFINED BY EQUATION  A-2
C     ALPHA     GENERATING ANGLE OF THE CONE                                   11
C     BETA      ANGLE BETWEEN DIRECTIONS OF SUN AND OBSERVER
C     PHIS      ANGLE BETWEEN ROLL AXIS AND SUN
C     PHIT      ANGLE BETWEEN ROLL AXIS AND OBSERVER
C     LEN       LENGTH OF A CYLINDER (OR SECTION)                              18
C     A1        TOP RADIUS OF FRUSTUM -OR OF CYLINDER
C     A2        BOTTOM RADIUS OF FRUSTUM WHERE A2 IS GREATER THAN A1           20
C     FIGURE A-2
C     GAMAS     ANGLE=PI/2=TERMINATOR FOR SOLAR ILLUMINATION IN PLANE OF EPSI
C     GAMAT     ANGLE=PI/2=TERMINATOR FOR THE OBSERVER IN PLANE OF EPSI
C     FIGURE A-3
C     R         DISTANCE FROM CENTER OF EARTH TO OPTICAL SITE                  21
C     X         POSITION COORD IN ECF SYSTEM                                   22
C     Y         POSITION COORD IN ECF SYSTEM                                   23
C     Z         POSITION COORD IN ECF SYSTEM                                   24



C     DECLARATIONS                                                             28
      INTEGER ENUM(4)                                                          29
      REAL HS,JCYLIN,JTOTAL,       TRAJ(25,8),RADAR(3),SHAPE(13,5)             30
     1     ,SUN(2),LEN,SLANT(25),JTOT                                          31
      COMMON PI,RO,HS                                                          32
      READ(5,99)HS                                                             34
   99 FORMAT(3X,F8.2)                                                          35
      READ(5,100)RO                                                            38
  100 FORMAT(3X,F9.7)                                                          39
C     INPUT RADAR SITE,LAT,LON,ALT(FRM CNTR)TO ECF X,Y,Z (EARTH CNTR FIX)      40
      READ(5,101)RADAR(1),RADAR(2),RADAR(3)                                    41
  101 FORMAT(4X,F8.3,6X,F8.3,6X,F10.1)                                         42
C     LAT GEOCENTRIC, LON GEODETIC                                             43
C     CONVERT TO RADIANS
      RADAR(1)=.01745*RADAR(1)                                                 44
      RADAR(2)=.01745*RADAR(2)                                                 45
       X=RADAR(3)*COS(RADAR(1))*COS(RADAR(2))                                  46
       Y=RADAR(3)*COS(RADAR(1))*SIN(RADAR(2))                                  47
       Z=RADAR(3)*SIN(RADAR(1))                                                48
       RADAR(1)=X                                                              49
       RADAR(2)=Y                                                              50
       RADAR(3)=Z                                                              51
      PI=ACOS(-1.0)                                                            52
```

```
C      INPUT NUMBER OF CARDS DEFINING SHAPE= ISHAPE
       READ(5,98)ISHAPE                                                  53
    98 FORMAT(I3)                                                        54
C      INPUT SHAPE OF ROCKET BY STAGES     MUST BE ISHAPE CARDS          55
C      COLUMN 1=STAGES PRESENT ON TRAJECTORY                             56
C           1=STAGE 1,2= SKIRT1,3=STAGE 2,4=SKIRT 2,5=STAGE 3,6=CONE     57

C           OR 6.5 CONE WITHOUT SHROUD (IF .LT. 3 STAGES START           58
C           NUMBERING WITH PRESENT STAGES. I.E. SHPE(1,1)=3)             59
C      COLUMN 2=SHAPE, 1=FRUSTRUM, 2=CYLINDER
C      COLUMN 3= RADIUS 1, COLUMN 4= RADIUS 2 ,COLUMN 5=LENGTH
       DO 20 I= 1,ISHAPE                                                 62
        READ(5,102) (SHAPE(I,J),J=1,5)                                   63
   102 FORMAT(4X,F3.1,4X,F3.1,4X,F6.3,4X,F6.3,4X,F7.3)                   64
    20 CONTINUE                                                          65
C      INPUT TRAJECTORY (TRAJ),EACH READING IS A ROW, COLUMNS ARE        66
C      TIME,STAGES,X,Y,Z,COSX,COSY,COSZ  (XIX,XIY,XIZ)                   67
C           STAGES ARE ON ROCKET,INPUT OF TRAJECTORY MUST INCLUDE CODE   68
C               0=FULL ROCKET,1=NO STAGE1,2=NO SKTS STG2,3=NO STAGE2,    69
C               4=NO SKTS STG3,5=NO STAGE3,  X.5 LOSS OF SHROUD          70
C               (IF LT 3 STAGES, START STAGES WITH THOSE PRESENT,IE TRAJ(1,2)=271
C      INPUT NUMBER OF CARDS DEFINING TRAJ= ITRAJ
       READ(5,104) ITRAJ                                                 72
   104 FORMAT(I3)                                                        73
       DO 21 I=1,ITRAJ                                                   74
            READ(5,105) (TRAJ(I,J),J=1,8)                                75
   105      FORMAT(F7.2,1X,F3.1,1X,F11.1,1X,F11.1,1X,F11.1,1X,F7.5,      76
     1           F7.5,F7.5)                                              77
    21 CONTINUE                                                          78
C      INPUT F/NUMBERS TO BE USED,MUST BE 4 OF THEM
       READ(5,110) (FNUM(I),I=1,4)                                       88
   110 FORMAT(14X,I3,1X,I3,1X,I3,1X,I3)                                  89
C      INPUT POSITION ANGLES OF SUN FOR LOCAL TIME FOR RADAR SITE,       90
C      HOUR ANGLE IN DEGREES(SUN(1)),DECLINATION IN DEGREED(SUN(2))
C      SEE FIG A-4
       READ(5,103)SUN(1),SUN(2)                                          92
   103 FORMAT(9X,F7.2,6X,F5.2)                                           93
    40 PRINT 112,SUN(1)                                                  95
   112 FORMAT("1HR ANGLE=    ",F7.2)                                     96
C      CONVERT TO RADIANS
       SUN(1)=.01745*SUN(1)                                              97
       SUN(2)=.01745*SUN(2)                                              98
       WRITE(6,109)                                                      99
   109      FORMAT("     TIME          LUMINOUS INTENSITY          SLANT",100
     9      " RANGE(FEET) GROUND ILLUMINANCE              ",            101
     9      "F/NUMBER  FOCAL PLANE",/,19X,"(LUMEN/STER)",               102
     9      30X,"(LUMEN/FT**2)=EG",20X,"ILLUMINATION=ET")               103
C      LIGHT1 HERE IS A DUMMY VARIABLE
       LIGHT1=3
C          LOOP PER LINE OF TRAJECTORY                                   104
       DO 23 I=1,ITRAJ                                                   105
C      SLANT RANGE FROM RADAR SITE TO ROCKET                             79
       SLANT(I)=SQRT(((RADAR(1)-TRAJ(I,3))**2)+((RADAR(2)-TRAJ(I,4))
     2      **2)+((RADAR(3)-TRAJ(I,5))**2))
            JTOTAL=0.0                                                   106
C           CALCULATING PHIT FOR TIME I                                  107
            PHIT=ACOS((((TRAJ(I,3)-RADAR(1))*TRAJ(I,6))                  110
     6           +((TRAJ(I,4)-RADAR(2))*TRAJ(I,7))                       111
     7           +((TRAJ(I,5)-RADAR(3))*TRAJ(I,8)))/SLANT(I))            112
C      AL,BE,GA ARE DIRECTION COSINES FOR THE SUN
            AL=COS(SUN(1))*COS(SUN(2))                                   114
            BE=+SIN(SUN(1))*COS(SUN(2))                                  115
            GA=SIN(SUN(2))                                               116
C      LIGHT=SUBFUNCTION WHICH DETERMINS WHETHER MISSILE IN IN SUNLIGHT
C      LIGHT1 AND LIGHT2 INDICATE PRESENT SUN OR SHADOW STATUS
       LIGHT2=LIGHT(AL,BE,GA,TRAJ(I,3),TRAJ(I,4),TRAJ(I,5))
       IF(LIGHT1.EQ.LIGHT2) GO TO  45
```

```
      LIGHT1= LIGHT2
      IF(LIGHT1.EQ.0)  PRINT 141
  141 FORMAT(" MISSILE IN SHADOW")
      IF(LIGHT1.EQ.1) PRINT 140
  140 FORMAT(" MISSILE IN SUNSHINE")
C           CALCULATE PHIS                                                  113
45        PHIS=ACOS(((TRAJ(I,6)*AL)+(TRAJ(I,7)*BE)+(TRAJ(I,8)*GA))    )    117
C           CALCULATE BETA                                                  118
            BETA=ACOS((((TRAJ(I,3)-RADAR(1))*AL)+((TRAJ(I,4)-RADAR(2))      119
     9          *BE)+((TRAJ(I,5)-RADAR(3))*GA))/SLANT(I))                   120
            IF(TRAJ(I,2).LE.AINT(TRAJ(I,2))) GOTO 50                        121
                TRAJ(I,2)=AINT(TRAJ(I,2))                                   122
                DO 25 II=1,ISHAPE                                           123
                    IF (SHAPE(II,1).NE. 6.0) GO TO 10                       124
                    SHAPE(II,1)=6.5                                         125
                    GO TO 25                                                126
   10               IF(SHAPE(II,1).EQ. 6.5) SHAPE(II,1)= 6.0                127
   25               CONTINUE                                                128
   50       DO 24 J=1,ISHAPE                                                129
                IF (SHAPE(J,1).EQ.  6.5) GO TO 24                           130
                IF(TRAJ(I,2).GE.SHAPE(J,1)) GOTO 24                         131
                IF(SHAPE(J,2).EQ. 1.0) GO TO 51                             132
C               CYLINDRICAL SECTION ,EQU A-1                                133
                    A1=SHAPE(J,3)                                           134
                    LEN=SHAPE(J,5)                                          135
C                   EQU A-2
                    EPSI=ACOS((COS(BETA)-COS(PHIS)*COS(PHIT))/              136
     1                  (SIN(PHIS)*SIN(PHIT)))                              137
                  JCYLIN=(RO/PI)*HS*(A1*LEN/2)*(((PI-EPSI)*COS(EPSI)+       138
     1                  SIN(EPSI))*SIN(PHIS)*SIN(PHIT))                     139
                    JTOTAL=JTOTAL+JCYLIN                                    140
                    GO TO 24                                                141
C               FRUSTRUM SECTION,EQU A-3                                    142
   51               A1=SHAPE(J,3)                                           143
                    A2=SHAPE(J,4)                                           144
                    LEN=SHAPE(J,5)                                          145
                    JTOTAL=JTOTAL+ FRUST(A1,A2,LEN,PHIS,PHIT,BETA)          146
   24       CONTINUE                                                        147
      JTOT=JTOTAL/SLANT(I)**2                                               148
C     ET=FOCAL PLANE ILLUMINATION VS F/NUMBER
      ET=2.5*10**10*JTOT/FNUM(1)**2                                         149
           WRITE(6,108)TRAJ(I,1), JTOTAL,SLANT(I),JTOT,FNUM(1),ET           150
  108      FORMAT(1X,F7.2, 5X,F20.10,5X,F20.10,5X,E12.5 ,15X,I3,5X,         151
     8     E13.5)                                                           152
      DO 26 K=2,4                                                           153
      ET=2.5*10**10*JTOT/FNUM(K)**2                                         154
      WRITE(6,111) FNUM(K),ET                                               155
  111 FORMAT(90X,I3,5X,E13.5)                                               156
   26 CONTINUE                                                              157
   23 CONTINUE                                                              158
      READ(5,103) SUN(1),SUN(2)                                             159
      IF(EOF(5)) 41,40                                                      160
   41 STOP                                                                  161
      END                                                                   162
```

```
      FUNCTION FRUST(A1,A2,L,PHIS,PHIT,BETA)                                1
C     EQUATIONS A-2
      REAL L                                                                2
      COMMON PI,RO,HS                                                       3
      ALPHA=ATAN((A1-A2)/L)                                                 4
      EPSI=ACOS((COS(BETA)-COS(PHIS)*COS(PHIT))/                            5
     1     (SIN(PHIS)*SIN(PHIT)))                                           6
      IF(TAN(ALPHA).GT.ABS(TAN(PHIS))) GO TO 6                              8
      IF(TAN(ALPHA).GT.ABS(TAN(PHIT))) GO TO 6                              9
      GAMAS=ASIN(TAN(ALPHA)/TAN(PHIS))                                      10
      GAMAT=ASIN(TAN(ALPHA)/TAN(PHIT))                                      11
      FRUST=(RO/PI)*HS*(A1+A2)*L*COS(ALPHA)/4                               12
C     CASE 1                                                                13
      IF (PHIS.GT.ALPHA.OR.PHIT.GT.ALPHA) GO TO 2                           14
     1     FRUST=FRUST+2*PI*(2*COS(PHIS)*COS(PHIT)*TAN(ALPHA)**2+           15
     1     COS(EPSI)*SIN(PHIS)*SIN(PHIT))                                   16
      RETURN                                                                17
C     CASE 2
     2 IF (PHIS.GT.ALPHA.OR.PHIT.LT.ALPHA) GOTO 3                           18
        FRUST=FRUST+(2*(PI+2*GAMAT)*COS(PHIS)*COS(PHIT)*TAN(ALPHA)**2       19
      2     +4*COS(GAMAT)*COS(PHIS)*SIN(PHIT)*TAN(ALPHA)                    20
      2     +4*COS(EPSI)*COS(GAMAT)*SIN(PHIS)*COS(PHIT)*TAN(ALPHA)          21
      2     +((PI+2*GAMAT)-2*SIN(GAMAT)*COS(GAMAT))*COS(EPSI)*              22
      2     SIN(PHIS)*SIN(PHIT))                                            23
      RETURN                                                                24
C     CASE 3                                                                25
     3 IF (PHIS.LT.ALPHA.OR.PHIT.GT.ALPHA) GO TO 4                          26
        FRUST=FRUST+(2*(PI+2*GAMAS)*COS(PHIT)*COS(PHIS)*TAN(ALPHA)**2       27
      3     +4*COS(GAMAS)*COS(PHIT)*SIN(PHIS)*TAN(ALPHA)                    28
      3     +4*COS(EPSI)*COS(GAMAS)*SIN(PHIT)*COS(PHIS)*TAN(ALPHA)          29
      3     +((PI+2*GAMAS)-2*SIN(GAMAS)*COS(GAMAS))*COS(EPSI)               30
      3     *SIN(PHIS)*SIN(PHIT))                                           31
      RETURN                                                                32
     4 GAMA=GAMAS+GAMAT                                                     33
      PIE=PI-EPSI                                                           34
C     CASE 4                                                                35
      IF(GAMAS.LT.0.0) GO TO 5                                              36
      IF (GAMA.LT.PIE)GO TO 5                                               37
        FRUST=FRUST+((4*GAMA*COS(PHIS)*COS(PHIT)*TAN(ALPHA)**2  )           38
      4     +4*(COS(GAMAT)+COS(EPSI)*COS(GAMAS))*COS(PHIS)*SIN(PHIT)        39
      4     *TAN(ALPHA)+4*(COS(GAMAS)+COS(EPSI)*COS(GAMAT))                 40
      4     *SIN(PHIS)*COS(PHIT)*TAN(ALPHA)+2*(GAMA-SIN(GAMAS)              41
      4     *COS(GAMAS)-SIN(GAMAT)*COS(GAMAT))*COS(EPSI)*SIN(PHIS)          42
      4     *SIN(PHIT))                                                     43
      RETURN                                                                44
C     CASE 5                                                                45
     5 IF(GAMAS.GE. 0.0 .AND. GAMAT.GE. 0.0 ) GO TO 55                      46
      IF(PIE.GT.GAMA)GO TO 6                                                47
    55 FRUST=FRUST+(2*(PIE+GAMA)*COS(PHIS)*COS(PHIT)*TAN(ALPHA)**2          48
      5   +2*(COS(EPSI-GAMAS)+COS(GAMAT))*COS(PHIS)*SIN(PHIT)*TAN(ALPHA)    49
      5   +2*(COS(GAMAS)+COS(EPSI-GAMAT))*COS(PHIT)*SIN(PHIS)*TAN(ALPHA)    50
      5   +((PIE+GAMA-SIN(GAMAS)*COS(GAMAS)+SIN(EPSI-GAMAT)*COS(EPSI       51
      5     -GAMAT))*COS(FPSI)                                              52
      5   +(COS(GAMAS)**2-COS(EPSI-GAMAT)**2)*SIN(EPSI))*SIN(PHIS)          53
      5         *SIN(PHIT))                                                 54
      RETURN                                                                55
     6 FRUST=0                                                              56
      RETURN                                                                57
      END                                                                   58
```

```
      FUNCTION LIGHT(AL,BE,GA,XM,YM,ZM)
C     SUBFUNCTION WHICH DETERMINS WHETHER MISSILE IN IN SUNLIGHT
C     IT IS ASSUMED THAT THERE IS NO ATMOSPHERE
      COMMON PI
C     RE= THE RADIUS OF THE EARTH
      RE=20926435.2
      RM=SQRT(XM**2+YM**2+ZM**2)
      DIST=AL*XM+BE*YM+GA*ZM
      IF(ABS(ACOS(DIST/RM))-PI/2) 2,2,1
    1 IF(RM**2-DIST**2-RE**2) 3,2,2
C     RETURNS 0 FOR SHADOW AND 1 FOR SUNSHINE
C     IN SUNSHINE
    2 LIGHT=1
      RETURN
C     IN SHADOW
    3 LIGHT=0
      RETURN
      END
```

Input Variables

HS is the illuminance from the sun in lumens/ft^2.

RO is the reflectance coefficient of the target.

LAT is the latitude,

LON is the longitude, and

ALT is the altitude above sea level for a detector site, in this case Anderson Peak was used.

The shape of the Missile is as follows:

STGE stands for stage,

SKT stands for skirt,

CNE stands for cone.

The input shape of the missile is given by stages, first giving the number of cards (ISHAPE) which is 11 here.

The first column of numbers is the number of stages present on the missile (shape)

1 is stage 1
2 is skirt 1
3 is stage 2
4 is skirt 2
5 is stage 3
6 is cone and
6.5 is the cone without the shroud.

The second column of numbers is the shape, SHP, where

1 indicates Frustum, and
2 indicates cylinder.

The third column is the first radius and the fourth column is the second radius of a frustum.

Column 5 is the length of the section (Fig. 7, page 17.

The 19 Time, Shape, and location cards indicate

TIME in seconds, after launch
SHAPE of the missile, which gives the number of stages present

X,Y,Z which are the position coordinates of the missile and COS X, COS Y, COS Z which are the direction cosines of the roll axis of the missile.

The F/NUMBERS ARE 1 (6° FOV), 11 (18' FOV) and 232 (34" FOV) (the 2 is for a telescope not used in this report).

The hour angle, HR ANGLE, and declination, DEC, are found in a Nautical almanac for the dates indicated.

Input

```
HS=12700.00    LUMENS/FT**2                                                    1
RD=0.100000                                                                    2
LAT= 36.183, LON=-121.650, ALT=20904500.0, FOR ANDERSON PEAK                   3
 11  SHAPE   OF MISSILE AS EXPLAINED IN COMMENT CARDS IN PROGRAM               4
STGE1.0,SHP2.0,RAD 2.750,RAD 0.0  ,LEN 24.200                          R      5
SKT 2.0,   1.0,    2.750,    2.150,     5.000                          O      6
STG 3.0,   2.0,    2.150,              15.700                          C      7
SKT 4.0,   2.0,    2.150,               5.000                          K      8
STG 5.0,   2.0,    2.150,               5.500                          E      9
CNE 6.0,   2.0,    2.150,               8.400                          T     10
CNE 6.0,   1.0,    0.900,    0.800,     2.000                          S     11
CNE 6.0,   1.0,    0.800,    0.600,     2.000                          H     12
CNE 6.0,   1.0,    0.600,               2.000                          A     13
CNE 6.5,   2.0,    2.150,          ,    8.400                          P     14
CNE 6.5,   1.0,    1.000,    0.000,     6.000                          E     15
 19 TIME,SHAPE,  X,          Y,          Z,       COS X,COS Y, COS Z          16
   0.00,0.0,- 8748584.7,-14794751.4, 11893118.2,-.41779-.70626 .57153         17
   3.15,0.0,- 8748584.7,-14795897.8, 11893228.7,-.41779-.70626 .57153         18
  53.44,0.0,- 8792477.8,-14846749.8, 11928962.4,-.96077-.05916 .27097         19
  61.09,0.0,- 8824489.3,-14853670.1, 11940074.1,-.96764-.02985 .25057         20
  61.5080.08- 8826261.8,-14854006.6, 11940660.2,-.96798-.02832 .24941         21
  61.65,1.0,- 8826911.6,-14854128.9, 11940874.2,-.96811-.02776 .24899         22
  77.65,2.0,- 8903783.4,-14864511.1, 11963718.2,-.97556 .01327 .21932         23
 119.85,2.0,- 9215832.5,-14862396.4, 12029757.1,-.97746 .02334 .20980         24
 124.80,2.0,- 9264438.0,-14859263.3, 12038372.3,-.97770 .02321 .20870         25
 125.40,2.5,- 9270467.6,-14858844.1, 12039420.8,-.97774 .02312 .20850         26
 126.75,3.0,- 9284122.4,-14857868.1, 12041777.8,-.97798 .02254 .20748         27
 127.75,4.0,- 9294267.3,-14857118.5, 12043512.7,-.98153 .01166 .19096         28
 183.53,4.0,-10094899.6,-14778530.1, 12169179.7,-.97462-.00832 .22369         29
 185.09,5.0,-10126179.8,-14775366.0, 12174085.6,-.97499-.00940 .22206         30
 198.59,5.0,-10396950.6,-14745931.4, 12215173.8,-.97499-.00940 .22206         31
 206.59,5.0,-10556339.2,-14726761.1, 12238120.2,-.97499-.00940 .22206         32
 550.00,5.0,-16502619.1,-12873287.9, 12329011.1,-.97499-.00940 .22206         33
1692.15,5.0 -20851014.3, 14533055.0, 36824975.6, .43358 .72392-.53661         34
1723.89,5.0,-20571123.8, 18560821.5, 33453140.2, .47792 .69930-.53159         35
F/NUMBERS ARE,  1,  2, 11,232                                                  36
HR ANGLE=  0.00,DEC.=26.60      JUNE 21,1965, 1/2 HR BEFOR SUNRIS AT -120LO    37
HR ANGLE=-240.00,DEC.=26.60     JUNE 21,1965, 1/2 HR AFTER SUNSET AT -120LO    38
HR ANGLE=-247.50,DEC.=26.60     JUNE 21,1965,   1 HR AFTER SUNSET AT -120LO    39
HR ANGLE=-262.50,DEC.=26.60     JUNE 21,1965,   2 HR AFTER SUNSET AT -120 L    40
```

Output Variables

HR ANGLE is the hour angle of the sun for time of day indicated.

TIME is the time, in seconds after launch.

LUMINOUS INTENSITY (LUMENS/STER) is the total luminous intensity from the target.

SLANT RANGE (FEET) is the range from the detector to target.

GROUND ILLUMINANCE (LUMEN/FT**2)=EG is the total luminous intensity divided by the square of the slant range.

FOCAL PLANE ILLUMINATION = EG is in lumens/ft^2, and is given with the F/NUMBER it was calculated with.

The values for ET are calculated assuming neither earth nor its shadow, therefore, the words MISSILE IN SHADOW, and MISSILE IN SUNSHINE, indicate when the target is actually in sunlight. These are calculated by subfunction LIGHT.

Output ½ hr before Sunrise at -120° Longitude

HR ANGLE= 2.62

TIME	LUMINOUS INTENSITY (LUMEN/STER)	SLANT RANGE(FEET)	GROUND ILLUMINANCE (LUMEN/FT**2)*EG	F/NUMBER	FOCAL PLANE ILLUMINATION*ET
MISSILE IN SHADO*					
2.62	26879.9736184842	625422.1514878832	.53381E-07	1	.13345E+04
				2	.33363E+03
				11	.11329E+02
				232	.24794E-01
3.15	22909.7282078307	626609.8314019404	.53220E-07	1	.13305E+04
				2	.33265E+03
				11	.10996E+02
				232	.24726E-01
53.44	5253.0641119921	632986.7313154750	.13111E-07	1	.32777E+03
				2	.81942E+02
				11	.27288E+01
				232	.67096E-02
61.09	4728.2773472675	629109.2625903914	.11946E-07	1	.29866E+03
				2	.74664E+02
				11	.24682E+01
				232	.55488E-02
61.50	4702.9573767311	628931.6475357741	.11884E-07	1	.29711E+03
				2	.74276E+02
				11	.24555E+01
				232	.55201E-02
61.65	2475.6974373424	628867.7654471382	.62604E-08	1	.15651E+03
				2	.39129E+02
				11	.12935E+01
				232	.29079E-02
77.65	2145.7238331847	624949.5262977742	.54939E-08	1	.13735E+03
				2	.34337E+02
				11	.11351E+01
				232	.25510E-02
MISSILE IN SUNSHINE					
119.05	1563.3195758502	689203.5347252785	.39586E-08	1	.98964E+02
				2	.24741E+02
				11	.81786E+00
				232	.18387E-02
124.82	1798.5224720488	710434.9548670847	.35634E-08	1	.89086E+02
				2	.22271E+02
				11	.73624E+00
				232	.16551E-02
125.42	1768.2694684136	713250.8060207350	.35152E-08	1	.87832E+02
				2	.21972E+02
				11	.72626E+00
				232	.16327E-02
126.75	964.6743141099	719769.2886389551	.18621E-08	1	.46552E+02
				2	.11638E+02
				11	.38472E+00
				232	.86488E-03

Output ½ hr before Sunrise

127.75	717.9452832984	724736.7786726215	.13667E-08	1	.34167E+02
				2	.85416E+01
				11	.28237E+00
				232	.63482E-03
183.53	225.3671571919	1323892.8350616276	.12874E-09	1	.32165E+01
				2	.80462E+00
				11	.26599E-01
				232	.59796E-04
185.29	129.9877464463	1351030.9864898938	.71215E-10	1	.17804E+01
				2	.44529E+00
				11	.14714E-01
				232	.33276E-04
198.59	84.2569264572	1596574.2349558120	.32896E-10	1	.82245E+00
				2	.20561E+00
				11	.67971E-02
				232	.15282E-04
206.59	63.7563515752	1747884.7273156012	.20869E-10	1	.52172E+00
				2	.13043E+00
				11	.43117E-02
				232	.96933E-05
552.22	84.5683574613	7798574.9552776177	.13908E-11	1	.34771E-01
				2	.86928E-02
				11	.28737E-03
				232	.64602E-06
1692.15	4210.8134678224	34735120.7745404243	.26670E-11	1	.66674E-01
				2	.16669E-01
				11	.55103E-03
				232	.12387E-05
1723.89	3835.2195990861	40835306.0950236320	.23000E-11	1	.57499E-01
				2	.14375E-01
				11	.47520E-03
				232	.10683E-05

½ hr after Sunset at -120° Longitude

HR ANGLE= -208.29

TIME	LUMINOUS INTENSITY (LUMEN/STER)	SLANT RANGE(FEET)	GROUND ILLUMINANCE (LUMEN/FT**2)=EG	F/NUMBER	FOCAL PLANE ILLUMINATION=ET
MISSILE IN SHADOW					
2.22	569.1412594722	625422.1514878833	.14550E-08	1	.36376E+22
				2	.90942E+21
				11	.33063E+20
				232	.67583E-03
3.15	565.8010442921	626809.6514019404	.14401E-08	1	.36002E+22
				2	.90006E+21
				11	.29754E+20
				232	.66889E-03
53.44	283.2402611288	632986.7313154759	.50725E-09	1	.12681E+22
				2	.31703E+21
				11	.10486E+20
				232	.23561E-03
61.09	164.5376679101	629109.2626903914	.41573E-09	1	.10393E+22
				2	.25983E+21
				11	.85895E+01
				232	.19316E-03
61.50	162.4786201488	628431.6475357741	.41076E-09	1	.10269E+22
				2	.25673E+21
				11	.84856E+21
				232	.19079E-03
61.65	85.3572639129	628667.7654471882	.21583E-09	1	.53959E+21
				2	.13490E+21
				11	.44594E+01
				232	.10025E-03
MISSILE IN SUNSHINE					
77.65	54.8927217191	624949.5262977748	.14055E-09	1	.35137E+01
				2	.87843E+00
				11	.29039E-21
				232	.65281E-04
119.65	53.2988947954	609203.5347252205	.11221E-09	1	.28052E+01
				2	.70130E+00
				11	.23183E-21
				232	.52116E-04
124.80	54.6536796219	710434.9548676667	.10020E-09	1	.27072E+01
				2	.67675E+00
				11	.22372E-21
				232	.50293E-04
125.40	54.8422760962	713250.6060207358	.10780E-09	1	.26951E+21
				2	.67377E+20
				11	.22273E-21
				232	.50072E-04
126.75	35.2997828607	719769.2866384531	.68137E-10	1	.17034E+21
				2	.42586E+20
				11	.14076E-21
				232	.31646E-04

½ hr after Sunset

127.75	26.189680458J	724736.7760726215	.49710E-10	1	.12427E+21
				2	.31269E+20
				11	.10271E-01
				232	.23289E-04
183.53	109.3044184440	1323092.0350016276	.61869E-10	1	.15467E+21
				2	.38666E+20
				11	.12785E-01
				232	.28737E-04
185.29	66.3250565601	1351030.4064596938	.47294E-10	1	.11824E+21
				2	.29554E+20
				11	.97715E-02
				232	.21967E-04
198.59	110.8213381924	1548574.2349556120	.43359E-10	1	.10840E+21
				2	.27099E+20
				11	.89585E-02
				232	.20139E-04
206.59	128.3259045712	1747689.7273156012	.42004E-10	1	.10501E+21
				2	.26252E+20
				11	.86784E-02
				232	.19511E-04
550.23	2012.6440622561	7798574.9532776177	.33093E-10	1	.82733E+20
				2	.20683E+20
				11	.68374E-02
				232	.15371E-04
1692.15	12983.1021542090	39735126.7745404243	.8223dE-11	1	.20557E+20
				2	.51394E-01
				11	.16990E-02
				232	.38194E-05
1723.89	13057.0714470141	40835306.0950236320	.78306E-11	1	.19576E+20
				2	.48941E-01
				11	.16179E-02
				232	.36371E-05

1 hr after Sunset at -120° Longitude

HR ANGLE= -247.59

TIME	LUMINOUS INTENSITY (LUMEN/STER)	SLANT RANGE(FEET)	GROUND ILLUMINANCE (LUMEN/FT**2)=EG	F/NUMBER	FOCAL PLANE ILLUMINATION=ET
MISSILE IN SHADOW					
0.00	272.7236272644	625426.1514678652	.69723E-09	1	.17431E+02
				2	.43577E+01
				11	.14486E+00
				232	.32585E-03
3.15	270.6766824764	626809.8314019404	.68894E-09	1	.17223E+02
				2	.43059E+01
				11	.14234E+00
				232	.32003E-03
53.44	192.3660833609	632986.7313154750	.48016E-09	1	.12004E+02
				2	.3001[illegible]E+01
				11	.9923[illegible]E-01
				232	.22302E-03
61.09	162.9233600436	629109.2626903914	.41165E-09	1	.10291E+02
				2	.2572[illegible]E+01
				11	.85[illegible]E-01
				232	.19[illegible]E-03
61.50	161.3297371509	628451.8475357741	.40781E-09	1	.1019[illegible]E+02
				2	.25[illegible]E+01
				11	.84257E-01
				232	.1894[illegible]E-03
61.65	84.8279045918	628867.7654471882	.21450E-09	1	.53624E+01
				2	.13[illegible]E+01
				11	.44317E-01
				232	.99629E-04
77.65	59.0444653660	624949.5262977742	.15118E-09	1	.3779[illegible]E+01
				2	.94[illegible]E+00
				11	.31235E-01
				232	.7[illegible]219E-04
119.85	56.7715173216	689203.5347252265	.11952E-09	1	.29[illegible]E+01
				2	.74[illegible]E+00
				11	.24[illegible]E-01
				232	.55514E-04
124.80	58.2228272506	710434.9548670667	.11536E-09	1	.28459E+01
				2	.72[illegible]E+00
				11	.23834E-01
				232	.53581E-04
MISSILE IN SUNSHINE					
125.40	58.4257778088	713250.8060207350	.11485E-09	1	.2871[illegible]E+01
				2	.71779E+00
				11	.23729E-01
				232	.53[illegible]E-04
126.75	34.7[illegible]97868	719769.2865389531	.71024E-10	1	.1775[illegible]E+01
				2	.44[illegible]E+00
				11	.14674E-01
				232	.32989E-04

1 hr after Sunset

127.75	27.1936176121	724736.7788728715	.51773E-10	1	.12943E+01
				2	.32356E+00
				11	.10697E-01
				232	.24144E-04
183.53	110.1219334653	1323892.035061687b	.62906E-10	1	.15727E+01
				2	.39316E+00
				11	.12997E-01
				232	.29216E-04
185.09	84.9530712543	1351030.9064698938	.47638E-10	1	.11912E+01
				2	.29774E+00
				11	.98426E-02
				232	.22127E-04
198.59	112.3634970315	1598574.2349558100	.43970E-10	1	.10993E+01
				2	.27481E+00
				11	.90[illegible]E-02
				232	.20423E-04
206.59	132.5046983455	1747689.7273153012	.42749E-10	1	.10687E+01
				2	.26718E+00
				11	.88325E-02
				232	.19956E-04
550.28	2127.9340708437	7798574.9532776177	.34873E-10	1	.87183E+00
				2	.21796E+00
				11	.72252E-02
				232	.16198E-04
1692.15	13013.7824612871	39735120.7745404743	.82424E-11	1	.20606E+00
				2	.51515E-01
				11	.17030E-02
				232	.38284E-05
1723.09	13208.0332772176	40855306.0950236320	.78368E-11	1	.19592E+00
				2	.48980E-01
				11	.16192E-02
				232	.36420E-05

2 hr after Sunset at -120° Longitude

HR ANGLE= -262.50

TIME	LUMINOUS INTENSITY (LUMEN/STER)	SLANT RANGE(FEET)	GROUND ILLUMINANCE (LUMEN/FT**2)=EG	F/NUMBER	FOCAL PLANE ILLUMINATION=ET
MISSILE IN SHADOW					
0.00	17.157020[illegible]469	625422.151487[illegible]832	.36195E-10	1	.90483E+00
				2	.22621E+00
				11	.74774E-02
				232	.16811E-04
3.15	13.[illegible]75[illegible]5[illegible]212[illegible]	626639.[illegible]3140[illegible]4404	.35315E-10	1	.88286E+00
				2	.22072E+00
				11	.72956E-02
				232	.16403E-04
53.44	151.[illegible]048[illegible]06197	632980.731315[illegible]750	.32771E-09	1	.81920E+01
				2	.20482E+01
				11	.67704E-01
				232	.15221E-03
61.09	120.[illegible]993[illegible]89381	629189.2626936[illegible]914	.30345E-09	1	.75863E+01
				2	.18966E+01
				11	.62696E-01
				232	.14095E-03
61.50	119.4511312577	628931.8475357741	.30193E-09	1	.75483E+01
				2	.18871E+01
				11	.62383E-01
				232	.14024E-03
61.65	62.93727[illegible]5626	628867.765447[illegible]862	.15907E-09	1	.39767E+01
				2	.99417E+00
				11	.32865E-01
				232	.73883E-04
77.65	49.2117901597	624944.5262977742	.12600E-09	1	.31501E+01
				2	.78752E+00
				11	.26034E-01
				232	.58535E-04
119.85	47.16400[illegible]1104	689203.5347252265	.99292E-10	1	.24823E+01
				2	.62056E+00
				11	.20515E-01
				232	.46119E-04
124.80	48.68049[illegible]9848	710434.954867[illegible]967	.96451E-10	1	.24113E+01
				2	.60282E+00
				11	.19928E-01
				232	.44799E-04
125.40	48.4897419354	713250.6[illegible]0207350	.96102E-10	1	.24026E+01
				2	.60064E+00
				11	.19856E-01
				232	.44637E-04
126.75	53.2920411549	719769.2[illegible]86[illegible]551	.58081E-10	1	.14522E+01
				2	.36321E+00
				11	.12000E-01
				232	.26977E-04

2 hr after Sunset

127.75	22.3571455192	724736.7768728215	.42556E-10	1	.10639E+01
				2	.26597E+00
				11	.67925E-02
				232	.19766E-04
183.53	97.4524373564	1323892.0350816275	.55657E-10	1	.13914E+01
				2	.34786E+00
				11	.11499E-01
				232	.25652E-04
185.09	76.4772624279	1351030.9064696938	.41900E-10	1	.10475E+01
				2	.26187E+00
				11	.86572E-02
				232	.19462E-04
198.59	101.6[illegible]944234	1548574.2349556108	.39789E-10	1	.99472E+00
				2	.24868E+00
				11	.82220E-02
				232	.18431E-04
MISSILE IN SUBMARINE					
226.59	119.9[illegible]7499234	1747899.7273150912	.39247E-10	1	.98116E+00
				2	.24529E+00
				11	.81188E-02
				232	.18229E-04
550.20	2220.0329270673	7748574.9532776177	.36174E-10	1	.90435E+00
				2	.22609E+00
				11	.74746E-02
				232	.16802E-04
1692.15	12513.8478250479	37735122.7745404245	.79955E-11	1	.19989E+00
				2	.49972E-01
				11	.16520E-02
				232	.37137E-05
1723.89	12611.6[illegible]2154915	40835306.0950236320	.75631E-11	1	.18920E+00
				2	.47264E-01
				11	.15626E-02
				232	.35129E-05

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