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PROPAGATION MODELING AND ANALYSIS FOR HIGH ENERGY LASERS

Science Applications, Incorporated

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This report analyzes simplified propagation codes and recommends improved models for characterizing the propagation of high energy CW laser beams.

(1)

PROPAGATION MODELING AND ANALYSIS
FOR HIGH ENERGY LASERS

FINAL REPORT

SAI-74-629-WA

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This work was performed under Contract No. N60921-75-C-0007, July 1974 through March 1975.

April 1975

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FOREWORD

This is the final report covering work performed for the Naval Surface Weapons Center under contract N60921-75-C-0007. The purpose of the contract was to analyze simplified propagation codes and recommend improved models for characterizing the propagation of high energy CW laser beams. The work was performed under the direction of Mr. Larry Jobson of NSWC.

This report documents the work performed during the period January-March 1975. It also provides a review of the earlier work (July 1974-January 1975). The earlier work was described in detail in interim reports SAI-74-587-WA (October 1974) and SAI-74-622-WA (January 1975).

The authors wish to express their appreciation to Dr. Tom Tuer of the SAI Ann Arbor office for his development of the multi-line absorption coefficients. We also thank Mrs. T. Peckham for implementing the numerous code modifications.

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Section 1

INTRODUCTION

In support of the Systems Analysis Team of the Naval Surface Weapons Center, Science Applications, Inc. (SAI), performed a series of tasks designed to develop a better understanding of the modeling alternatives available to laser systems analysts and to assist in the continual improvement of the NOL Engagement Code (NOLEC). Emphasis was placed on the resolution of propagation issues of interest to systems analysts. The tasks involved quantitative comparison of simplified HEL propagation codes used by DOD analysts, clarification of the beam quality problem, development of beam distortion and displacement models, development of a simplified optical train model, and expansion and improvement of the AFWL COMBO code.

The work was divided into six tasks. The first four tasks are reviewed in this report (Section 4), but are covered more extensively in interim reports (References 1 and 2):

<u>First Interim Report - July-September 1974, SAI-74-587-WA, October 1974 (Reference 1)</u>

Task 1. Quantitative Comparison of Simplified Propagation Codes

Task 3. Beam Quality Modeling.

<u>Second Interim Report - September 1975-January 1975, SAI-74-622-WA, January 1975 (Reference 2)</u>

Task 2. Beam Shape and Displacement Due to Thermal Lensing.

Task 4. Effect of Truncation and Obscuration on the Far-Field Beam Profile.

Task 5 required the development of a simplified optical train model. This work is described in Section 2 of this report. Task 6 involved modification and extension of the AFWL COMBO code and included the incorporation of models developed in the earlier tasks. The new version of the code was named SAICON. Section 3 describes the modifications and provides a user's guide to SAICON.

Section 2

A SIMPLIFIED OPTICAL TRAIN MODEL

When performing laser application studies, the system analyst all too frequently assumes that the characteristics of the beam leaving the transmitting optic are the same as the characteristics of the beam leaving the laser device without regard for any changes induced by the optical elements and/or components required to get the beam from the laser device to the transmitting optic, i.e., the optical train. It is known, however, that significant changes to the characteristics of the beam do occur as it propagates through the optical train (see for example References 3 and 4). The finite absorptivity of the high power mirrors, clipping and blockage of a portion of the high power beam, and diffraction effects all reduce the available power in the beam at the transmitting optic. In addition the optical quality of the beam is affected by nearly every component or element through changes in the phase and amplitude distribution of the beam. Therefore, if realistic estimates of the performance of candidate laser systems are to be obtained during these application studies, it is important to include the effect of the optical train on the characteristics of the laser beam.

An accurate assessment of the impact of the optical train is a tedious and difficult calculation requiring a wave optics approach and sophisticated analytical tools for modeling each of the elements in the optical train. Obviously these are not very practical for use in systems analysis application studies in which a large parameter space must be investigated. Therefore, if the effect of the optical train is to be included in such analyses, the development of simple but reasonably accurate models is required.

One such model has been developed by the AFWL (Reference 5) which is used in their simplified propagation code (COMBO). However, its use is somewhat restrictive in that most of the component effects are left for the user to specify. Prescriptions for scaling these effects in terms of system parameters are not given. In addition, the impact of the optical train on the beam quality is assessed in terms of peak intensity reduction. Based on work under this contract, it is felt that an assessment in terms of the far-field power distribution provides a better characterization of the beam quality (see Reference 1 and Section 4.3 of this report).

We have developed a more comprehensive "simplified" optical train model which can be used to estimate the degradation in system performance caused by the optical components required to direct the beam from the laser device to the transmitting optic (i.e., aerodynamic window, mirrors, beam expander, etc.). The intent of the model is not to provide detailed engineering design data but rather to provide the systems analyst with a rapid assessment capability which will allow him to perform more realistic systems analyses of candidate HEL systems. Hence, emphasis is placed on formulating simple but reasonably accurate models for the various factors influencing the performance of the laser system. The approach is similar to that taken by the AFWL in their simplified model but with new additions and modifications to make the model more flexible. The model has been implemented in a subroutine called OPTRAIN and is included in the SAICOM code as described in Section 3 below.

2.1 MODEL FORMULATION

Conceptually, the optical train may be viewed as a "black box" located between the laser device and the transmitting optic. The input to the box is the output beam from the laser. The model operates on this beam according to the number and type of elements in the train, and its output, in the form of certain performance parameters, provides the input to an atmospheric propagation model. The performance parameters are: (1) the power available at the transmitting optic, (2) beam quality, (3) beam divergence, and (4) beam jitter. In addition, the actual diameter of the beam at the exit aperture is computed for use in the propagation model.

The essential features of the model are illustrated in Figure 2.1. The optical elements and components include (1) an aerodynamic window, (2) a beam clipper, (3) several high power mirrors, (4) a beam expander, (5) an exit aperture, and (6) a focusing element for transmitting the beam to the target plane. In most practical cases the beam expander and focusing element are combined into a single telescope. However, it is convenient for the present analysis to separate them into an ideal beam expander which simply expands the beam and a separate element which applies the curvature to the beam phase front for focusing purposes.

2.1.1 Input Beam

Although it is not an optical element or component, the input beam is necessarily an integral part of the model since it has strong influence on the behavior of the rest of the optical train. In order to simplify the analysis of the components in the optical train, it is assumed that the beam from the laser is circular. However, because of

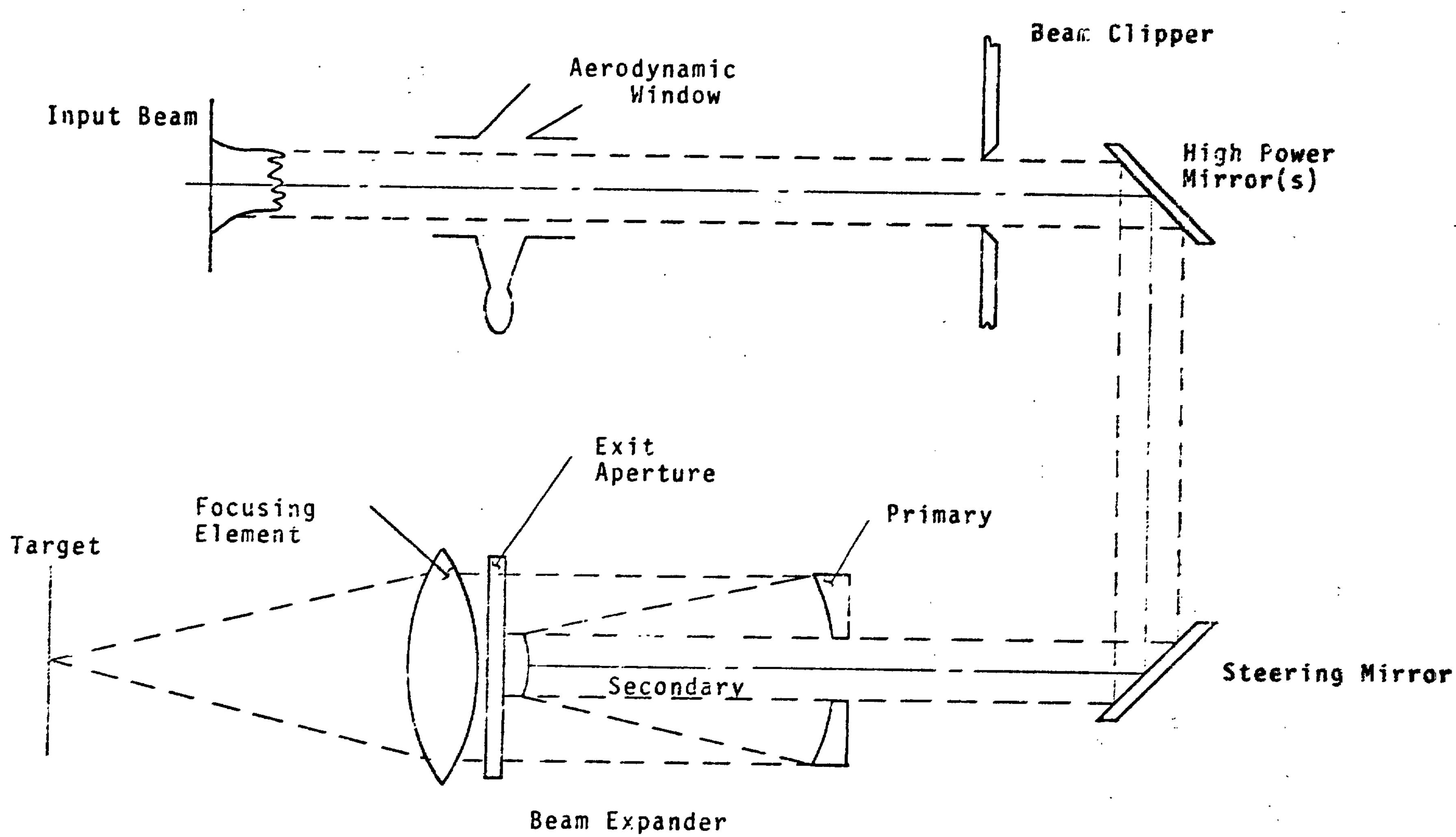


Figure 2.1 Typical Optical Train

the widespread use of unstable resonator configurations to extract power from high power devices, the possibility of a central obscuration in the input beam is incorporated into the model. The inner and outer diameters of the input beam are εD_B and D_B respectively. An unobscured input beam profile can be realized by defining $\varepsilon = 0$. Other parameters required to specify the input beam are (1) the power in the beam, P_L, (2) the pulse length, Δt, (3) the curvature of the phase front, R_L, and the beam jitter, Θ_L.

In order to evaluate the effect the beam has on the high power mirrors in the optical train, it is also necessary to characterize the intensity profile entering the optical train. This is achieved by specifying both the magnitude and scale size of the intensity fluctuations, the magnitude being specified as a fraction of the average intensity ($\Delta I/I_{ave}$) and the scale size as a fraction of the beam diameter (ℓ_I/D_B). Thus the input beam profile may be visualized as having a uniform intensity I_{ave} with fluctuations ΔI superimposed upon this level.

The optical quality of the input beam is specified by a wavelength scaling factor, n_L. Unfortunately, this definition of beam quality does not allow one to easily incorporate the other beam quality degrading factors induced by the various elements of the optical train. Therefore this parameter is converted by the model into an equivalent root-mean-square phase distortion, σ_L.

Two alternative approaches for this conversion were investigated for use in the model. The first approach is to define the equivalent phase distortion so as to match the reduction in the peak intensity, I_p. According to the analysis presented in Reference 6, the peak intensity reduction is (for a gaussian beam containing small scale random phase variations)

$$I_p/I_g = \exp(-\sigma_L^2)$$

where I_g is the ideal on-axis intensity. According to the wavelength scaling definition of beam quality

$$\frac{I_p}{I_g} = \frac{1}{n_L^2}$$

so that

$$\sigma_L = \sqrt{2\ln(n_L)} \; . \qquad (1)$$

It should be noted that this approach is equivalent to the power scaling definition of beam quality and is also the approach taken by the AFWL in their optical system model (Reference 5).

The second approach investigated was to define the equivalent phase distortion to match the power in the "bucket" ($R\lambda/D = 1$) predicted by wavelength scaling. This is given by (Reference 1):

$$P(R\lambda/D) = P_o\{1 - \exp(-\pi^2/2n_L^2)\}.$$

Again, following the analysis of Reference 4, the power in the bucket for a non-diffraction-limited gaussion beam is given by

$$P(R\lambda/D) = P_o \exp(-\sigma_L^2) \; \{1 - \exp\;(-\pi^2/2)\}$$

assuming all of the quality degradation can be characterized as a scattering loss. Equating these expressions and solving for σ_L yields,

$$\sigma_L = \left\{ -\ln \left[\frac{1 - \exp(-\pi^2/2n_L)}{1 - \exp(-\pi^2/2)} \right] \right\}^{1/2} \quad (2)$$

Intuitively it would seem that both of these approaches should yield approximately equivalent results. Quantitatively however, substantial differences were found. These are illustrated in Figure 2.2 which compares the phase distortion computed from Equations (1) and (2). The phase distortion based on matching the peak intensity reduction is always considerably higher than that based on matching the power-in-the-bucket, e.g., over a factor of 2.5 for a 1.5 times diffraction-limited input beam. The reasons for these differences are not clear. One possible explanation is the equivalence of wavelength and power scaling methods of defining peak intensity reduction. It was found during previous work under this contract (Reference 1) that power scaling was always more pessimistic in its predictions of the beam quality than wavelength scaling. Therefore, matching the peak intensity based on a method that is equivalent to power scaling might be expected to produce more pessimistic results (i.e., higher σ_L) than matching the power-in-the-bucket based on wavelength scaling.

Whatever the reasons for the differences, we recommend the use of Equation (2) because the power-in-the-bucket is a more meaningful measure of laser performance than peak intensity reduction. The latter suffers from its sensitivity to defocusing errors and difficulty in experimental measurement.

2.1.2 Aerodynamic Window

The first component in the optical train is the aerodynamic window isolating the optical cavity of the laser

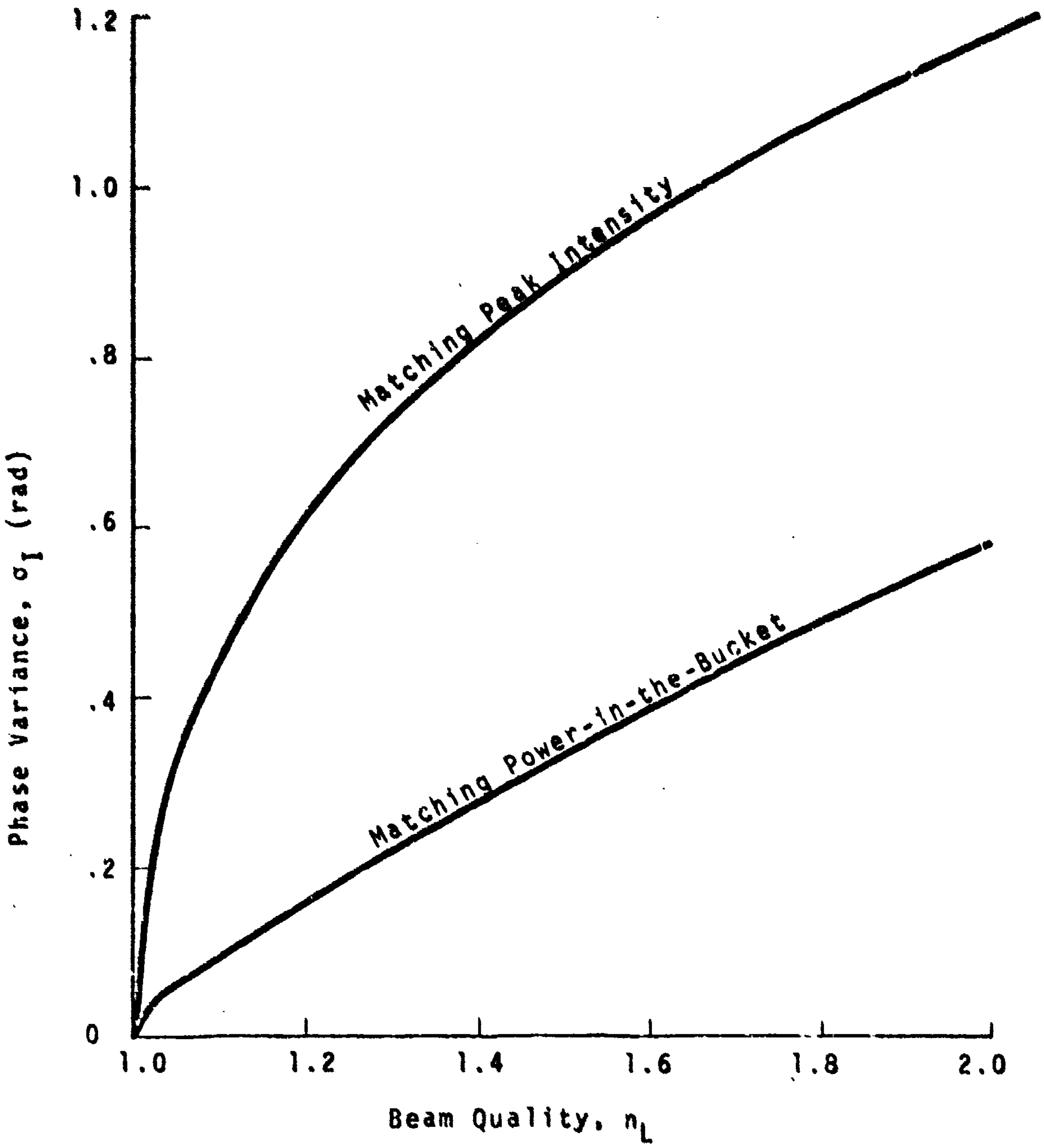


Figure 2.2. Comparison of Input Beam Quality Specifications

from the atmosphere. Basically there are two types of aerodynamic windows currently being considered for HEL applications: (1) focused and (2) unfocused. In both cases, if the window is properly designed, there should be little or no power loss when the beam passes through it. In addition, it is also assumed that no spherical distortion to the phase front will be induced by the aerodynamic window. The shock waves supporting the pressure rise and the turbulence generated by the aerodynamic window will, however, induce a loss in the beam quality. An expression for this loss is given by (Reference 4)

$$\Delta I/I = 2.84 \times 10^{-10} \left(\frac{\Delta\rho}{\rho_s} \frac{D_B}{\lambda} \right)^2$$

where $\Delta\rho$ is density change across the shear layer and ρ_s is a reference density at STP. Again this formalism of beam quality degradation is not convenient for use in the model and is converted into an equivalent phase distortion, σ_{aw}^2 by use of the Strehl formula (Reference 4):

$$\Delta I/I \approx \sigma_{aw}^2 .$$

Solving for the phase distortion yields

$$\sigma_{aw} = 1.69 \times 10^{-5} \left(\frac{D_B}{\lambda} \frac{\Delta\rho}{\rho_s} \right) .$$

A typical value of σ_{aw} for a 10 cm beam from a chemical laser (λ = 3.8 μm), assuming $\Delta\rho/\rho_s$ = 0.25 for the density variations, is σ_{aw} = 0.11 radians. This corresponds to an intensity reduction of $\Delta I/I \approx 1.2\%$.

For the focused aerodynamic window, the beam diameter will typically be very small (<0.1 cm) so that the phase distortion can be neglected, i.e., $\sigma_{aw} \approx 0$.

2.1.3 Beam Clipper

For HEL systems in which the laser device and the pointer/tracker are not closely coupled, a beam clipper or scraper will probably be employed near the pointer/tracker to control the size of the high power beam entering the transmitter. The beam clipper will influence both the power available at the transmitting optic and the beam quality, the latter by limiting the maximum diameter at the transmitting optic.

The loss in power at the beam clipper is due primarily to diffractive spreading of the beam as it propagates between the aerodynamic window and the beam clipper. In general, the diffractive spreading will depend upon the phase and amplitude aberrations in the input beam profile. An accurate assessment of the actual losses requires a detailed calculation involving numerical solutions of the Fresnel diffraction integral or spatial frequency approaches to optical propagation (i.e., Fourier Optics). These techniques are very time consuming and were not considered as viable candidates for the "simplified" model. Instead, an empirical approach based on curve fits of available data in the literature was taken. Unfortunately very little data were available for examination. Only two sources were found (References 4 and 7). The data obtained from these sources are illustrated in Figure 2.3 which shows the variation in power diffracted into the geometric shadow of a uniformly illuminated aperture as a function of the propagation distance from the aperture. The AFWL data were calculated for a one-dimensional beam profile while the HAC (Hughes

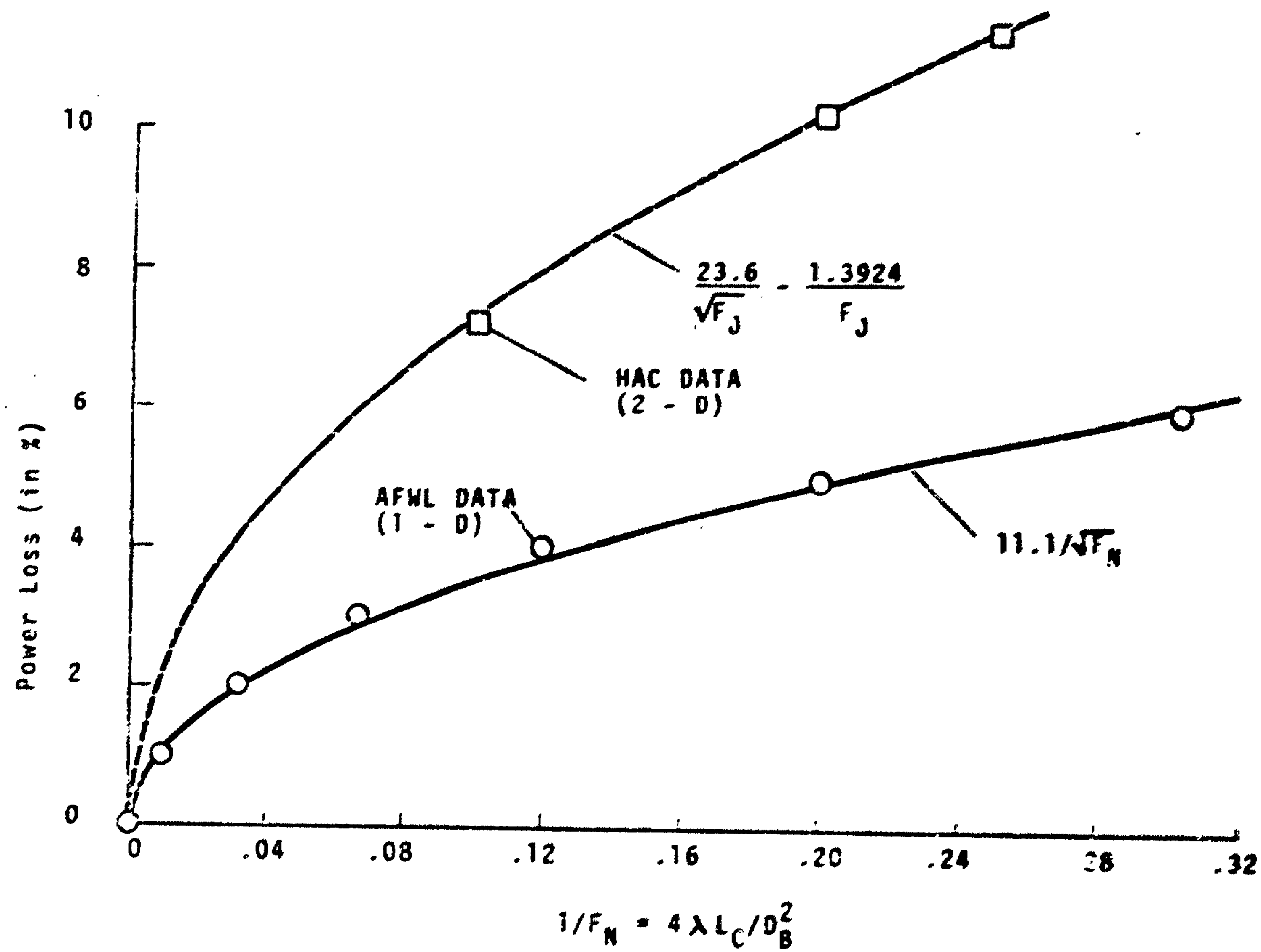


Figure 2.3. Diffractive Spillover Losses

Aircraft Company) calculations were performed for a round beam. Therefore, the data must be adjusted for these differences before a direct comparison can be made.

Intuitively one would expect a factor of two difference between the data based on simple geometrical arguments. For example, a square beam profile would have twice the loss of a one-dimensional profile because of the two additional edges. For a round beam, however, the ratio is not quite as straightforward. Assuming circular symmetry, the fractional power loss is

$$\Delta_{2-D} = \frac{2\pi \int_a^\infty I(\sigma)\ \sigma d\sigma}{\pi a^2\ I_o}$$

where a is the radius of the aperture and I_o is the initial intensity. The major contribution to the integral occurs near the edge of the aperture. Thus over this region the radius can be taken as being approximately constant (= a) and removed from the integral without affecting its value, i.e.,

$$\Delta_{2-D} = \frac{2}{aI_o} \int_a^\infty I(\sigma)\ d\sigma .$$

For the one-dimensional beam profile the fractional power loss is given by

$$\Delta_{1-D} = \frac{\int_a^\infty I(x)\ dx\ (1)}{a\ I_o\ (1)}$$

so that if one further assumes that the intensity profiles at the aperture plane are the same in either case, i.e., $I(r) = I(x)$, then one again gets a factor of two difference between the power losses.

The actual ratio indicated by the data was somewhat higher than a factor of 2 as shown by the corresponding curve fits of the data. Both sets of data correlated very well as a function of the reciprocal of the square root of the Fresnel number. However, the proportionality constant for the HAC data was found to be 23.6 versus 11.1 for the AFWL data.

In order to use these results in the optical train model, the power loss was assumed to be related to an effective increase in the beam diameter at the aperture plane, i.e.,

$$\frac{D_B}{D_{B_o}} = (1 - \text{loss})^{1/2} \quad 1 - \frac{0.112}{\sqrt{F_N}}$$

where D_{B_o} is the new diameter of the beam at the beam clipper station and $F_N = D_B^2/4\lambda L_C$ is the propagation Fresnel number. It was also assumed, for the case of an obscured beam, that the hole in the beam filled in as much as the diameter of the hole would grow were it a uniformly illuminated aperture (i.e., Babinet's Principle). Thus the inner diameter of the obscured beam, D_{Bi}, is computed by

$$D_{Bi} = \epsilon D_B \left(1 - 0.112/\epsilon\sqrt{F_N}\right).$$

If D_c is the diameter of the beam clipper, then the power transmission through the aperture is

$$T_c = \begin{cases} 1.0 & \text{if } D_{B_o} \le D_c \\ (D_c/D_{B_o}) & \text{if } D_{B_o} > D_c \end{cases} .$$

In the latter case, the beam diameter is set equal to the clipper diameter for the remaining calculations in the model.

2.1.4 High Power Mirrors

The mirrors in the optical train will affect all the performance parameters. Although it is not necessary we assume that all of the mirrors are identical in order to reduce the number of inputs.

A mirror alters the amplitude of the beam by absorbing a fraction of the incident radiation. For a series of N mirrors each having a surface reflectivity R, the transmission factor is

$$T_M = R^N.$$

It should be noted that in the present analysis N includes all of the mirrors in the optical train, i.e., relay, steering, secondary and primary.

The beam quality degradation is due to (1) surface roughness and manufacturing errors in the mirror figure, and (2) surface distortions due to absorption of power from the incident beam. The former are independent of the power in the beam while the latter is a function of both the power and the irradiance distribution. In addition, if cooled mirrors are used, there will also be distortions induced by the pressure variations inside the coolant passages. However, these distortions will depend upon the details of the mirror construction and their characterization is felt to be beyond the scope of this model. Therefore, for this analysis, distortions of this type will be included in (1) above.

The beam quality degradation induced by the mirrors is incorporated into the optical train model through an equivalent phase variance, σ_M where

$$\sigma_M^2 = N\sigma_f^2 + [(N - 1)\,\sigma_I + \sigma_I/M^2]^2.$$

The first term on the right hand side of the above expression represents the uncorrelated sum of the phase distortion due to fabrication errors such as surface roughness, figure error, coolant passage distortion, etc. The remaining terms represent the correlated sum of the irradiance mapping phase distortion. The distortion of the primary mirror is reduced by the square of the magnification of the beam expander to account for its reduced thermal loading.

In practice, σ_f is not known but is instead specified as a tolerance on the manufacturing process. Therefore, for modeling purposes this parameter was left to the user to specify.

The approach taken to model σ_I was to assume that the distortions scale directly with the irradiance fluctuations. That is,

$$\sigma_I = KI_{rms}$$

where K is a constant which depends upon the physical parameters of the mirror, the cooling scheme, etc. If we assume that the peak to peak intensity fluctuations specified in the input beam description are uniformly distributed and random in character, then

$$I_{rms} = \frac{I_{ave}}{\sqrt{12}} \left(\frac{\Delta I}{I_{ave}}\right)$$

where, for a circular beam,

$$I_{ave} = \frac{4\ P_L}{\pi\ D_B^2}$$

Expressions for the evaluation of K depend upon whether the mirror is water cooled or not, i.e., for cooled optics

$$K(m^2/watt) = 5 \times 10^{-14}\ (1 - R)\ (2\pi/\lambda)$$

whereas, for uncooled optics

$$K = 4\pi\ (1 - R)\ \alpha \Delta t/\lambda C \rho$$

where

α = the thermal expansion coefficient of the mirror material

C = the specific heat of the mirror material

ρ = density of the mirror material.

The expression for cooled optics is based on the NPT/Chemical Laser Compatibility Study conducted by Hughes Aircraft Company for NSWC (Reference 8) in which similar expressions were employed to compute the phase distortion caused by the NACL irradiance profile. The expression for uncooled optics is based on a simplified one-dimensional heat transfer analysis (Reference 9).

Local surface distortion is not the only performance degrading factor caused by the finite absorptivity of the mirrors. A bending distortion is also induced by the differential growth of the front and rear mirror surfaces. For properly designed, cooled mirror configurations, this distortion can be kept small. However, for uncooled mirrors, it may be important.

To first order, the bending distortion is primarily a function of the total beam power and not the irradiance distribution. In addition it produces mostly a spherical phase front distortion. Thus in the optical train model, we compute this distortion mode as a beam divergence instead of a quality loss since, in theory, it could be corrected by the focusing optic (if detected).

For an uncooled mirror that was initially flat, the change in the focal length with time can be approximated as (see Reference 9)

$$f = \frac{D_B^2 \, \ell \cos \Theta}{2.44 \, P_L \, (1 - R) \, \alpha} \left(\frac{D \rho K}{\Delta t} \right)^{1/2}$$

where

ℓ is the mirror thickness

Θ is the beam angle of incidence on mirror

K is the thermal conductivity of the mirror material

f is the focal length of the distorted mirror.

The mechanism by which the defocusing errors induced by the individual mirrors are accumulated throughout the optical train is explained later.

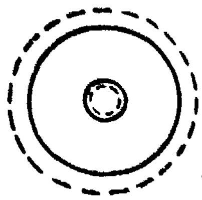
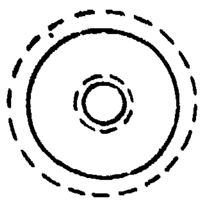
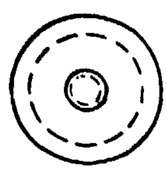
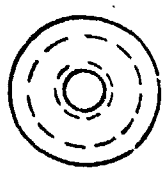
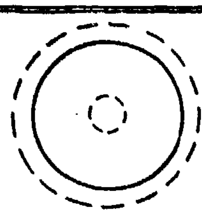
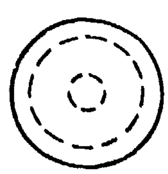
2.1.5 Beam Expander

In the formulation of the beam expander model, we allow for two types: (1) an on-axis or (2) an off-axis system. Either type system affects the available power at the transmitter, the beam quality, beam jitter and beam divergence. A discussion of the methodology for computing the transmission factor and beam quality is given below. The beam jitter and divergence are discussed in a later section.

The power transmission through the beam expander is computed by projecting the exit aperture (defined by the user) onto the plane of the beam clipper station. Simple geometry then allows one to compute the power lost due to a mismatch between the beam diameters and exit aperture diameters. The formulas are illustrated in Table 2.1 for both the on-axis and off-axis cases.

The beam quality is not affected by the off-axis system except to the extent that the limiting diameter is $MD_{B_0} \leq D_t$ for spot size calculations at the target plane. This is also true of the on-axis case. However, the on-axis system also introduces a central obscuration ε, which reduces the beam quality. The expressions used in the model to compute the final obscuration of the beam leaving the optical train are also given in Table 2.1.

Table 2.1. Summary of Beam Expander Transmissions and Obscuration Calculations

TYPE	GEOMETRY	TRANSMISSION	OBSCURATION
ON AXIS		$\frac{D_o^2 - D_i^2}{D_{B_o}^2 - D_{B_i}^2}$	D_i/D_o
		$\frac{D_o^2 - D_{B_i}^2}{D_{B_o}^2 - D_{B_i}^2}$	D_{B_i}/D_o
		$\frac{D_{B_o}^2 - D_i^2}{D_{B_o}^2 - D_{B_i}^2}$	D_i/D_{B_o}
		1.0	D_{B_i}/D_{B_o}
OFF AXIS		$(D_o/D_{B_o})^2$	D_{B_i}/D_o
		1.0	D_{B_i}/D_{B_o}

The effect of the obscuration on the beam quality is again computed by relating it to an equivalent phase distortion. This relationship was derived empirically based on the results of the previous work under this contract (Reference 2), and is illustrated graphically in Figure 2.4. Within the computer code, this relationship is represented by a third order polynomial developed from a "least-squares" regression analysis of the data presented in Figure 2.4. Also shown on the figure is the effective scale size of the phase distortion. Its use in the model will be explained below.

2.1.6 Exit Aperture

Provisions were also made in the optical train model for an exit aperture downbeam of the pointer/tracker. It can be either a material window or open port, with an aerodynamic curtain protecting the optics from the environment, based on user specified option parameters.

In either case the loss in power through this exit aperture will be

$$T_E = e^{-\beta L_W} (1 - A_S/A_B)$$

where

β = absorption coefficient of material window

L_W = thickness of material window

A_S = area of struts supporting window or secondary mirror in the case of an on-axis beam expander

A_B = beam area $(\pi M^2 D_{B_O}^2/4)$.

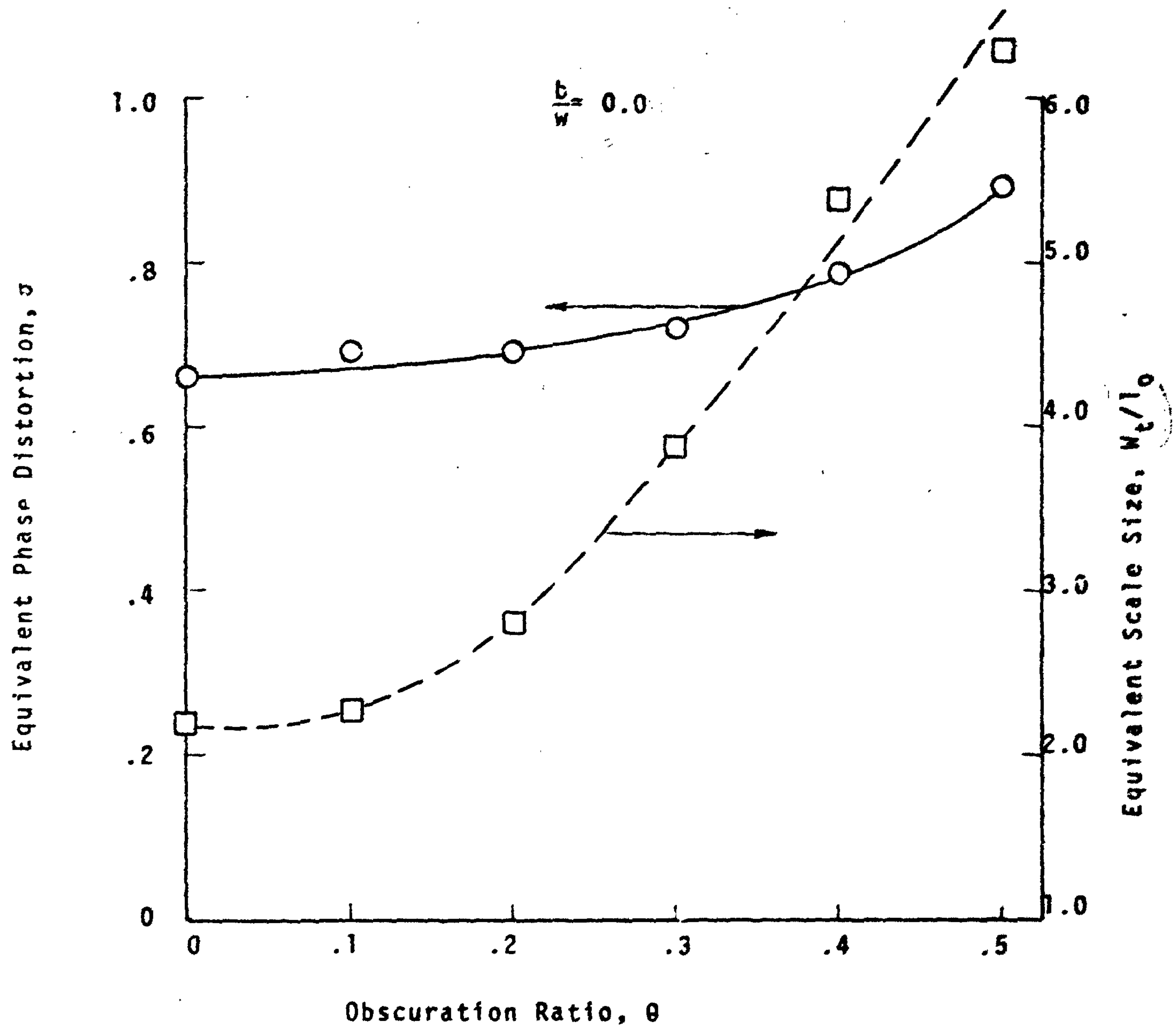


Figure 2.4. Beam Quality Loss Due to Central Obscuration in Terms of θ and W_t/l_o

Note that an open port can be simulated by setting $\beta = 0$.

For simplicity, the phase distortion induced by the material window is assumed to be proportional to the local intensity fluctuations in the beam profile. That is

$$\sigma_W = \left(\frac{2\pi}{\lambda}\right) \frac{\beta \Delta t L_W}{\rho c} \left[(n - 1)\,\alpha + \frac{\partial n}{\partial T}\right] \frac{I_{rms}}{M^2}$$

where (in addition to those parameters previously defined) n is the refractive index and T is the temperature. The magnification appears because of the assumed location of the window downstream of the beam expander. In order to minimize the number of inputs to the model, the material constants were lumped into a single parameter defined as

$$\gamma = \frac{1}{\rho C} \left[(n - 1)\,\alpha + \frac{\partial n}{\partial T}\right]$$

which varies between 4×10^{-12} m^3/j for the fluoride windows (CaF_2, MgF_2, SrF_2) to 15×10^{-12} m^3/j for the salt windows (NaCl, KCl). A value of 5×10^{-12} m^3/j was hardwired into the model as being representative of current window technology.

The presence of struts in the beampath will also cause a reduction in the beam quality. To first order, this loss will be directly proportional to the area of the beam blocked by the struts. Consider, for example, the on-axis intensity which, in the context of scalar diffraction theory, is given by the integral of the complex field leaving the transmitting aperture, i.e.,

$$I(o) \sim \left[\iint u(x,y)\, d\,x\, dy\right]^2.$$

Thus, for a constant field aperture strength, the integral is simply the area of the clear aperture. That is

$$I(o) \sim (A_B - A_s)^2$$

so that the intensity reduction relative to no struts is simply

$$\frac{I(o)}{Io} = \left(1 - \frac{A_s}{A_B}\right)^2 = T_s \ (1 - A_s/A_B).$$

For modeling purposes, this intensity reduction was considered to be separable into (1) a power loss due to the transmission of the aperture, T_s, and (2) a beam quality loss characterized by wide angle scattering, $(1 - A_s/A_B)$. The latter can be related to an equivalent phase distortion via the Strehl equation

$$\sigma_s = (A_s/A_B)^{1/2} .$$

The phase distortion induced by an open port is not intensity dependent but instead a function of the turbulence level inside the beam expander and aerodynamic curtain. Because of the presence of turbulence, this effect is treated as an additional source of beam jitter in the model. The magnitude of the jitter is estimated from (Reference 8)

$$\Theta_J = 2.14 \times 10^{-7} \left[\frac{L_e^3 \ \Delta T^6}{\lambda \ D_t^2}\right]^{1/5}$$

where L_e is the path length through the beam expander and ΔT is the magnitude of the temperature fluctuations within the beam expander. Some representative values of the jitter are illustrated in Figure 2.5 for a 0.7 meter transmitter diameter. For example, a $1^{o}C$ temperature fluctuation produces approximately 4.5 μrad of beam jitter for a 3.8 μm wavelength beam.

2.2 ASSESSMENT OF OVERALL PERFORMANCE

The previous discussion was primarily concerned with the influence each of the elements has on the characteristics of the laser beam as it traverses the optical train. In the following section we show how these individual effects are accumulated to arrive at an overall assessment of system performance.

2.2.1 Transmitted Power

The power available at the transmitting optic is simply the input power from the laser device modified to account for all of the power losses that have occurred along the optical train. That is

$$P_t = T\,P_L$$

where T is an overall transmission factor. Since the power losses are multiplicative, the overall transmission factor is

$$T = (T_C)\,(T_M)\,(T_{BE})\,(T_E)$$

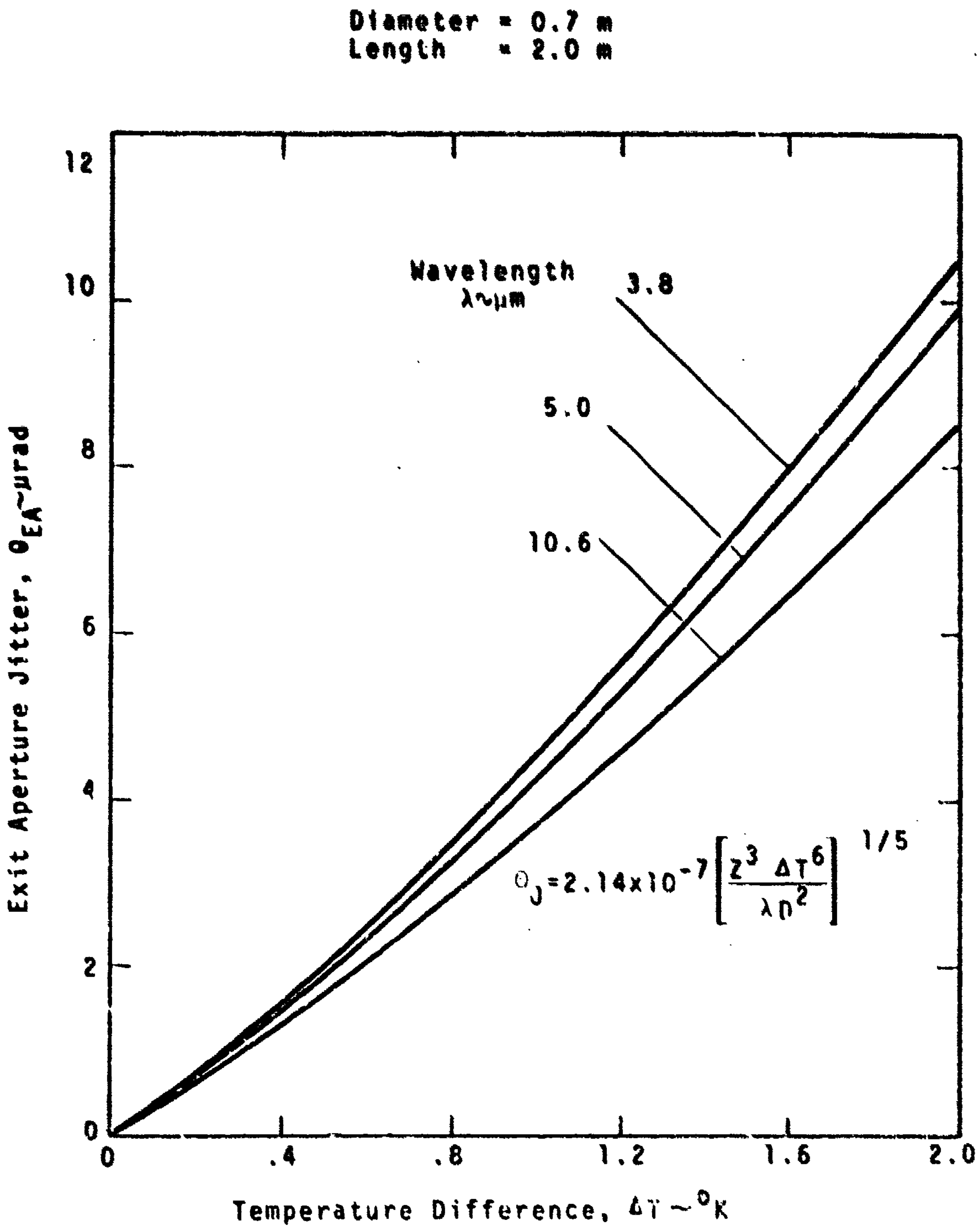


Figure 2.5. Effects of Exit Aperture Temperature Fluctuations on Beam Jitter

where T_C is the transmission factor of the beam clipper, T_M is the transmission factor of all the high power mirrors, T_{BE} is the transmission factor of the beam expander, and T_E is the transmission factor of the exit aperture. Formulas for all of these factors were given previously.

2.2.2 Beam Quality

The quality of the beam at the transmitting optic is characterized by the two beam quality parameters, m_1 and m_2 (see Reference 1 and Section 4.3 of this report). Unfortunately, the calculation of m_1 and m_2 is not simple. The basic problem is to combine the effect of all the quality degrading factors occurring within the optical train. This is somewhat complicated because the phase distortions induced by the individual components do not add up in a straightforward manner but instead depend, in a complicated manner, upon the distribution as well as the magnitude of the phase distortion. For example, a "smooth" distortion behaves differently than a very "rough" distortion even though their magnitudes are the same.

To circumvent this problem, a statistical approach is used within the model to accumulate the phase distortions. This approach is somewhat loosely based on the theoretical investigations of nondiffraction-limited gaussian beams by B. Hogge at the AFWL. Briefly, the approach is to consider the overall beam profile at the focal plane as being composed of two gaussian beam profiles of different relative amplitudes and widths. That is, a certain fraction of the energy in the beam is propagated completely unaffected by the phase distortion, i.e.,

$$I_u(r) = e^{-\sigma^2} \exp\left(-\frac{2r^2}{w_f^2}\right) I_o$$

where w_f is the diffraction limited waist parameter, I_0 is the on-axis intensity and σ^2 is the variance of the phase distortion (assumed to a gaussian random variable). The remaining energy is smeared or spread by the phase distortion into a somewhat larger beam profile, i.e.,

$$I_s(r) = (1 - e^{-\sigma^2}) \left(\frac{w_f^2}{w_f^2 + 2\Theta^2 f^2}\right) \exp\left(\frac{-2r^2}{w_f^2 + 2\Theta^2 f^2}\right) I_0$$

where Θ is the angular spread of the scattered beam.

The problem thus reduces to characterizing the overall phase variance, σ, and beam spread parameters, Θ, that "best" model the summation of all of the phase distortions in the optical train.

A true characterization of σ and Θ is, in reality, not possible. Some theoretical arguments can be made for isolated phase ditributions such as the random gaussian noise model investigated by Hogge. In the real world, however, optical systems do not produce such amiable distortions. Nevertheless, using these results as being at least qualitatively correct, we compute the total phase distortion as simply the uncorrected sum of each of the individual distortions, i.e.,

$$\sigma^2 = \sigma_L^2 + \sigma_{AW}^2 + \sigma_M^2 + \sigma_{BE}^2 + \sigma_S^2 + \sigma_W^2.$$

Instead of computing the beam spread, Θ, it is more convenient to compute an effective scale size or correlation length of the overall phase distortion, L. This scale size is related to the beam spread via $\Theta^2 = (\lambda/\pi L)^2$. In the aforementioned work of Hogge, it was noted that the effective correlation length for a number of sources of phase distortion was found to be an average of the correlation lengths of the individual sources, each weighted by its respective variance. Again, taking the inductive leap, we compute L from

$$L = \frac{1}{\sigma^2}\left[\ell_L\sigma_L^2 + \ell_{AW}\sigma_{AW}^2 + \ell_M\sigma_M^2 + \ell_{BE}\sigma_{BE}^2 + \ell_S\sigma_S^2 + \ell_W\sigma_W^2\right].$$

In practice very little is known about the magnitude of the scale sizes characterizing the individual components. Therefore, for the present model, we have made some additional assumptions regarding their respective sizes. For example, the irradiance mapping phase distortions such as σ_I and σ_W are assumed to have the same scale size as the intensity fluctuations in the input beam profile. For other components, such as the laser device, the aerodyanmic window and the struts, we assume that the scale size is zero. In effect this is assuming that each of these components scatters the energy in the beam beyond a usable radius in the focal plane and therefore is somewhat conservative. The scale size of the beam expander was determined empirically since the effect of obscuration on the near-field beam profile was readily calculated (see Figure 2.4). Within the model this relationship is represented by a third order polynomial.

The computed values of the phase variance and scale size are used to evaluate the power distribution at two radial positions in the far-field, namely $r = w_f$ and $r_2 = 2w_f$. These power points are then used to generate the beam quality parameters m_1 and m_2. The procedure for doing this is outlined in Reference 1.

2.2.3 Beam Jitter

The beam jitter is accumulated throughout the optical train by assuming that the sources of beam jitter are independent of each other. Thus they may be root-sum-squared to get the total jitter. The primary consideration for the beam jitter calculation is whether or not the source of the jitter is upbeam or downbeam of the beam expander. The beam expander reduces the jitter by a factor of $1/M^2$ where M is the magnification.

The sources of beam jitter considered by the model are

- Tracking jitter, Θ_{TR}
- Boresight jitter, Θ_{BS}
- Autoalignment system jitter, Θ_{AA}
- Servo jitter, Θ_S
- Device jitter, Θ_L
- Exit aperture induced jitter, Θ_E.

The jitter of the input beam and the jitter induced by the beam steering mirror in the autoalignment system are assumed to occur before the beam expander. The remaining jitter sources are assumed to occur after the beam expander. Thus the total jitter leaving the optical train is given by:

$$\sigma_J = \{\Theta_{TR}^2 + \Theta_{BS}^2 + \Theta_S^2 + \Theta_E^2 + (\Theta_L^2 + \Theta_{AA}^2)/M^2\}^{1/2}.$$

2.2.4 Beam Divergence

The beam divergence represents the spherical phase curvature in the beam as it enters the transmitting optic and results in a larger spot size at the target than one would expect had the beam been collimated when it entered the transmitting optic. As an example, consider a collimated ideal gaussian beam which has been focused to produce a spot size of w_f (actually a radius to the e^{-2} intensity point) at a target. If the beam is instead diverging (or converging) with a radius of curvature $-R_B$ ($+R_B$) as it is reflected from the same transmitting optic, the new spot size w_f' is larger than the original by

$$\left(\frac{w_f'}{w_f}\right)^2 = 1 + \left(\frac{\pi D_B^2}{4\lambda R_B}\right)^2$$

where D_B is the (e^{-2}) diameter of the ideal gaussian beam and λ is the wavelength. For example, 0.1λ spherical phase error will increase the spot size approximately 20% for a 100 cm diameter optic transmitting at $\lambda = 3.8\ \mu$. For the present study we assume that any phase curvature in the output beam from the optical train behaves in a similar manner.

The change in the curvature of the phase front of the beam as it propagates through the optical train is computed by employing a simplified geometric optics calculation through the optical elements preceding the beam expander. The usual simplifying assumptions, i.e., paraxial rays, thick lenses, etc., are made in order to make the calculation tractable.

Following the ray matrix approach of Reference 10 we first obtain the equivalent ray matrix of the optical train illustrated in Figure 2.6 by multiplying together the individual ray matrices of the individual elements, i.e.,

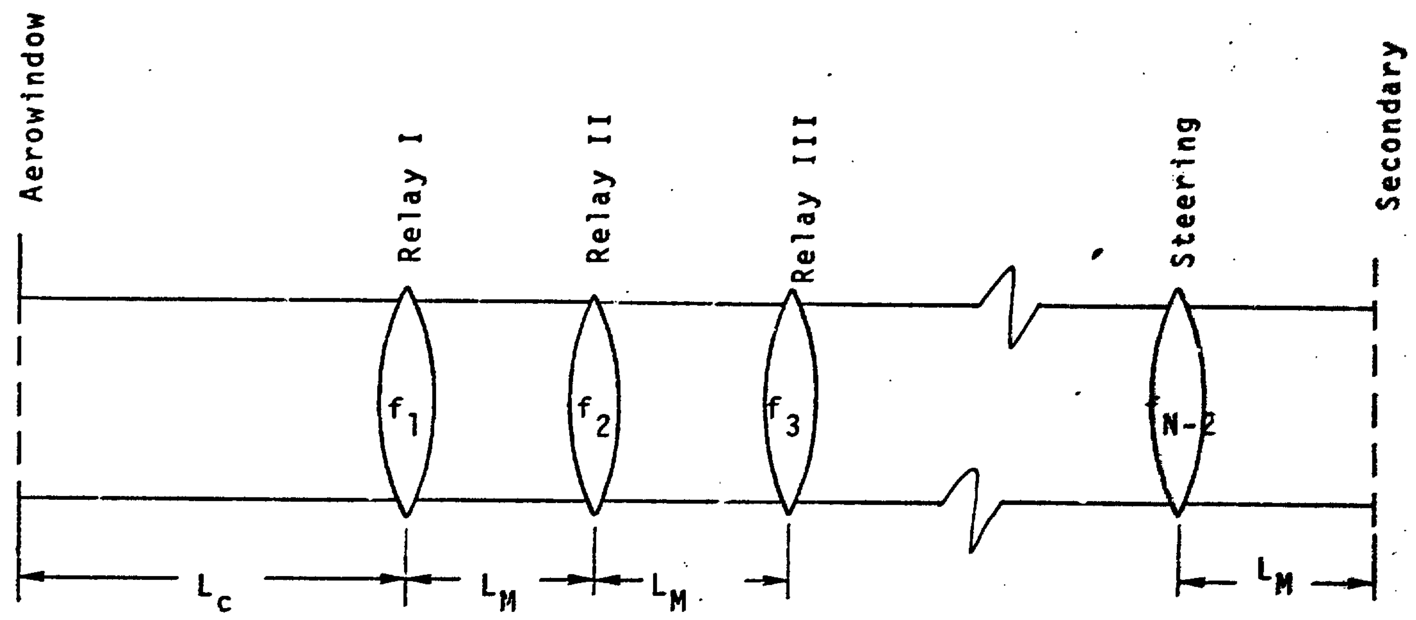


Figure 2.6. Simplified Optical Train Employed in Defocus Calculations

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & L_M \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f_{N-2} & 1 \end{bmatrix} \cdots \begin{bmatrix} 1 & 0 \\ -1/f_2 & 1 \end{bmatrix} \begin{bmatrix} 1 & LM \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & L_C \\ 0 & 1 \end{bmatrix}$$

where (going from right to left) the first matrix represents the propagation distance between the aerodynamic window and the beam clipper, the second matrix represents the reflection of the beam from the first relay mirror in the optical train, the third matrix represents the propagation distance between the first relay mirror and the second relay mirror, the fourth matrix represents the reflection of the beam from the second relay mirror, and so on until the beam is incident upon the secondary mirror. At this point we assume that the beam expander simply expands the beam by the specified magnification. The curvature of the phase front at this point, R_B, is related to the phase front curvature of the input beam, R_L, by

$$R_B = M\left(\frac{AR_L + B}{CR_L + D}\right).$$

The computed value of R_B is then used to compute the new spot size of the focused beam. In order to transfer this information to the propagation model, the beam quality parameter, m_2, which characterizes the spread of the beam profile in the absence of other effects, such as thermal blooming, turbulence and beam jitter, is internally adjusted by the model to reflect the increased beam spread, i.e.,

$$(m_2)_{final} = \sqrt{1 + \left(\frac{\pi D_B^2}{4\lambda R_B}\right)^2} \quad (m_2).$$

2.3 SAMPLE CALCULATIONS

As an illustration of how the optical train influences the performance of a laser system, we present below a sample calculation for the optical train schematically illustrated in Figure 2.7.

The laser device is assumed to be operating in an unstable confocal resonator mode with the power coupled out of the device via a scraper mirror located in front of the convex optic of the resonator. Accordingly, the output beam contains a central obscuration. The parameters assumed for this beam are:

Beam Diamter	=	0.1 meters
Power	=	400 kw
Wavelength	=	3.8 microns
Obscuration	=	0.5

In addition, it is assumed that the beam is essentially collimated ($R_L = \infty$) and contains peak-to-peak intensity fluctuations that are 50 percent of the average intensity ($\Delta I/I_{ave} = 0.5$). The scale size of these fluctuations is taken to be 1 cm or $\ell_I/D_B = 0.1$. We also assume that the quality of the beam leaving the device is characterized as being 1.2 times diffraction-limited ($n_L = 1.2$). This corresponds to an equivalent rms phase distortion in the beam of $\sigma_L = 0.16$ radians or about $\lambda/40$ (see Figure 2.2).

The output beam from the laser device is focused through an aerodynamic window to a collimating mirror. Since the beam size is very small (typically < 0.1 cm) at the aerodynamic window, we neglect any phase distortion induced by the aerodynamic window (i.e., $\sigma_{aw} = 0$).

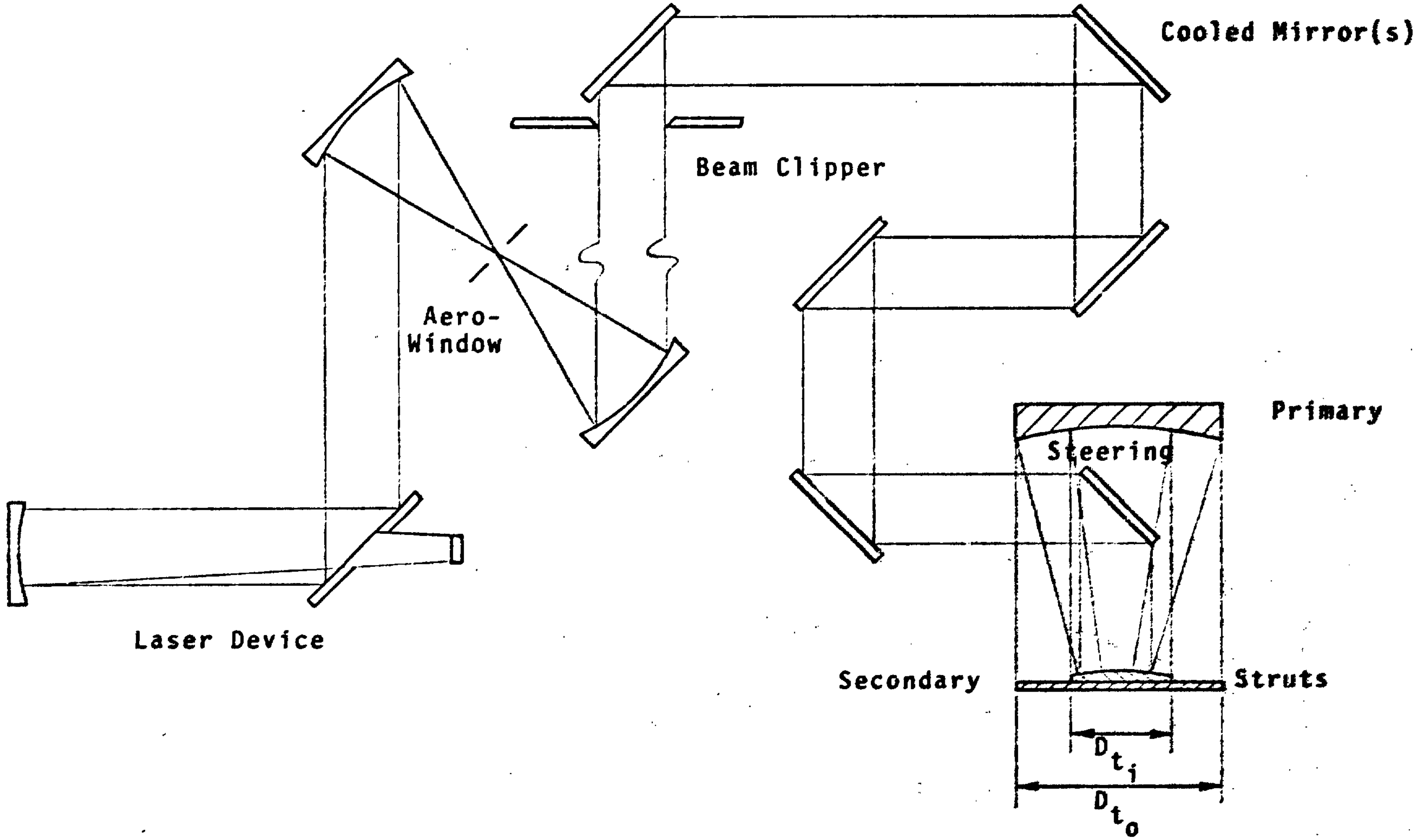


Figure 2.7. Schematic of Optical Train for Sample Calculations

For the example, we assume that the beam expender is located 50 meters from the aerodynamic window. Over this distance, diffraction effects cause the beam to expand somewhat. The Fresnel number for this propagation distance is

$$F_N = \frac{4D_B^2}{\lambda L_c} = 13.16$$

so that the beam diameters at the entrance to the beam expander are

$$D_{B_o} = \frac{D_B}{1 - 0.112/\sqrt{F_N}} = 0.103 \text{ m}$$

and

$$D_{B_i} = \left(\varepsilon - \frac{0.112}{\sqrt{F_N}}\right) D_B = 0.047 \text{ m.}$$

In this example, we have assumed that the diameter of the beam clipper is 16 cm so that no power loss due to clipping occurs, i.e., $T_c = 1.0$.

The nine (9) mirrors employed in the optical train are assumed to be water cooled with a reflectivity of $R_i = 0.986$. We also take the fabrication error as being $\lambda_v/8$ where λ_v is 0.564 microns. Accordingly, the power lost to the beam due to the finite absorptivity of the mirrors is

$$T_M = (0.986)^9 = 0.88.$$

The phase distortion induced by each mirror depends upon the rms intensity fluctuations, which for the case being considered are

$$I_{rms} = \frac{4P_L}{\pi D_B^2} \frac{\Delta I/I_{ave}}{12} = 7.35 \times 10^6 \text{ w/m}^2$$

so that

$$\sigma_I = 5 \times 10^{-14} (1 - R)(2\pi/\lambda) I_{rms} = 0.0085 \text{ radians.}$$

Combining this with the fabrication error yields (for all of the mirrors in the optical train)

$$\sigma_M = 9\sigma_f^2 + [8\sigma_I + \sigma_I/M^2]^2 = 0.3454 \text{ radians.}$$

The beam expander is an on-axis system of magnification, M = 4.375. The inner and outer diameters of the clear output aperture are $D_{t_o} = 0.7$ and $D_{t_i} = 0.252$ meters respectively. Since the beam entering the expander is not perfectly matched to the reduced clear aperture dimensions (i.e., $D_{t_o} = 0.16$ and $D_{t_i} = 0.576$), there is a power loss induced by the beam expander. From the geometry of the case being considered, this loss is computed to be approximately 13 percent or $T_{BE} \approx 0.87$. In addition, the beam expander has altered the obscuration of the input beam because of clipping. final obscuration of the beam leaving the beam expander is $\varepsilon = 0.0576/10.3 = 0.558$. Note that the final obscuration is not the observation of the telescope (D_{t_i}/D_{t_o} = 0.36) because the input beam was not large enough to fill the transmitting optic. The effective phase distortion of the actual beam is therefore much larger than one would compute based on the obscuration of the telescope. For the example being considered, this equivalent phase distortion is σ_{BE} = 0.72 radians.

The exit aperture was assumed to be an open port so that the only power loss is that due to blockage by the struts required to support the secondary mirror of the beam expander. Thus, T_E = 0.95. The quality loss due to the struts is

$$\sigma_S = (A_S/A_B)^{1/2} = 0.2236 \text{ radians.}$$

Within the model, the open port would also induce jitter into the beam. However, for the purposes of this example, we have ignored any performance loss caused by beam jitter.

Combining the above losses, we get for the overall transmission factor

$$T = T_C \cdot T_{BE} \cdot T_E = 0.727.$$

Thus, the power from the device that is available for propagation to the target is

$$P_t = 0.727\ P_L = 290 \text{ kw.}$$

The total distortion is

$$\sigma = \left(\sigma_m^2 + \sigma_{BE}^2 + \sigma_S^2 + 0.433\right)^{1/2} = 1.06 \text{ rads.}$$

This phase distortion is characterized by a scale size

$$\frac{\ell}{DB} = \frac{1}{\sigma^2} \left\{ \frac{\ell_{BE}}{D_B} \sigma_{BE}^2 + \frac{\ell_I}{D_B} \left[(N - 1)\sigma_I + \frac{\sigma}{M^2} \right]^2 + 0.196 \right\} = 0.114$$

in terms of the two parameter descriptions of the beam quality employed by the model $m_1 = 0.3536$ and $m_2 = 1.1076$. For this example, there were no defocusing errors induced by any of the components in the optical train so that no adjustment was made to the beam spread parameter m_2. Note that the constraints in the last two equations (0.433 and 0.196) are needed to ensure the proper conversion of σ and $\frac{\ell}{D_B}$ to m_1 and m_2.

In order to quantify the impact of the optical train, we evaluate the power delivered to a particular spot in the focal plane, namely $r^* = f\lambda/D_{t_o}$. In the absence of atmospheric effects and beam jitter, this power is simply

$$P(r^*) = P_t m_1 \left\{ 1 - \exp\left[- \frac{\pi^2}{m_2^2} \left(\frac{D_B}{D_{t_o}} \right)^2 \right] \right\}$$

where D_B is the actual diameter of the beam on the transmitting optic, i.e., $D_B = M\, D_{B_0} \leq D_{t_o}$.

The results of this calculation for the example being considered is shown in Figure 2.8 along with some additional calculations made for various input beam diameters. For the conditions described above, only 83 kw of the initial 400 kw are delivered to the target. Note, however, that by expanding the input beam a significant increase in power can be achieved. The initial beam size of 10 cm was too small to effectively use the entire diameter of the transmitting optic. Hence, the beam profile at the target was

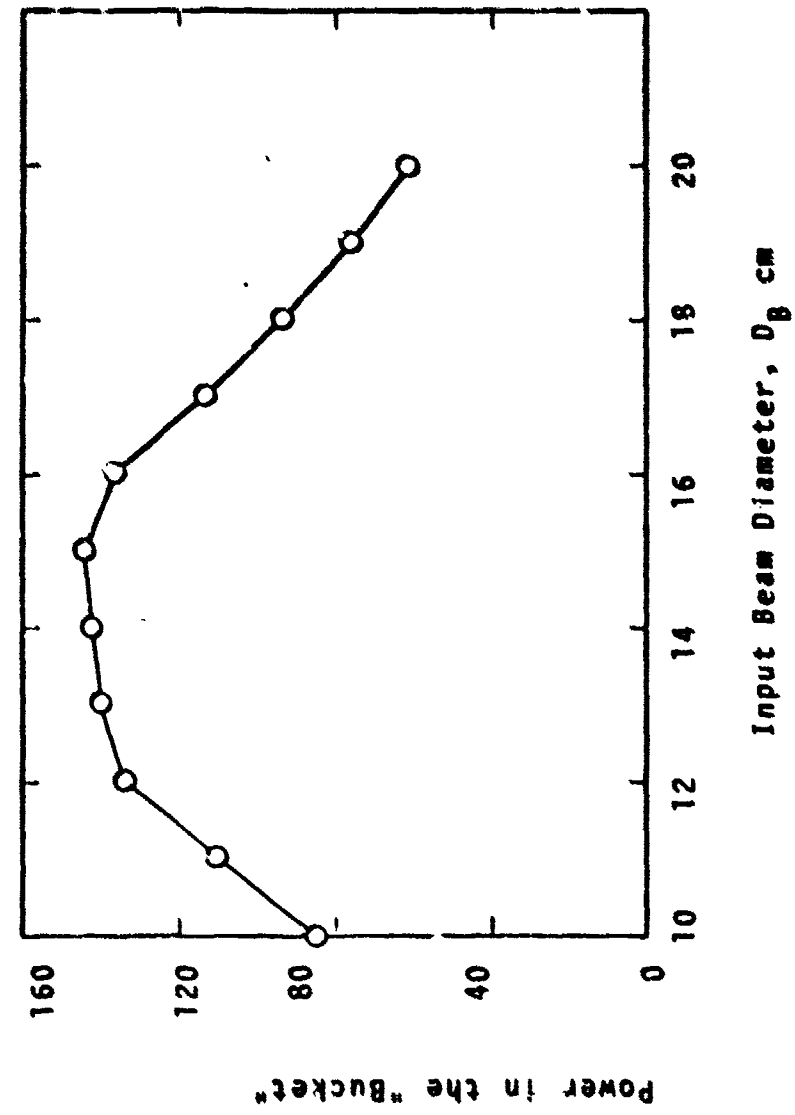


Figure 2.8. Results of Sample Calculations

larger than it should have been. In addition, because of the mismatch of device output beam and beam expander clear aperture, a significant power loss occurred. As the beam diameter is allowed to increase, both of these effects are reduced. Of course, at the point where the beam begins to spill-over onto the beam clipper, the near-field power is again reduced resulting in the performance fall-off shown in the figure.

It is recognized that a true performance evaluation cannot be made without including the propagation effects between the transmitter and target plane. However, the example does point out the necessity of including the effects of the optical train in any application study, since it indeed has a substantial impact on the near-field characteristics of the beam. In addition, the model also should provide some insight into the problems of integrating lasers and pointer/tracker systems. It is interesting to note that a detailed study of a similar system using a wave optics code resulted in an additional beam expander (M = 1.3) being placed in the optical train.

The simplified optical train model has been developed using state-of-the-art knowledge of the contribution of each element (windows, mirrors, etc.). It should be noted, however, that the model has not been verified using the more detailed wave optics codes. Such comparisons would be useful to not only verify, but also to improve, these simplified models.

Section 3

CREATION OF SAICOM

One of the High Energy Laser (HEL) propagation codes commonly used by the laser systems analysts is the COMBO (or ATM) code developed by the Air Force Weapons Laboratory (Reference 11). ATM is the propagation model documented in Reference 11. COMBO is a code which combines ATM with the Air Force HEL weight and volume projections (Reference 12). COMBO also includes some additional features such as the ability to perform reverse calculations in which the user specifies a desired intensity and the code determines the range at which the intensity can be delivered (given the power) or the power required (given the range). The primary asset of COMBO (or ATM) is its ability to make variable altitude calculations, including propagation paths extending to or from space.

One of the tasks performed under the present contract was devoted to modifying COMBO. The objectives were to reduce execution time, improve computational accuracy and to incorporate several of the newer developments resulting from the other tasks of this contract. A number of other minor additions, corrections and deletions were also made.

All of the primary modifications are discussed in Section 3.1. Collectively, they are sufficient to warrant a new code name -- SAICOM. A brief user's guide to SAICOM is provided by Section 3.2.

3.1 MODIFICATIONS OF COMBO

The primary modifications are dealt with in individual subsections below. The basic structure and organization of the code remain essentially the same as in the original version (Reference 11). A summary of the more important equations is given in Section 3.1.9.

3.1.1 Improvements to Computational Speed and Accuracy

A substantial part of the COMBO modification effort was devoted to improving the speed of the calculations. Several modifications simply involved improvements in coding techniques. These included: (1) reducing the number of calls to MEGAIR (the subroutine which provides altitude dependent parameters such as temperature, pressure, etc.); (2) lumping several blooming parameters (viz., n, $\partial n/\partial T$, and C_p) into a single curvefit (GALTIN); (3) using a better search algorithm in the reverse calculations; and (4) reducing the subroutine calls.

Most of the improvement in both speed and accuracy was obtained by developing a completely new algorithm for performing the double integration required to compute the blooming parameter, NI. The expression for NI is of the form

$$NI = C \int_0^L \frac{1}{r(z')} \int_0^{z'} G(z'')dz''dz'$$

where C is fixed for a given set of conditions (Reference 13). The integration paths are along the beam. In the original code, the double integral was evaluated by assuming the integrals to be constant between uniformly spaced points along the beam. The evaluation was successively repeated with reduced spacing until the results for consecutive evaluations agreed with 10 percent. This procedure was found to be inefficient and often inaccurate. This should be readily apparent from Figure 3.1, which shows the important elements of the integral for a particular case of a highly focused beam. Note that the value of NI is dominated by the conditions within the last few percent of the range.

The new algorithm examines the local behavior of the integrand and chooses an efficient scheme and mesh spacing dynamically. It selects either a locally quadratic or locally exponential representation of the integrand. If neither is satisfactory, it reduces the mesh spacing and tries again. On the other hand, if the local convergence exceeds the accuracy requirements, it increases the mesh size to increase speed. Both integrations as well as a third implicit in G are performed in a single loop.

When the new algorithm was used for the severe example illustrated in Figure 3.1, the calculation required 1.49 seconds; the original COMBO exceeded a time limit of 200 seconds without completing the calculation!

As mentioned earlier, an additional improvement in computation time was obtained by modifying the convergence algorithm used in the reverse propagation calculation where the range is successively adjusted to obtain a desired target plane intensity. The range R' for one iteration is determined by modifying the previous range, R, viz.,

$$R' = KR\sqrt{I/OI}$$

where OI and I are the desired and computed intensities, respectively. In the original COMBO, the constant K was always 1.0, whereas in SAICOM, it varies between 0.7 and 1.0 to accelerate convergence. In addition, the convergence criterion was relaxed from 1% to 5%.

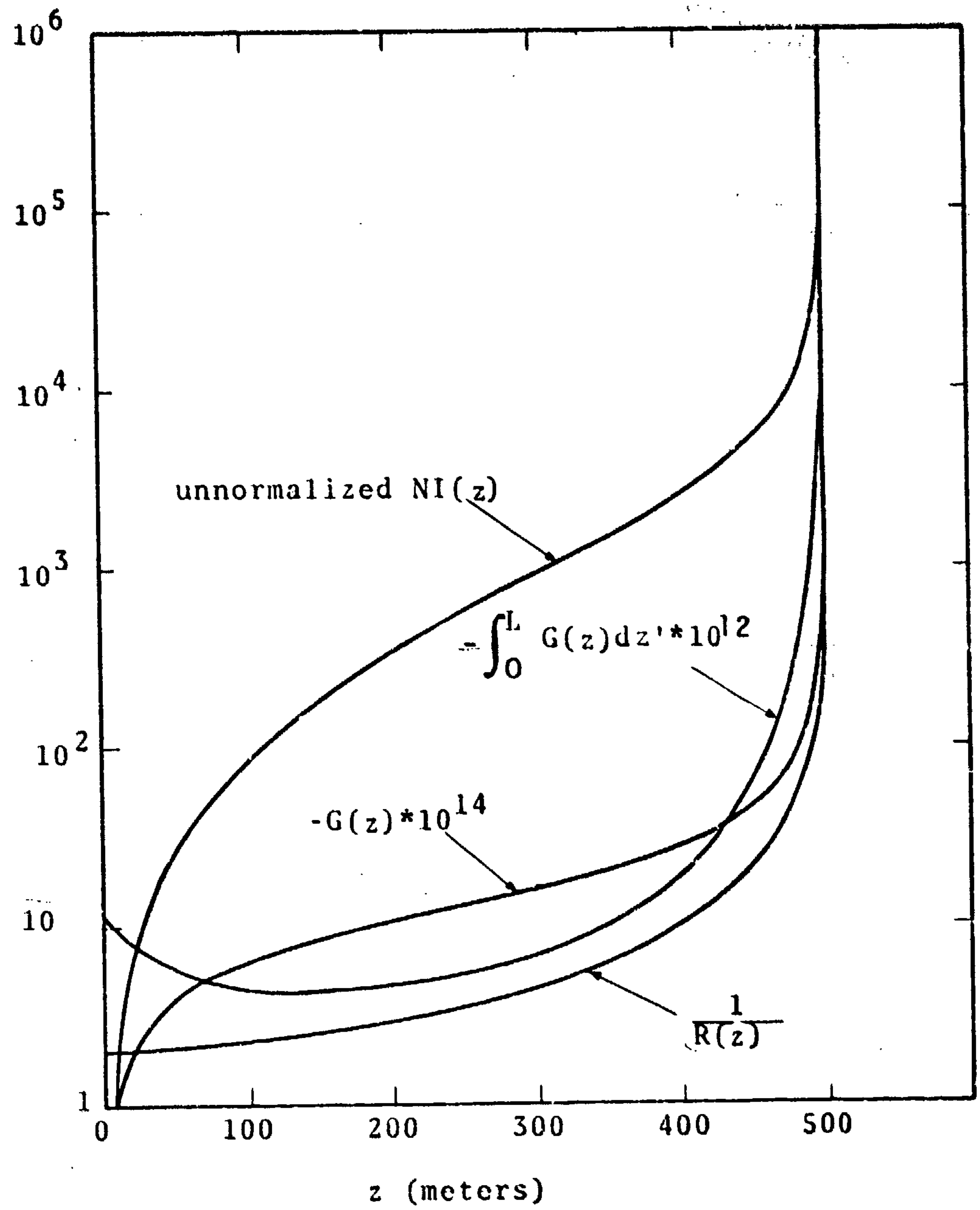


Figure 3.1 Variations in Elements of the Blooming Calculation

3.1.2 Beam Quality

The SAICOM code includes a significant innovation in the treatment of beam quality. It essentially replaces the usual one parameter concept of an "m x diffraction limited" beam by a two parameter representation. The two parameters, designated m_1 and m_2, are used to specify a gaussian representation of the focal plane intensity profile so as to approximate the actual integrated power distribution. The two parameter model is inherently capable of including effects leading both to beam spreading (m_2) and to power loss due to wide angle scattering (m_1).

The origin and interpretation of m_1 and m_2 are discussed in some detail in Reference 1 and in Section 4.3 of this report. Their use in characterizing the effects of beam truncation and obscuration is discussed in Reference 2. In general, they are calculated in the new optical train model which is an integral part of SAICOM (see Section 2).

SAICOM incorporates the two parameter approach even though the user is only required to stipulate a single parameter, m. If the device power (P_D) and beam quality (m) are stipulated, the optical train portion of the code converts them to the appropriate aperture or transmitted power (P_T) and beam quality (m_1, and m_2). If the optical train calculations are bypassed because the user specifies P_T, the specified beam quality is assumed to be pure beamspread.

The SAICOM intensity expression for a focused beam is of the form

$$I = \frac{[1 - (1 - 0.865\ m_1\ z/L)]\ P_T e^{-\alpha z}}{\pi r^2(z)}$$

where

$$r^2(z) = \frac{D}{4L^2} |L - z|^2 + 4z^2 \left[\left(\frac{0.3183 \; m_2 \lambda}{D} \right)^2 + \sigma_T{}^2 + \sigma_J{}^2 \right].$$

The term in the numerator that decreases as z increases represents the power losses that may be thought of as wide angle scattering. The 0.865 factor is present because the basic propagation equation used in the code is based on the $1/e^2$ radiance of an infinite Gaussian beam. Since m_1 and m_2 are used to account for the effect of different beam profiles as well as phase perturbation, these terms may be not the unity even for perfect beams. This situation is clarified in Table 3.1. In this table the M1 and M2 terms are the parameters computed in the optical train subroutine while m is the user specified beam quality for the total system. Note that if the optical train is bypassed (the user specifies P_T) and m=1, m_1 and m_2 are 0.89 and 1.29 respectively for a uniform beam and not unity because the basic propagation equation is based on an infinite gaussian model. But if the optical train is not bypassed, m_1= M1=0.89 and m_2=M2=1.29 because the basic profile used in the optical train subroutine is uniform.

3.1.3 The Optical Train Model

The development of an improved optical train model was the prime objective of Task 5 and is discussed in detail in Section 2 of this report. The model has been incorporated into SAICOM as subroutine OPTRAIN. It computes power losses, jitter, and beam quality degradation associated with transmission of the beam from the laser through

Table 3.1 Beam Quality Parameters

Aperture	Intensity Profile	Infinite Gaussian	$1/e^2$ Gaussian	Uniform
OPTRAIN	m_1	1	1	0.89
BYPASSED	m_2	1	1.41 m	1.29 m
OPTRAIN	m_1	0.89 M1	0.89 M1	M1
USED	m_2	0.775M2	1.092M2	M2

the final t[illegible]smitting optic. It accepts a quite general specificati[illegible] of the optical train through a list of input parameters. [illegible]PTRAIN accounts for beam truncation and obscuration and for various contributions to phase perturbations. The output includes the two beam quality parameters m_1 and m_2 described above.

[illegible]AIN can be bypassed simply by specifying the transmit[illegible]ed power, P_T, rather than the device power in the i[illegible]put. In this case, beam quality is based on wavelength scaling as usual.

3.1.4 Multi-Line Propagation

Since many of the lasers of interest for high energy applications emit several lines simultaneously, it is desirable to include these multi-line characteristics in the simplified propagation codes.

The approach used in SAICOM is to compute the amount of energy absorbed by the air on a line-by-line basis. This means that $\exp\{-\int_0^R d(z''')dz'''\}$

$$\sum_i \frac{P_i}{P_T} \exp\left\{-\int_0^R \alpha_i(z''')dz'''\right\}$$

and $\alpha(Z'')\exp\left\{-\int_0^{Z''} \alpha(Z'')dZ''\right\}$ in the integrand of the expression for the blooming parameter becomes

$$\sum_i \frac{P_i}{P_T} \alpha_{ai}(Z'')\exp\left\{-\int_0^{Z''} \alpha_{ei}(Z''')dZ'''\right\}$$

where

α_{ai} = absorption coefficient of the i^{th} line

α_{ei} = extinction coefficient of the i^{th} line.

In SAICOM, the 3.8 μm DF propagation has been extended to include three distinct families of lines. These encompass ten lines of the DF laser, and represent 80% of the output of the BDL device. With the basic modification having now been made, it is straightforward to include multi-line HF or CO propagation.

The derivation of the DF absorption coefficients is given in Appendix A and is based on the BDL spectral data. The resulting SAICOM equations are

$$\alpha_i = A_o e^{-A_1+h(-A_2+A_3h)}$$

where $A_o = 1 + (0.9446\ RH-1)e^{-h(6.738\times10^{-5}+9.61\times10^{-9}h)}$,

for groups 1 and 2

= 1, for group 3

A_1 = 10.047, 10.082, and 9.948 for group 1, 2 and 3, respectively

A_2 = 6.388×10^{-4}, 6.952×10^{-4}, and 2.199×10^{-4}

A_3 = 2.25×10^{-8}, 1.55×10^{-8}, and -1.96×10^{-8}

h = altitude in meters.

These equations imply that at sea level α varies between 0 and 0.0409 km^{-1} as relative humidity varies between 0 and 100%, α_2 between 0 and 0.0395 km^{-1}, and α_3 is a constant 0.0478 km^{-1}.

The above equations are only valid to around h=13 km; for the higher altitude the original COMBO coefficients are used. Unfortunately, a discontinuity existed at the 13 km altitude; so transition equations were created to connect the multi-line data below 13 km with the single-line data above that point. Figures 3.2, 3.3, 3.4, and 3.5 plot the α_1, α_2, α_3, and $\alpha_{resultant}$ equations where

$$\alpha_{resultant} = \frac{\alpha_1 + \alpha_2 + \alpha_3}{3}$$

The scattering equations are the same as those used in the original COMBO (Reference 11).

3.1.5 Modification of Turbulence and Jitter to Include Short and Long Term Effects

During the code comparison work in Task 1 of this contract, it was noted that one of the useful features of ESP was the flexibility of including beam jitter in the blooming calculation if the frequency were high enough and excluding it otherwise (References 1 and 14). This feature has been included in SAICOM. The output jitter factors in SAICOM are high-frequency jitter (σ_{JHF}) and low-frequency jitter (σ_{JLF}). The former is used in the calculation of the blooming parameter and both are combined to give the total beamspread due to jitter. Similarly, the turbulence calculations are expanded to include the total, long-term turbulence (σ_{TLT}) and the high-frequency, short-term turbulence (σ_{TST}). The turbulence equations in SAICOM are based on work of Yura (References 15 and 16) whereas the COMBO code was based on Fried's work (Reference 17), but the results differ only slightly in the regions of interest. The equations used are

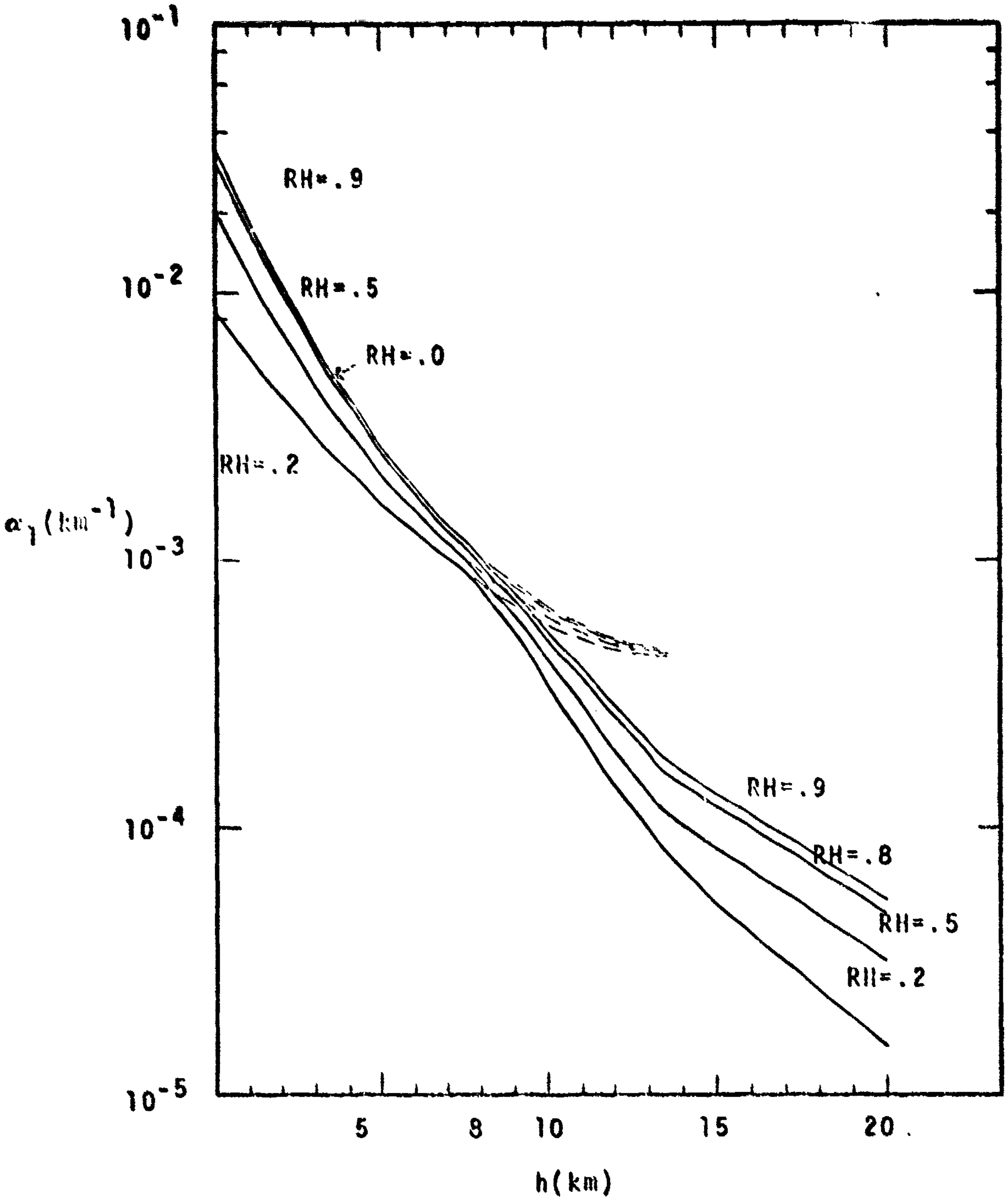


Figure 3.2. α_1 as a Function of Altitude

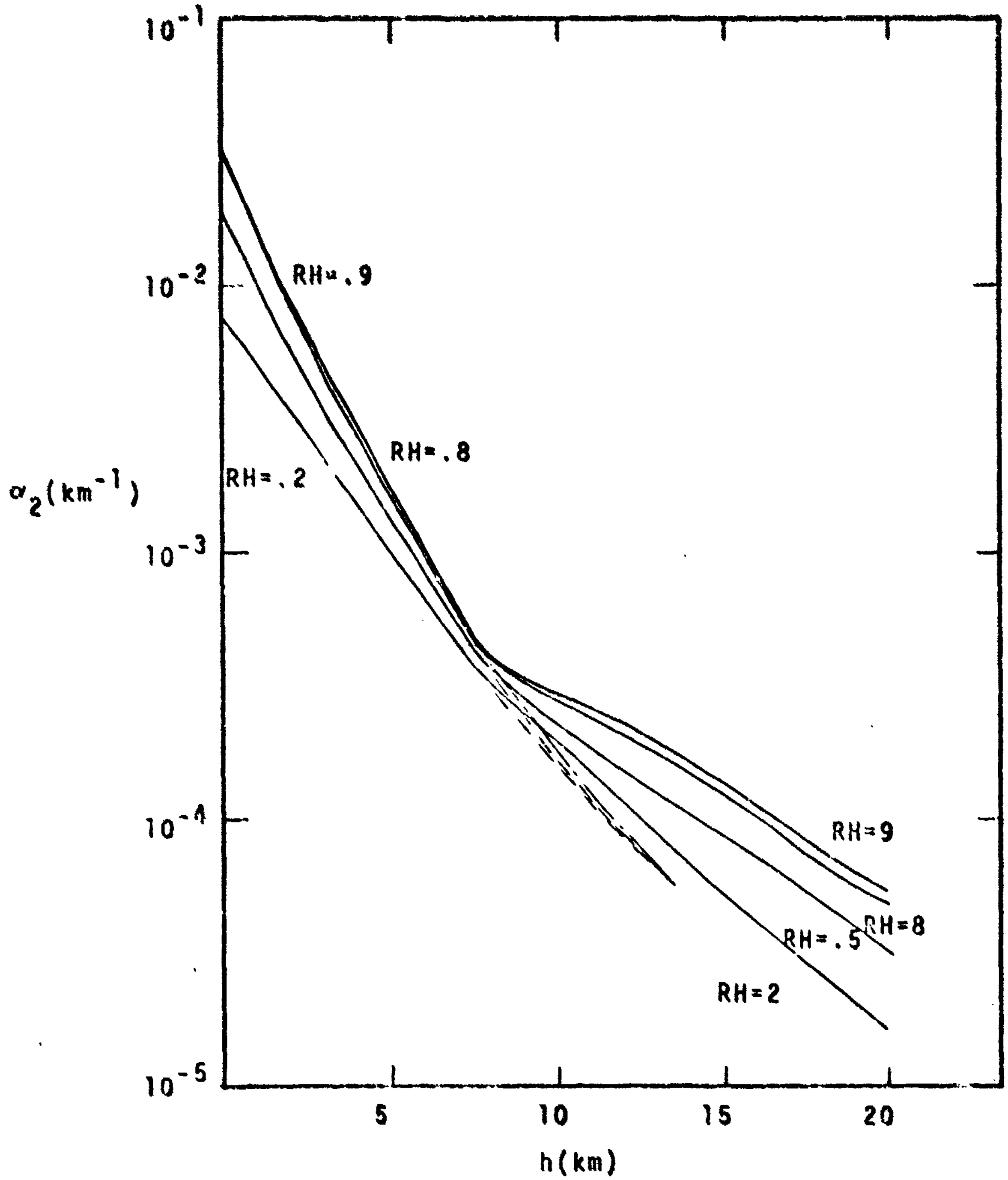


Figure 3.3. α_2 as a Function of Altitude

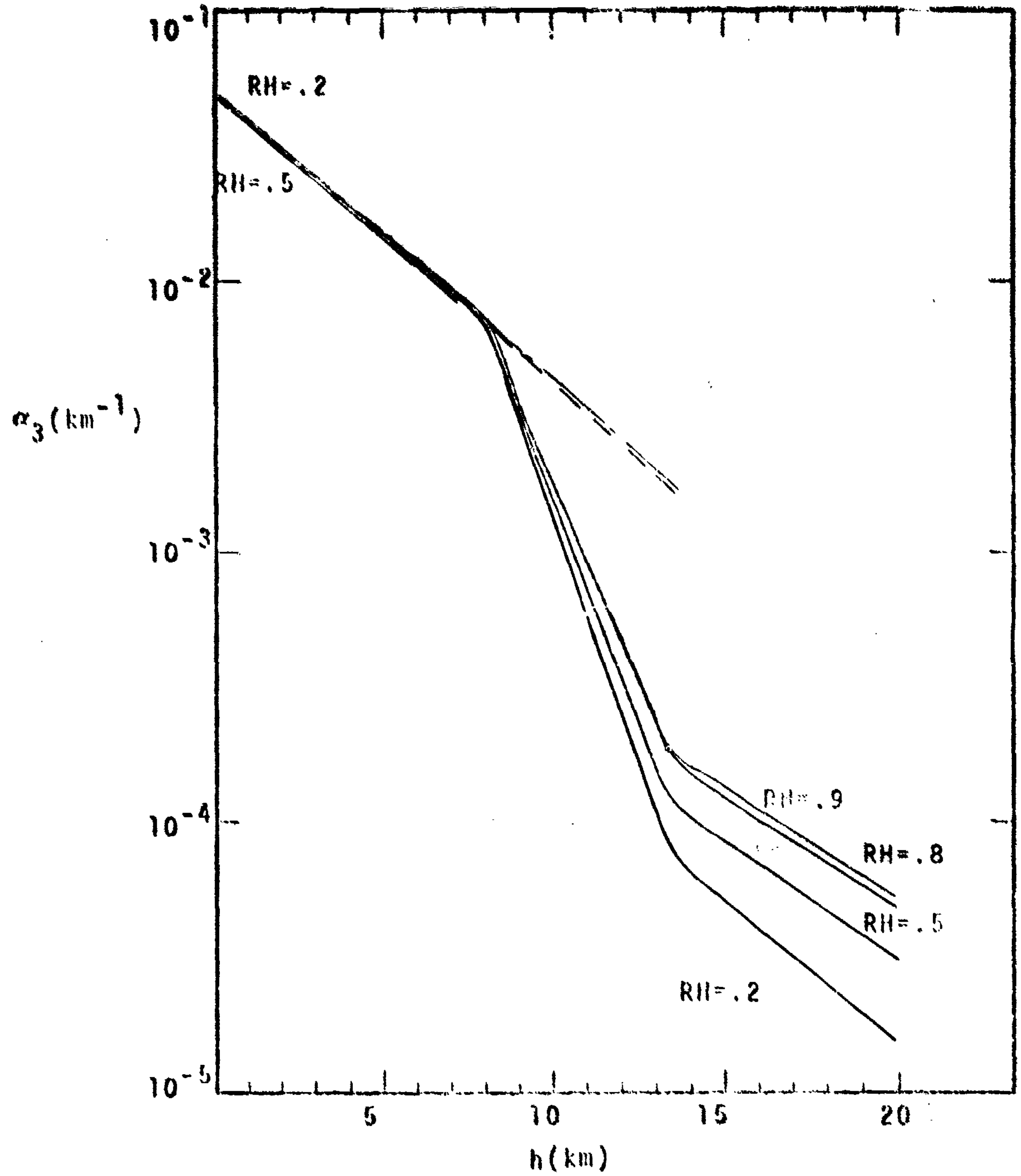


Figure 3.4. α_3 as a Function of Altitude

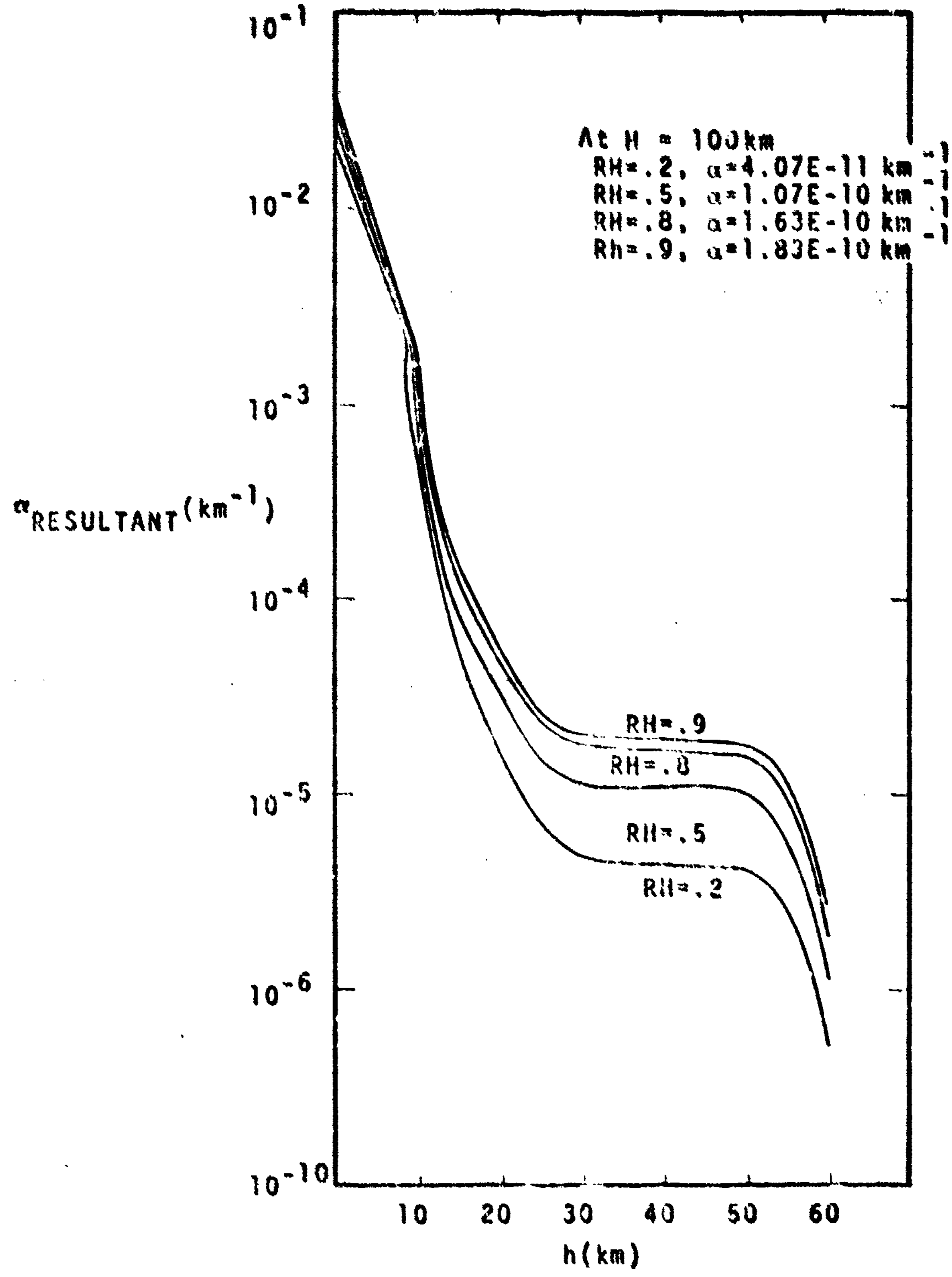


Figure 3.5. $\alpha_{RESULTANT}$ as a Function of Altitude

$$\sigma_{TLT} = \frac{2.549}{\lambda^{1/5}} \left[\int_0^L C_N^2 \quad (Z) \left(\frac{L-Z}{L}\right)^{5/3} dZ \right]^{3/5}$$

and $$\sigma_{TST} = \left[1-0.37 \left(\frac{\rho_o}{D}\right)^{1/3}\right] \sigma_{TLT}$$

where $$\rho_o = \frac{1.439}{k^{1.2}} \left[\int_0^L C_N^2 \quad (Z) dZ \right]^{3/5}$$

$k = 2\pi/\lambda$

D = diameter of the exit aperture.

These equations are generalizations of the co-altitude expression developed in Reference 16. In the blooming calculation σ_{TST} is used instead of the long-term expression, but it should be noted that some research indicates that no turbulence should be included in the beamspread before the blooming calculation (Reference 18).

3.1.6 Far-Field Intensity Distribution

In COMBO the standard calculation of the average intensity is based on the $1/e^2$ intensity radius in the far-field with a few other radii available for user specification (e.g., $1/e$ and $1/2$ intensity points). Since SAICOM is based on a gaussian approximation to the actual far-field distribution, it is a simple matter to use the $1/e^2$ results to describe the complete far-field profile. In addition to $I(1/e^2)$, the peak intensity $I_p = 2.312 \times I(1/e^2)$, is printed along with contour data. These contour data assume a bivariant normal profile of the beam due to blooming distortion as developed in Reference 2. For each 10% contour ($I=\gamma I_p$, $\gamma=0.9, 0.8, \ldots, 0.1$) the area within that contour,

$$A(I>\gamma I_p) = \frac{a r^2 \ln(1/\gamma)}{2\ KIP}$$

the total power within that area,

$$P(I>I_p) = P(1-\gamma)$$

and the corresponding average intensity are printed. In addition, the beam displacement due to non-linear bending into the wind and the eccentricity of the resulting eliptical profile are computed and printed.

3.1.7 Calculation of Optimum Power

One of the more useful bits of information that comes from laser effectiveness studies is specification of optimum power based on maximizing energy on the target (Reference 19). Using the Gebhardt and Smith curve-fit for the intensity reduction due to blooming (Reference 20), the far-field intensity is related to transmitted power, P_T, by

$$I = aP_T\ I_{REL}(N)$$

where $N=bP_T$ and a and b are constants (independent of power). Setting $\partial I/\partial P_T=0$ leads to

$$\partial \ln(I_{REL}) = -\partial \ln N$$

as the optimum condition. For the Gebhardt and Smith curve, this condition is satisfied when N=5.54. Therefore, the optimum power is given by

$$P_{optimum} = \frac{5.54 P_T}{N}$$

where N is the value of the blooming parameter corresponding to the power P_T. The corresponding maximum intensity is

$$I_{optimum} = \frac{1.205\, I}{N\ KIP}$$

(KIP is the computer variable representing I_{REL}). It should be noted that the optimization does not include the possible effects associated with the optical train, i.e., it does not involve an iterative recall of OPTRAIN.

SAICOM prints the optimum power as derived above unless the corresponding intensity exceeds the air breakdown threshold. In that case, it prints the power at which breakdown would occur as the optimum power. The breakdown power level is estimated on the basis of peak intensity without blooming.

3.1.8 Miscellaneous Modifications

Several relatively minor additions, deletions and corrections are described below.

3.1.8.1 Variable Turbulence in Blooming Computations

In COMBO the turbulence is not varied as the blooming along the beampath is computed; instead only the final value is used. In SAICOM the distributive nature of turbulence is included in the integral calculation of the blooming parameter.

3.1.8.2 Extinction Calculations in Blooming Integral

In COMBO the linear power losses due to absorption and scattering are computed using $\exp[-\alpha_e(h)z]$ in the integrand whereas the expression should have been

$$\exp[-\int_0^z \alpha_e(h)dz].$$

This error causes an over-estimate of the extinction losses when firing downward and an under-estimate when firing upward. The appropriate correction has been made in SAICOM.

3.1.1.3 Power Variation

The reverse calculation option in COMBO involving calculation of the required power to deliver a desired intensity at a given range has been replaced in SAICOM. Now, whenever the intensity is calculated in a normal propagation run, the power is automatically varied between one-tenth the specified value and twice the original power. The output then lists the average intensity within the $1/e^2$ intensity area, the area over which the intensity is above a specified minimum value, and the total power available within that area. The equations used in these computations were discussed in Section 3.1.6. The user is allowed to stipulate the minimum intensity of interest through the input parameter OI. If the user does not specify the desired minimum intensity contour, the program automatically selects 10 kw/cm^2.

3.1.8.4 Deletion of Weight and Volume Calculations

The technology projection portion of COMBO is an interesting but seldom used facet of the code. Therefore, it has been eliminated.

3.1.9 Summary of Equations

The basic equations used in SAICOM are as follows:
Average intensity in the $1/e^2$ intensity radius

$$I(Z) = \frac{\left[1-(1-0.865\ m_1\frac{Z}{L})\right]\ P_T\ k_B e^{-\sum_i \int_0^Z \alpha_{ci}(Z')dZ'}}{\pi r^2(Z)}$$

where k_B = intensity reduction due to blooming (som. times written as KIP)
= $f(N)$

$$r^2(Z) = k_2 r_o^2 + k_3 \frac{r_o^2}{L^2} |L-Z|^2 + 4Z^2 \left[\left(\frac{0.3183 m_2 \lambda}{D}\right)^2 + \sigma_{TLT}^2 + \sigma_J^2\right]$$

$$\sigma_J^2 = \sigma_{JHF}^2 + \sigma_{JLF}^2$$

$$\sigma_{TLT} = \frac{2.549}{\lambda^{1/5}} \left[\int_0^L C_N^2\ (Z) \left(\frac{L-Z}{L}\right)^{5/3} dZ\right]^{3/5}$$

The blooming parameter, N, is computed by

$$N = \frac{6.54}{\pi} \int_0^L \frac{1}{r(Z')} \int_0^{Z'} \frac{\left[1-(1.865 m_1\frac{Z}{L}\right]\ F(Z")G(Z")dZ"dZ}{v(Z")r^2(Z")}$$

where

$$F(Z'') = P_T \sum_i \frac{P_i}{P_T} \alpha_{Ai}(Z'') e^{-\int_0^{Z''} \alpha_{ei}(Z'') dZ''}$$

$$r^2(Z'') = k_2 r_o^2 + k_3 \frac{r_o^2}{L^2} |L-Z|^2 + 4Z^2 \left[\left(\frac{0.318 m_2 \lambda}{D} \right)^2 + \sigma_{TST}^2 + \sigma_{JHF}^2 \right]$$

$$\sigma_{TST} = \left[1 - 0.37 \left(\frac{\ell_o}{D} \right)^{1/3} \right] \sigma_{TLT}$$

$$\ell_o = \frac{1.439}{k^{1.2}} \left[\int_0^L C_N^2 (Z) dz \right]^{3/5}$$

$$k = 2\pi/\lambda$$

$$G(Z'') = \frac{\frac{\partial n}{\partial T}(Z'')}{n(Z'')\rho(Z'')C_p(Z'')}$$

3.2 A USER'S GUIDE TO SAICOM

A brief description of the key features of the SAICOM code is given along with a discussion of how to operate the code. Users familiar with COMBO (Reference 11) should have little trouble with SAICOM since many of the subroutines are unchanged and the same modular format has been retained. The basic structure of the executive routine (SAICOM) is shown in Figure 3.6. A substantial portion of this routine is devoted to initializing the input variables. As with COMBO, most of the input parameters are defined through a default namelist which requires the user to specify only those parameters which will differ from the default values. However, it should be noted that even if the propagation and optical train namelists are not used, namelist cards are required which read $INPUT $ and $CASES $, respectively. The optical train is called if the user specified PD; if PT is given, this subroutine is bypassed. A subtle point worthy of note is that when PD is given, SIGHF is assumed to refer to the device jitter only, and this term is combined with the four 1σ jitters (THIR, THES, THAA, and THSV) given in namelist CASE to determine the high-frequency jitter of the total system.

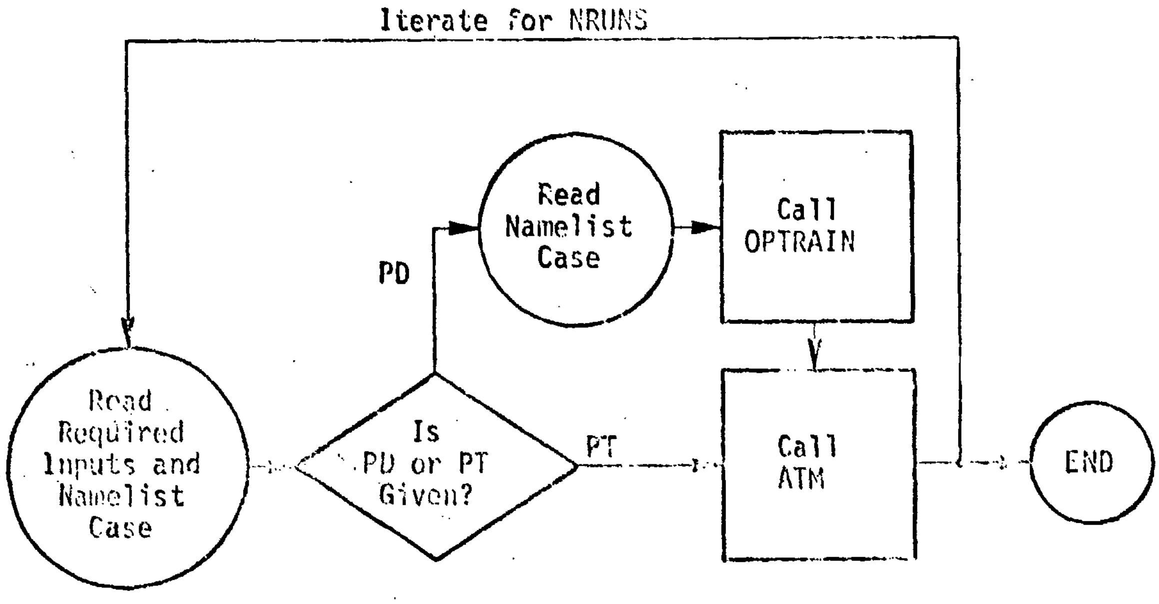


Figure 3.6 SAICOM Flow Diagram

Following these initialization activities, control is transferred to ATM, which handles the propagation calculations; control returns to SAICOM only after the calculations are completed and the results printed. Then SAICOM cycles through the same process until all of the specified cases have been completed.

In Table 3.2 a complete list of the SAICOM subroutines is given along with brief descriptions of their functions. Three of the subroutines, OPTRAIN, ATM, and BB, are discussed in further detail since they are the more important and complex portions of the program.

3.2.1 OPTRAIN

The calculation procedure within the Optical Train Model (OPTRAIN) is schematically shown in Figure 3.7. All inputs to the subroutine are passed through a labeled COMMON/OPTIN/statement and must be defined by the user prior to calling the subroutine. Following some initial calculations characterizing the input beam, the effect that each component within the optical train has on the transmitted power and beam quality is evaluated in a step by step manner. Although the specific elements within the optical train are fixed, i.e., aerodynamic window, beam clipper, mirrors, beam expander, and exit aperture, the user is allowed to specify, through the input parameters, different types of individual components such as cooled or uncooled mirrors, on-axis or off-axis beam expanders, and open port or material window exit apertures.

The output from the model is returned to the calling program via the labeled COMMON/OPTOUT/ and consists of (1) the diameter of the laser beam at the exit aperture, (2) the power in the beam, (3) the total beam jitter and (4)

Table 3.2 SAICOM Subroutines

NAME	DESCRIPTION
OPTRAIN	Calculation of Power Loss and Beam Degradations in the Optical Train.
ATM	Initialization of Propagation Parameters and Iteration of Reverse Calculations.
AA	Calculations for Laser and Target Above 100 km.
AB	Calculation for Laser Above 100 km and Target Below 100 km.
BA	Calculation for Laser Below 100 km and Target Above 100 km.
BB	Calculations for Laser and Target Below 100 km.
ALFSET	Sets Power Ratios for Multi-Line. Propagation.
ALFFAC	Calculations of $\alpha_A e^{-\alpha_e Z}$ and $e^{-\alpha_e Z}$.
ALFAAB	Single Line Absorption Coefficients.
ALFAEX	Single Line Scattering Calculation.
CNSQ	Atmospheric Structure Constant.
KI	Computer Reduction in Intensity Due to Blooming.
GALTIN	Altitude Dependent Parameters Used in Blooming Integral.
MEGAIR	Pressure, Density and Temperature as a Function of Altitude.
VX	Calculation of Total Crosswind.

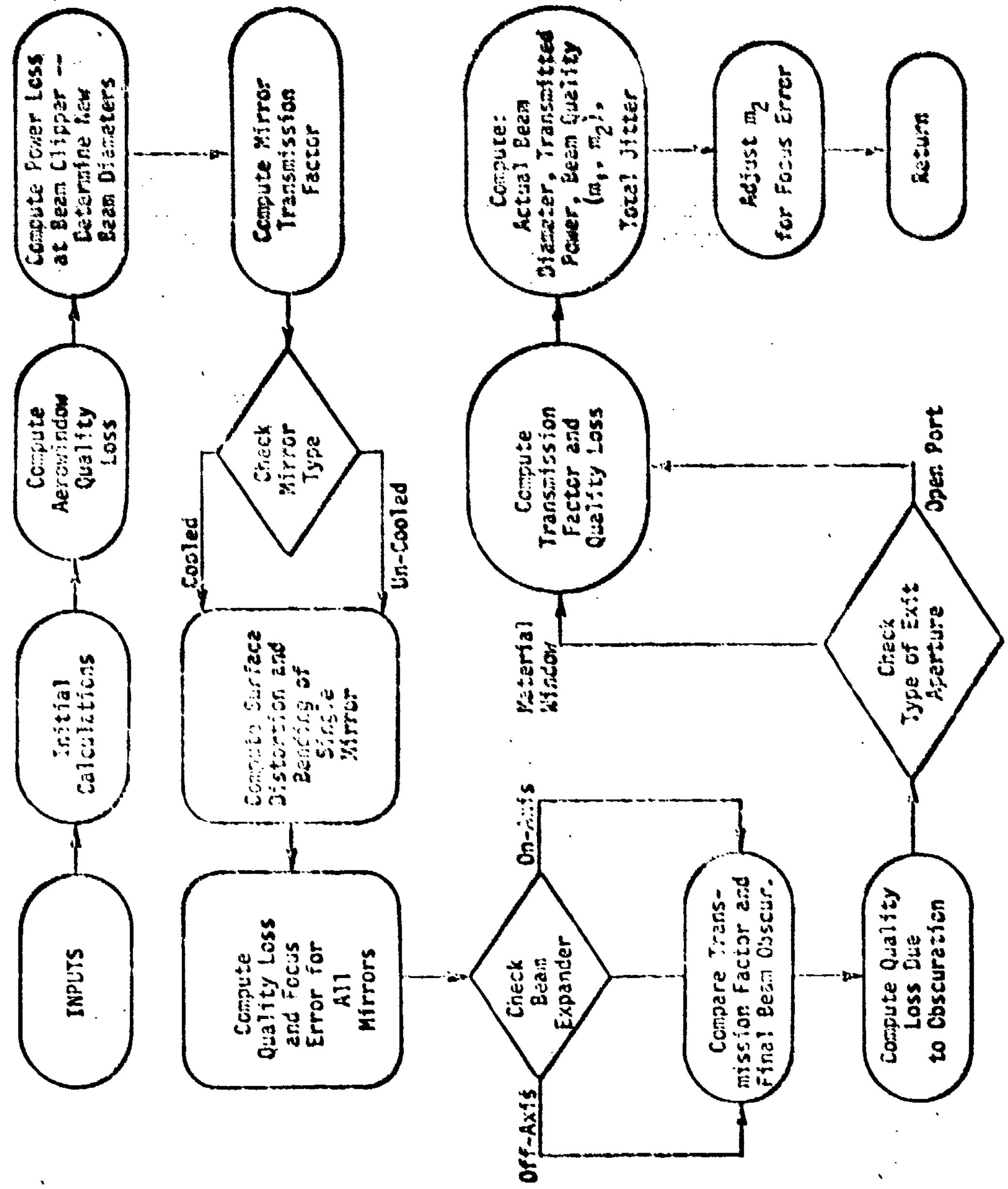


Figure 3.7 OPTRAIN Flow Diagram

two parameters (m_1 and m_2) characterizing the optical quality of the beam. The beam quality parameter m_2 is internally adjusted to account for any defocusing error induced by the high power mirrors in the optical train.

3.2.2 ATM

Part of the initialization process in ATM is to determine if the user has specified a negative wavelength (e.g., -1.06E-5 or -3.8E-6) which means the user is specifying his own single line absorption and scattering coefficients

$$\alpha_A = ABL * EXP\ (-ABE * H)$$

$$\alpha_S = SCL * EXP\ (-SCE * H)$$

or his own power ratios for the multi-line 3.8 μm propagation (see Figure 3.8). Note that single-line 3.8 μm propagation is available only if the user specifies his own coefficients. Also note that if one wishes to alter the power ratio, PLINE(I), I = 1, 2, 3 without altering the built-in multi-line coefficients, simply set LAMDA equal to -3.8E-6 and leave the absorption and scattering coefficients off namelist USPEC. The three power ratios need not total unity since the program is self-normalizing. The heart of ATM is the call to AA, AB, BA, or BB where the intensities for the pathlengths of interest are calculated. If AB or BA are called, they in turn call BB for those portions of the propagation path that lie below 100 km. Following the return to ATM, the beam displacement, eccentricity, contour data, breakdown power, optimum power, and effects of power variations are determined for straight propagation unless the propagation path is totally exoatmospheric (AA), or the blooming parameter NI is less

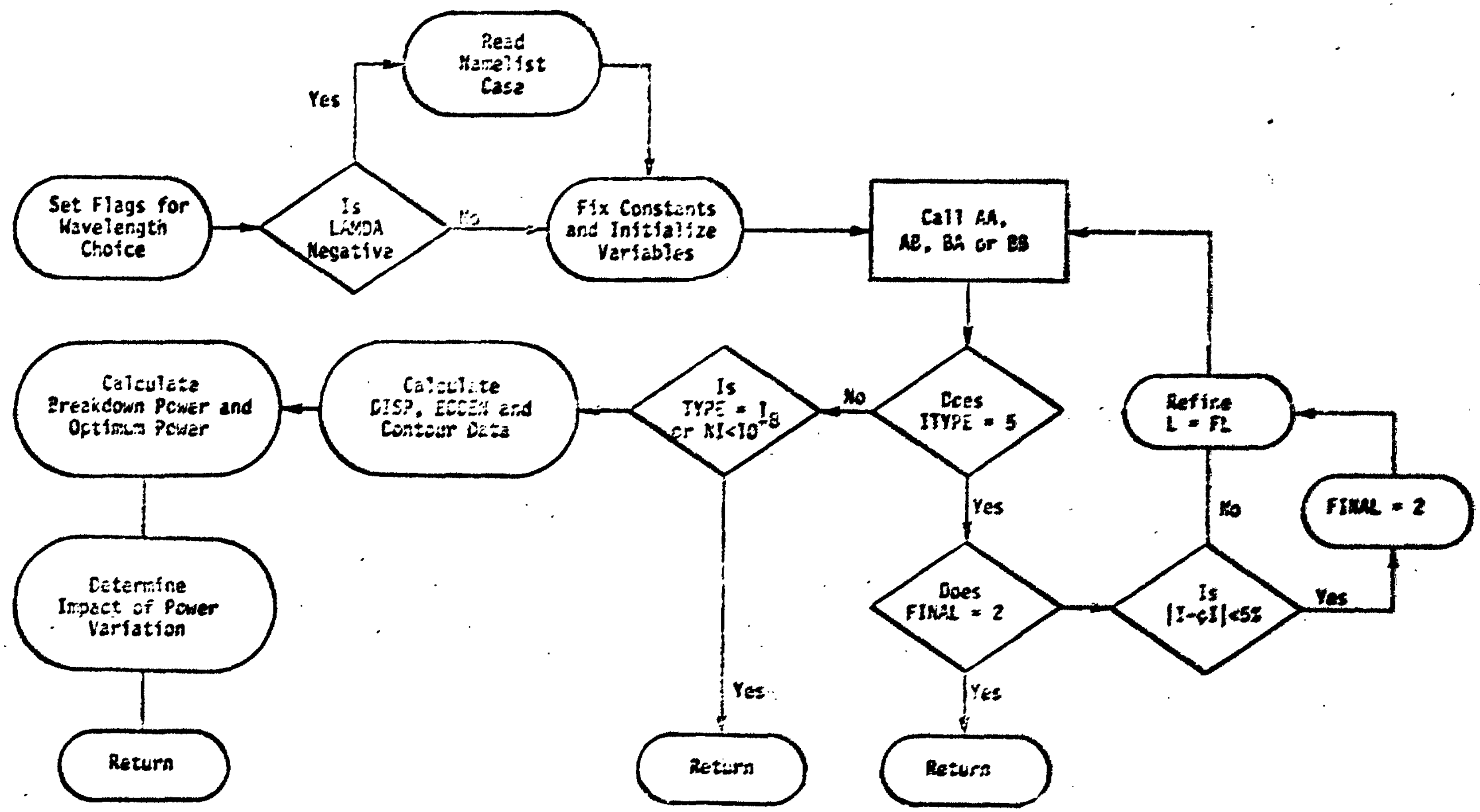


Figure 3.8 ATM Flow Diagram

than 10^{-8}. It should be noted that when the power is varied to compute the impact of propagating a beam that is more or less powerful than the specified level, the beam quality is not altered; this gives some error to the results since beam quality is affected by the total power transmitted through the optical train.

If the reverse propagation option (ITYPE = 5) has been chosen, the calculations are repeated using different target ranges (= focal ranges for ITYPE = 5) until the calculated intensity is within 5% of the desired value. If convergence is not achieved within 20 iterations, the program returns control to SAICOM and goes to the next case.

3.2.3 BB

In Figure 3.9, the logic flow for the BB subroutine is shown. all cases except AA use this subroutine to compute the atmospheric effects on the high-power beam propagation. The subroutine performs calculations at discrete points along the beampath. For calculations of the linear propagation effects, the pathlength intervals are fixed (NSTEP = 30 is the default value) while in the blooming loop the intervals are increased or decreased as required to minimize time and increase accuracy of the calculation. A series of linear or exponential extrapolations for the i^{th} interval based on the $i^{th} - 1$ interval are made and compared with the actual calculation for the i^{th} interval. If the comparison is unfavorable, the interval is decreased. If the comparison is favorable, the contribution from the interval is incorporated into the integral, if the comparison is unnecessarily good, the interval is increased. This procedure replaces the time-consuming multiple interations used in COMBO.

3.2.4 Input Data

In Table 3.3 a list of the input parameters and their functions is given. This reference list does not

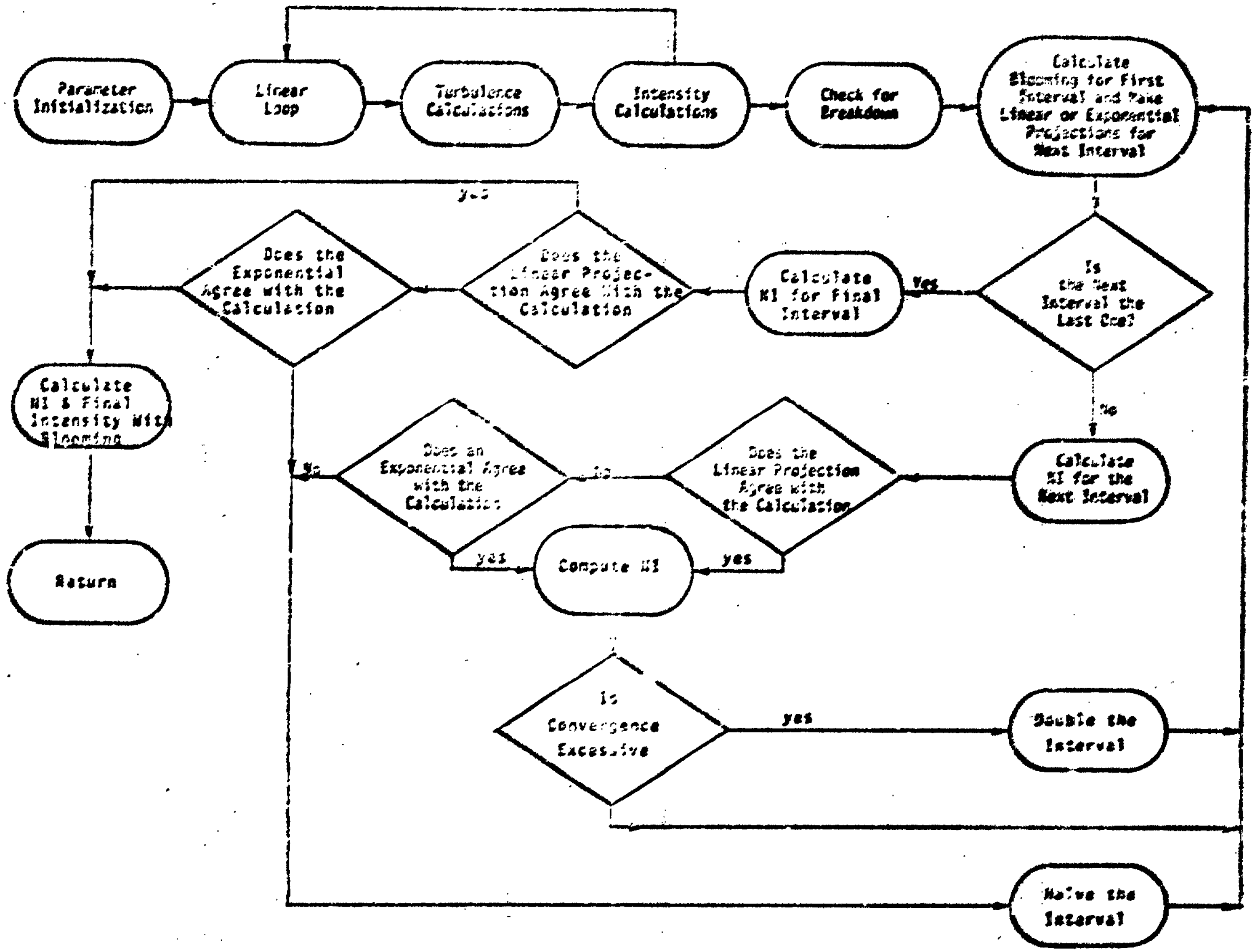


Figure 3.9. EB Flow Diagram

Table 3.3 Input Parameters

REQUIRED

ITYPE	If ITYPE = 5 reverse calculation is called with OI and PD or PT specific. All other entries will result in straight propagation.
PD or PT	User may stipulate either device power or telescope power; if PT is specified OPTRAN is bypassed.
OI	Desired intensity of ITYPE = 5; otherwise it is the minimum intensity contour in the variable power calculation.
L	Range from laser to the target if ITYPE ≠ 5; if ITYPE = 5, L is a first guess for the range.

OPTIONAL - NAMELIST/INPUT/

Beam	0 ⇒ Collimated, 1 ⇒ Focused.
CHI	Horizontal projection of beampath with respect to the direction of platform movement.
DEBUG	1 ⇒ no extra diagnostic statement, 2 ⇒ extra diagnostic statement.
FL	Focal length.
GL	Ground level.
HTM	Target altitude.
HOM	Laser altitude.

Table 3.3 (Continued)

OPTIONAL - NAMELIST/INPUT/ (Continued)

LANDA	Wavelength 3.8×10^{-6}, 5.0×10^{-6}, and 1.06×10^{-5} are the acceptable values. A negative sign in front is a flag that the user will specify the multi-line power ratios or the single line absorption and scattering coefficients.
M	Beam quality.
NSTEP	Beampath intervals in the linear calculation.
OMEGA	Slewing rate.
OUT	1 ⇒ standard output, 2 ⇒ extra output.
PHI	Firing angle with respect to zenith. If PHI is specified HIM should not be given and vice versa.
PROP	1 ⇒ $1/e^2$ 2 ⇒ plane wave, truncated Gaussian 3 ⇒ infinite Gaussian.
RH	Relative humidity.
RI	Radius of obscuration.
RO	Outer radius of exit aperture.
SIGHF	High-frequency turbulence.
VP	Platform velocity.
VXB	Total crosswind across beam. If it is specified VP, OMEGA and natural wind are inoperative.
WTHR	-1 ⇒ high turbulence, low natural wind 0 ⇒ nominal turbulence and natural wind 1 ⇒ low turbulence, high natural wind.

Table 3.3 (Continued)

OPTIONAL - NAMELIST/CASE/

DB	Beam diameter coming from the laser.
EPS	Obscuration ratio.
DL	Pulse length.
XRI	Phase front curvature.
DIOVI	Peak-to-peak intensity fluctuation.
DLI	Scale size of fluctuation wrt beam size.
DELTAR	Aerowindow.
RREF	Aerowindow density divided by ambient density.
XLC	Distance from laser exit to beam clipper.
DC	Clipper diameter.
N	Number of mirrors in optical train.
REFL	Reflectivity of each mirror.
SFAB	Mirror fabrication error.
ITYPEM	Mirror type: 1 ⇒ cooled, 2 ⇒ uncooled.
XLMIR	Distance between mirrors.
XMAG	Telescope magnification.
ITYPEB	Telescope type: 1 ⇒ on-axis, 2 ⇒ off-axis.
XLEA	Exit aperture width.
BETA	Exit aperture absorption coefficient.
ASAB	Strut area/beam area.
ITYPEA	Type of exit aperture: 1 ⇒ material window, 2 ⇒ open port.

Table 3.3 (Continued)

OPTIONAL - NAMELIST/CASE/ (Continued)

THTR	Tracker jitter (1σ).
THBS	Boresight jitter (1σ).
THAA	Autoalignment jitter (1σ).
THSV	Servo jitter (1σ).

OPTIONAL - NAMELIST/USPEC/

PLINE (1)	Percent (or actual) power in line 1.
PLINE (2)	Percent (or actual) power in line 2.
PLINE (3)	Percent (or actual) power in line 3.
ABL	User specified linear absorption coefficient.
ABE	User specified exponential absorption coefficient.
SCL	User specified linear scattering coefficient.
SCE	User specified exponential scattering coefficient.

include the first two cards which must precede each set of runs. The first uses I2 format in columns 1 and 2 to state the number of cases (NRUN) which will be run, the second uses free-field format to allow the user to title each of the runs. The first card appears only once while the title card must precede each new case. Hence, the data stream is as follows:

```
NRUN CARD
Title                                  }
Required Inputs                        }
Namelist INPUT                         }   Case 1
Namelist CASE                          }
Namelist USPEC (if required)           }

Title                                  }
Required Inputs                        }
Namelist INPUT                         }   Case 2
Namelist CASE                          }
Namelist USPEC (if required)           }
```

Table 3.4 provides a convenient work sheet format that may be used to specify each case. It includes a list of the default values and units. Those familiar with COMBO will recognize a change in some of the default values; the default statements now reflect sea level applications. Note that either PHI or HTM may be specified, but that PHI should always be given as a positive angle (measured from the zenith). A negative PHI is a flag that HTM was specified.

For additional convenience, Table 3.5 lists several of the important program flags which may be of interest to the user. A complete program listing and sample run is supplied along with a sample problem output in Appendix B.

Table 3.4 Sample Input Form with Default Values

Required	Type	Position	Units	Case 1	Case 2	Case 3
ITYPE ✓	(3,5)	I2				
PD[2] or PT	(3,5) (3,5)	11-20 21-30	w w			
OI[5] L	(3,5) (3)	31-40 41-50	w/m^2 m			

Namelist "INPUT" Optional	Default	Units	Case 1	Case 2	Case 3
BEAM ✓	1 (focused)				
CHI	0.52	rad			
FL	L	m			
GL	0.	m			
HOM	50.	m			
HTM	10.	m			
LAMDA	3.8E-6	m			
M	1.5				
NSTEP ✓	30				
OMEGA	0.	rad/sec			
OUT ✓	1 (short)				
PHI[3]	-1.E-6	rad			
PROP ✓	1 (Gaussian)				
RH	0.5				
RI	.08	m			
RO	.35	m			
SIGHF	5.E-6				
SIGLF	5.E-6				
VP	15.	m/sec			
VXB	0.	m/sec			
WTHR ✓	0 (normal)				

Table 3.4 (Continued)

Namelist "CASE" Optional	Default	Units	Case 1	Case 2	Case 3
ASAB	0.05				
BETA	0.01	m^{-1}			
DB	.16	m			
DC	0.166	m			
DELT	1.0	°K			
DELTAR	0.1				
DIOVI	0.5				
DLI	0.1	L/WT			
DT	2.0	seconds			
EPS	.36				
ITYPAW ✓	1 (focused)				
ITYPEA ✓	2 (open)				
ITYPEB ✓	1 (on-axis)				
ITYPEM ✓	1 (cooled)				
N ✓	5				
RFTL	0.986				
RI	1.E70	m			
RRLF	2.5				
SFAB	1./8.	vis lamda			
THAA	5.E-6	rad			
THBS	5.E-6	rad			
THSV	5.E-6	rad			
THTR	5.E-6	rad			
XLC	50.	m			
XLEA	0.05	m			
XLMIR	.15	m			
XMAC	4.375				

Namelist "USPEC" Optional	Default	Units	Case 1	Case 2	Case 3
Pline (1)	.338				
Pline (2)	.32				
Pline (3)	.342				
ABE	0.	m^{-1}			
ABL	0.	m^{-1}			
SCE	0.	m^{-1}			
SCL	0.	m^{-1}			

NOTES:

1. Check mark (✓) indicates "I" format is required.
2. User may specify either power exiting the device or telescope.
3. PHI need not be specified if HTM is given.
4. Although data on $INPUT$ card are optional, the card must be present even when all default values are to be used. The same applies to data card $CASE$. The namelist card $USPEC$ is only read when a negative lamda has been inserted on data card $INPUT$ as a flag.
5. If ITYPE = 5, OI is the desired intensity for the reverse calculation; otherwise it is the minimum useful intensity for the variable power tabulation (default value of 10^7 w/m^2).

Table 3.5 Flags

FORM	MEANING
Inputs	
Negative LAMDA	The users will specify the multi-line power ratios or the single-line absorption and scattering coefficients.
Negative PHI	HTM is specified (Default).
Internal	
CNVRGD	TRUE => the last blooming interval passed over the end point.
ENDED	TRUE => this is the last blooming interval.
ERR	TRUE => the reverse calculations have not converged in 20 iterations.
FINAL	= 1, the reverse calculations have not converged yet; = 2, last pass through the propagation calculation.
FRACT	Tells the fraction of the last blooming interval that is within L.
LAM	= 1, 10.6 μm = 2, 3.8 μm (multi-line) = 3, 5 μm (single-line at present) = 4, user will specify single-line absorption and scattering coefficients.
OK	TRUE => save previous values for multi-line absorption and scattering calculations.

Table 3.5 (Continued)

FORM	MEANING
Internal (Continued)	
TYPE	= 1, AA = 2, BB = 3, AB = 4, BA.
UNIFRM	TRUE => last two blooming intervals were the same.

Section 4

SUMMARY OF TASKS I-IV

The purpose of this section is to briefly review the objectives and results of the original four tasks. Specific details may be found in the first and second interim reports (References 1 and 2). The primary objective here is to highlight some of the issues which arose during the course of the work and to indicate some of their implications as they relate to propagation modeling in general.

4.1 REVIEW OF TASK I. CODE COMPARISONS

The objective of Task I was to quantitatively compare the results obtained from three propagation codes over a parameter space representative of realistic engagement conditions. The codes were: NOLEC (Naval Surface Weapons Center); COMBO (Air Force Weapons Laboratory); ESP-I (United Aircraft Research Laboratories). The comparisons were presented at the First DOD Conference on High Energy Laser Technology on 3 October 1974 in San Diego (Reference 14). An unclassified version of this paper is included as an appendix in the first interim report (Reference 1). The major conclusions from these comparisons were that all three codes give comparable results for situations in which thermal blooming is not severe, but that ESP-I gives intensities up to an order of magnitude or more higher than the other two codes when blooming is significant. NOLEC and COMBO agree reasonably well under most conditions.

A secondary objective of Task I was to ascertain the reasons for major discrepancies between the codes. The effort was concentrated on COMBO and ESP-I since there is considerable disparity in their results even though they both use essentially the same approach for calculating thermal blooming. NOLEC uses an entirely different approach. In reviewing the theoretical basis of the codes, several issues were raised whose significance goes beyond the immediate objectives of the present work.

The blooming subroutines in both COMBO and ESP-I are based on the theoretical and experimental work of Gebhardt and Smith (Reference 20). The essence of the basic approach is the representation of the ratio of the bloomed and unbloomed focal plane peak intensities, I_{REL}, as a function of a single "blooming parameter," N. N is a theoretically derived, dimensionless, similarity parameter. However, the relationship between I_{REL} and N was obtained experimentally. Both COMBO and ESP-I use the same empirical relationship for I_{REL} (N). They yield different results in blooming calculations because they compute N differently. The differences in the recipes for calculating N were identified explicity in the First Interim Report (Reference 1). The question as to which method is more "correct" could not be resolved on theoretical grounds for several reasons.

1. An approximation to the theoretically derived expression for N was used in correlating the experimental data. The approximation was not generally valid even for the conditions of the experiments. It is even more questionable for realistic engagement-scale conditions such as those for which the simplified propogation codes are used.

2. COMBO uses the theoretical expression for N except for a relatively minor *ad hoc* correction. In principle, this has some important advantages, such as an inherent capability to treat non-coaltitude engagements. Unfortunately, it is not consistent with the empirical relationship used to correlate the experimental data.

3. ESP-I uses the same expression for N as was used for the empirical correlation. In that sense, it is at least consistent. However, it does not engender much confidence in the extrapolation from small scale laboratory experiments to realistic engagement conditions.

To summarize the situation, both COMBO and ESP-I use a semi-empirical blooming model which is flawed by a basic inconsistency between its theoretical and empirical components. The First Interim Report implies a preference for COMBO simply because it was in closer agreement with NOLEC. It should be emphasized, however, that this may be, at least to some extent, fortuitous. Furthermore, there does not exist sufficient data to provide convincing validation of any of the codes.

Evaluation of the codes on theoretical grounds in any kind of absolute sense was beyond the scope of the study, but two observations are in order. First, the consistency problem with the Gebhardt and Smith blooming model does not necessarily reflect adversely on its basic approach; the deficiencies are primarily associated with its implementation. Secondly, there are no clear and obvious theoretical reasons why either of the basic approaches should be superior in accuracy to the other. All of the codes incorporate numerous simplifying assumptions and approximations, both explicit and implied, and rely to some extent on heuristic arguments.

4.2 REVIEW OF TASK II. BEAM SHAPE AND DISPLACEMENT

The objective of this task was to develop empirical models for predicting beam shape distortion and displacement in the focal plane due to thermal lensing. Results from the NRL non-linear propagation code were used as he data base for the analysis.

Since beam distortion and displacement both are closely related to thermal blooming, I_{REL} (the reduction in peak intensity due to blooming) was used as the primary correlation parameter. This automatically accounts for much of the dependence on the independent parameters and has the further advantage of being readily computed from the NRL scaling law.

The beam displacement model is represented by

$$\left(\frac{d}{a_f}\right) \eta^{.29} = \frac{-0.519 + \sqrt{(0.519)^2 + 1.500 \ln (1/I_{REL})}}{0.750}$$

where d is the displacement of the peak intensity into the wind, a_f is the e^{-1} beam radius (without blooming) in the focal plane, a_i is the e^{-1} beam radius in the source plane, and $\eta = a_f / a_i$.

The beam shape model represents the constant intensity contours as ellipses and the intensity distribution as

$$I(x,y) = I_{PEAK} \exp \left\{ -SD \left[\left(\frac{x}{a_f}\right)^2 + \left(\frac{y-d}{Da_f}\right)^2 \right] \right\}$$

where

$$D = 0.3 + 0.7\, I_{REL}$$

$$S = I_{REL}$$

$$I_{PEAK} = \frac{P\, e^{-\alpha R}\, I_{REL}}{\pi a_f^2} \quad .$$

This model automatically gives the correct peak intensity and conserves total power. It also provides an excellent representation of the data in terms of the area within a given constant intensity contour and the eccentricity of the constant intensity contours.

These models, of course, are subject to the same limitations as the data from which they were derived. For example, they do not apply (unless suitably modified) in the presence of jitter or turbulence or when slewing is not in the same plane as the wind. Actually, the most significant result of this task is that both distortion and deflection are probably too minor to have a significant impact on system effectiveness.

4.3 REVIEW OF TASK III. BEAM QUALITY

The objective of this task was to develop an approach to modeling the effect of phase and amplitude aberrations in the aperture plane on the far-field beam profile. In more general terms, it was desired to obtain a rational approach to representing beam quality.

The recommended approach involves approximating the far-field intensity profile (neglecting blooming) as a Gaussian distribution of the form

$$I(R) = \frac{m_1 P_T e^{-\alpha_e R} \exp\left\{- \frac{r^2}{2R^2\left(\frac{m_2^2 \sigma_{DL}^2}{I_{REL}} + \sigma_J^2 + \sigma_T^2\right)}\right\}}{2\pi R^2 \left(\frac{m_2^2 \sigma_{DL}^2}{m_1 I_{REL}} + \sigma_J^2 + \sigma_T^2\right)} .$$

The parameters m_1 and m_2 are the proposed beam quality parameters and are determined so that the integrated power distribution corresponding to the above expression matches the actual distribution at two specified points, e.g., $r = w_f$ and $r = 2w_f$, where w_f is the beam waist.

This two parameter representation of beam quality is a significant advance over the usual "m x diffraction limited" concept. It can account both for power loss due to wide angle scattering and for beam spreading. It should be fully adequate to represent all situations in which the far-field beam profile is dominated by a central lobe. Furthermore, the general approach is sufficiently flexible that it can include effects associated with beam truncation and obscuration (see following section) as well as with other amplitude perturbations and with phase aberrations. For example, the simplified optical train model (OPTRAIN) described in Section 2 provides a method of estimating m_1 and m_2 for a wide range of system parameters.

4.4 REVIEW OF TASK IV. BEAM TRUNCATION AND OBSCURATION

The effect of truncation and obscuration were investigated both analytically and within the empirical framework of the beam quality model developed in Task III, i.e., the results were presented in terms of the parameters m_1 and m_2. Detailed results of the analysis are presented in Reference 2. Since the degree of truncation and obscuration is determined by the optical train, the model itself has been incorporated into the optical train model (Section 2).

Section 5

CONCLUSIONS

In any high technology program, like the DOD laser program, it is important that technologists and analysts work together to resolve the issues and support the efforts of the other group. During the early phases of a new program the technologists severly bound the problem under study to facilitate modeling of complicated processes. On the other hand, the analysts use extremely simplistic models for the elements of the system under study because they must address every aspect of the problem albeit in a naive manner. As time passes these two groups move closer together with the theoreticians studying ever increasing segments of the problem and the systems analysts improving their models and studying the issues in greater depth.

The atmospheric propagation coding studied under this contract is really second generation modeling. Improving the speed and accuracy of a program, adding multi-line propagation, and studying beam shape are exemplary of the movement of HEL system analysts toward increasingly complex modeling. One of the other areas investigated -- the optical train analysis -- is less well developed. The detailed tools for modeling the beam propagation through the optical train have been operational only recently. Hence, the simplified codings developed under this contract are first generation models. The authors hope that both of these modeling tasks will contribute to the continuing covergence of laser technology and systems analysis.

APPENDIX A

Molecular Absorption of DF Laser Radiation

A.1 INTRODUCTION

This appendix was written by Dr. T. Tuer of the Ann Arbor SAI office. This work was undertaken to provide better values for the molecular absorption coefficients used in the thermal blooming code. These coefficients are required as a function of both altitude and of atmospheric water vapor content for several "typical" DF laser line groups. Here, "typical" means a characteristic laser propagation-altitude function (this will be clarified in Section A.3). For convenience in the thermal blooming code, the coefficients are given as a simple analytical function of altitude and water content, with different sets of coefficients (i.e., one for each typical group).

A.2 APPROACH

Due to time constraints, it was decided to use McClatchey's DF absorption coefficients (Reference A.1) rather than re-calculating them with our own line-by-line codes. The ten BDL laser lines that McClatchey considered were selected for this study (see Table A-1). However, since McClatchey did not include the water continuum absorption in his calculations, it was necessary to add this component. A simple computer program DAFT (DF Altitude Fitting Code), was written to: (1) evaluate this continuum component for the frequencies, altitudes and model atmospheres desired, (2) add this to McClatchey's results, and (3) plot the total absorption coefficient as a function of altitude.

Table A-1. List of DF-BDL Lines

DF Laser Line	Frequency (cm^{-1})	Relative Power	Considered by McClatchey and Here
$P_3(8)$	2546.37	10.7	yes
$P_3(7)$	2570.51	10.2	yes
$P_2(10)$	2580.16	6.2	yes
$P_3(6)$	2594.23	7.7	yes
$P_2(9)$	2605.87	9.7	yes
$P_3(5)$	2617.41	1.8	yes
$P_2(8)$	2631.09	12.9	yes
$P_2(7)$	2655.97	10.0	yes
$P_1(10)$	2665.20	3.9	yes
$P_2(6)$	2680.28	6.2	yes
$P_1(9)$	2691.41	9.1	no
$P_1(8)$	2717.54	6.6	no
$P_1(7)$	2743.03	3.5	no
$P_1(6)$	2767 91	2.0	no

The water contiuum absorption coefficient is given by (Reference A.2).

$$n = c_S^0 , {}_w p^*_w + c_N^0 , {}_w P^*$$

where p_W is the partial pressure of water vapor, P is the total pressure and the * indicates the density-equivalent-pressures[1]. This reference also gives measured values of c^{o}_{s,w_o} as a function of frequency at 294^{o} K[2], and recommends value of $c^{o}_{N,w} = 0.12\ c_{s,w}$. The absorption coefficient n differs from the usual coefficient k by:

$$k = nU/L$$

where U is the absorber thickness and L is the path length. Values for p*, P* and U were calculated as a function of altitude using data given by the Handbook of Geophysics and Space Environment (Reference A.3).

The attenuation of most of the DF laser lines is dominated by atmospheric water absorption (i.e., H_2O or HDO line absorption, or H_2O continuum absorption). In order to account for different atmospheric water content, the calculated absorption coefficient was normalized by:

$$k^* = k/\rho^*$$

Here ρ^* is a normalized water density-altitude profile which varies between a value of ρ^*_0 at sea level, to unity as $h \to \infty$. The quantity ρ^*_0 is the sea level density of the model atmosphere under consideration, normalized to that of the midlatitude summer model atmosphere. The form of ρ^* was arbitrarily taken to be:

$$\rho^* = 1 + (\rho^*_0 - 1)10^{R/2}$$

1 Since the pressures are generally less than one atmosphere, we used the usual pressure in place of the density-equivalent-pressure.

2 Since the temperature dependency of this quantity is uncertain, its value at 294°K was used throughout.

where R is the normalized water density profile based on the data in Reference A.3 (see Figure A-1). An example of the effect of this scaling is shown in Figure A-2, where the absorption coefficient profiles for the five different model atmospheres are seen to collapse nicely into a narrow band.

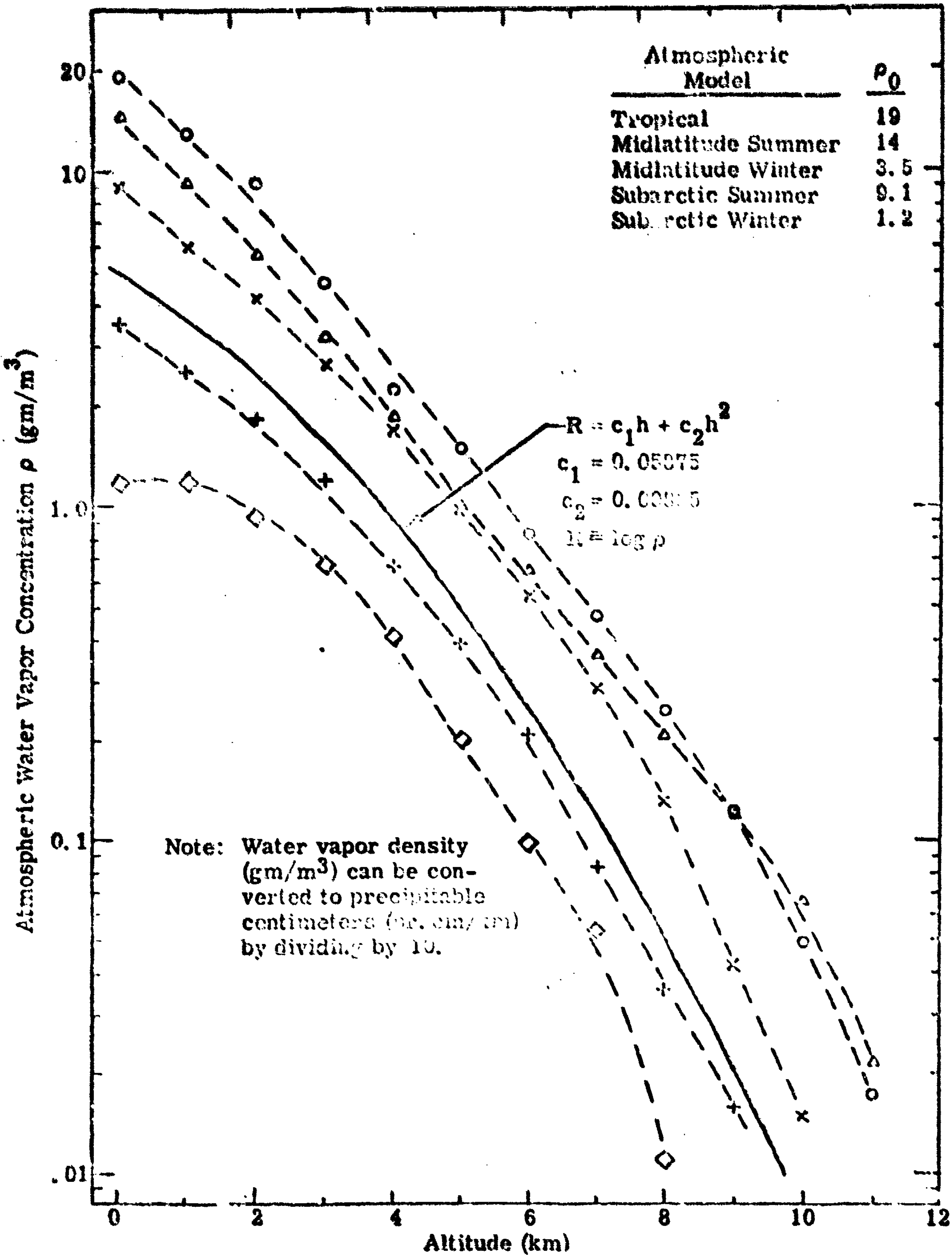


Figure A-1. Water Concentration Profiles for Five Model Atmospheres and Analytic Fit.

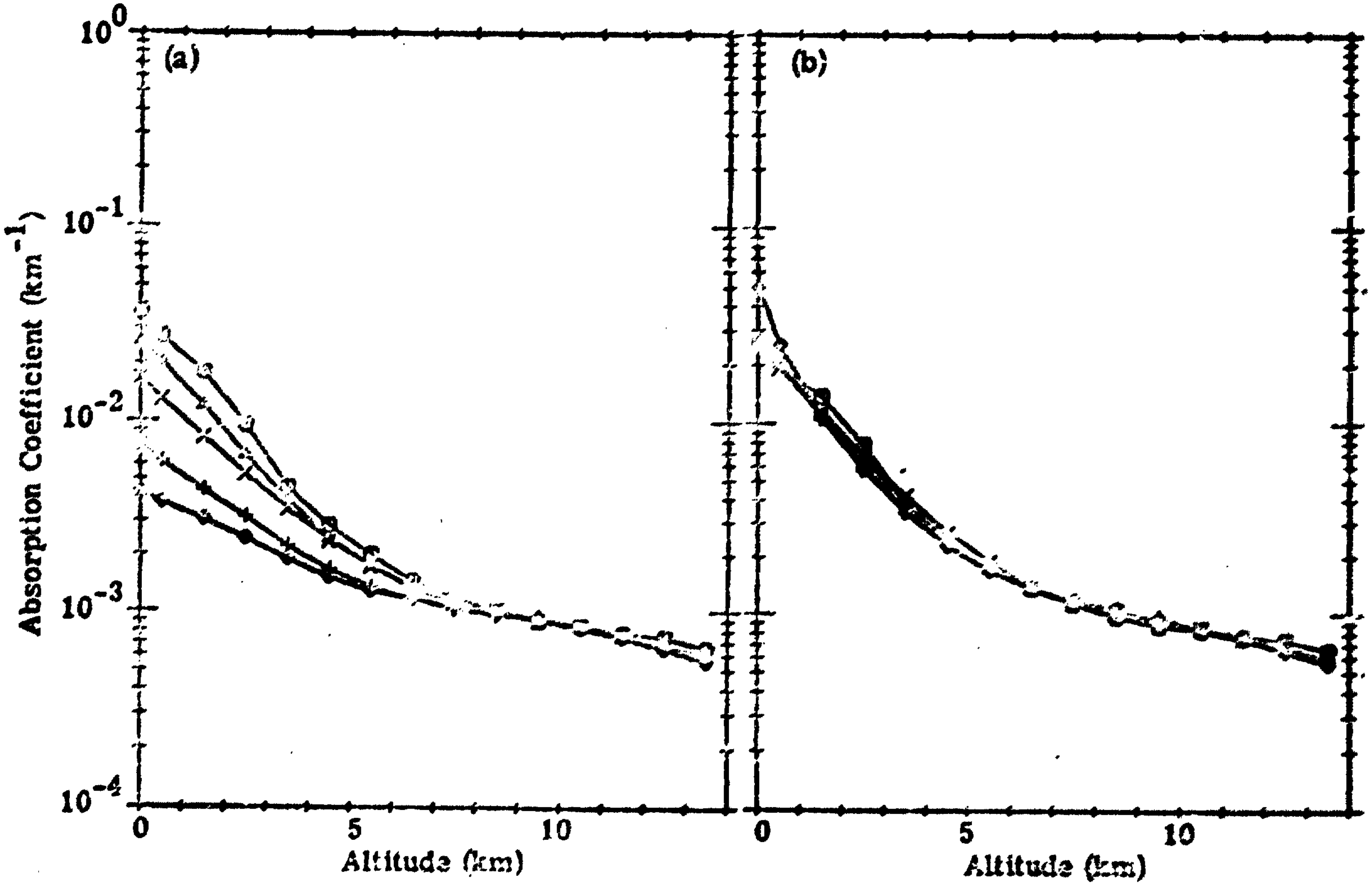


Figure A-2. Demonstration of the Effect of Scaling to Account for Various Atmospheric Water Concentrations - $P_2(8)$ DF Laser.
(a) No Scaling (b) With Scaling

A.3 DETERMINING TYPICAL GROUPS

Normalized profiles for all the water dominated laser lines were plotted on a common scale. Of course the lines which are dominated by other species (e.g., N_2O line absorption), were not normalized in this fashion but simply plotted. These plots tend to collect in three general groups. Those laser lines which are dominated by water at low altitudes, but happen to fall on underlying absorption lines (Type A), have a knee in their profile (see Figure A-3). Those that do not have underlying lines (Type B), do not have a pronounced knee but continue to decrease with altitude, at least for the altitude range considered here (see Figure A-4). Lines which are not dominated by water (Type C), have no knee but fall off less rapidly with altitude (see Figure A-5).

The mechanism for each type can be elucidated by examining the details of the absorbing lines and continuum. Figure A-6 shows components of the absorption coefficient of a Type A laser line at sea level. Notice the underlying CH_4 absorption line (M2), which will become important at higher altitude as the absorption by water diminishes. Figure A-7 shows a Type B laser line where there is no important underlying absorption lines. Finally, a Type C laser line is shown in Figure A-8, which is dominated by N_2O absorption even at sea level, and is affected little by water.

A.4 RESULTS

A least squares fit was applied to each group of laser lines (i.e., Types A, B and C). The analytic form used was:

$$\ln k^* = A_0 + A_1 h + A_2 h^2$$

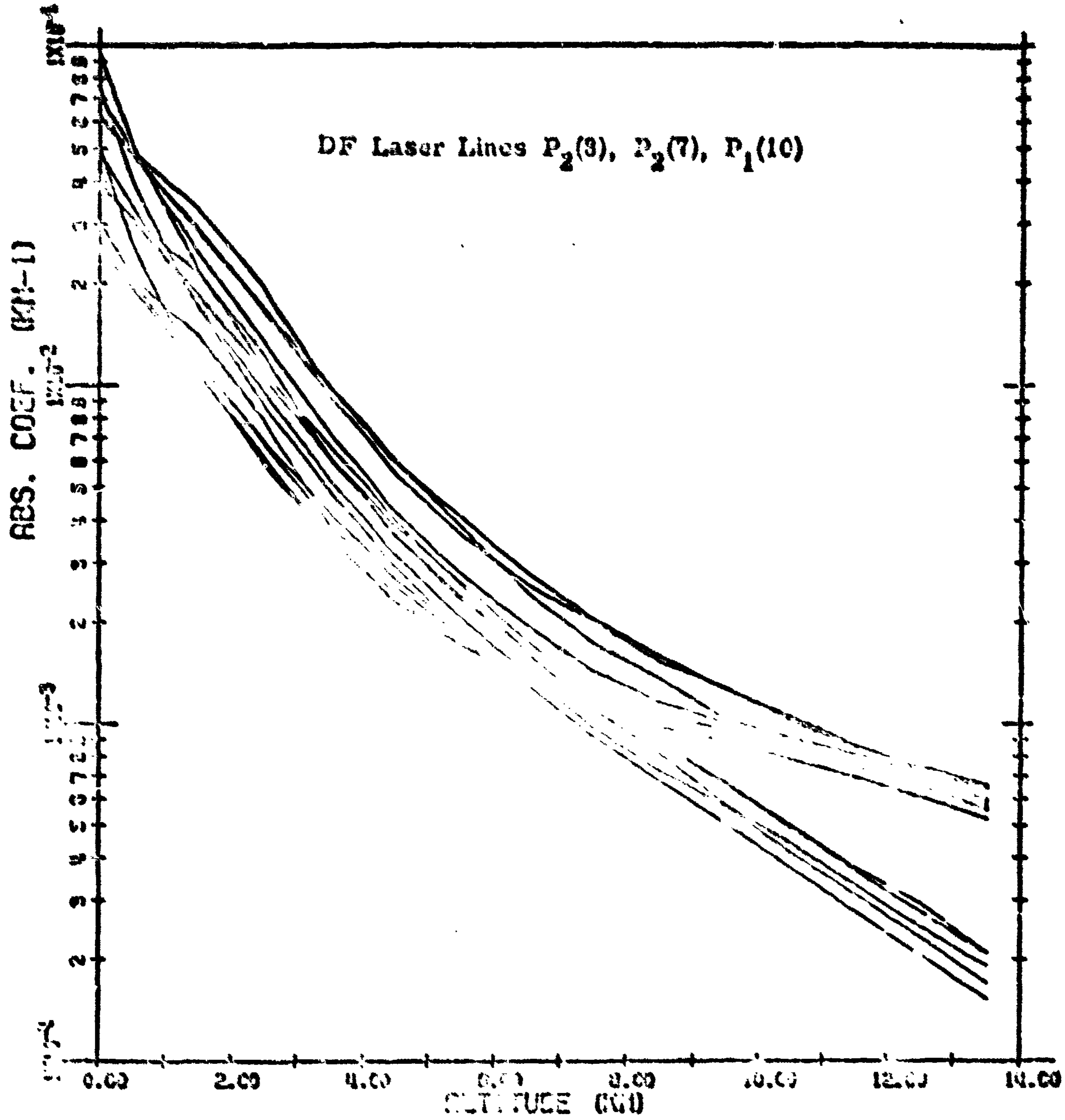


Figure A-3. Laser Propagation-Altitude Function Type A: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.

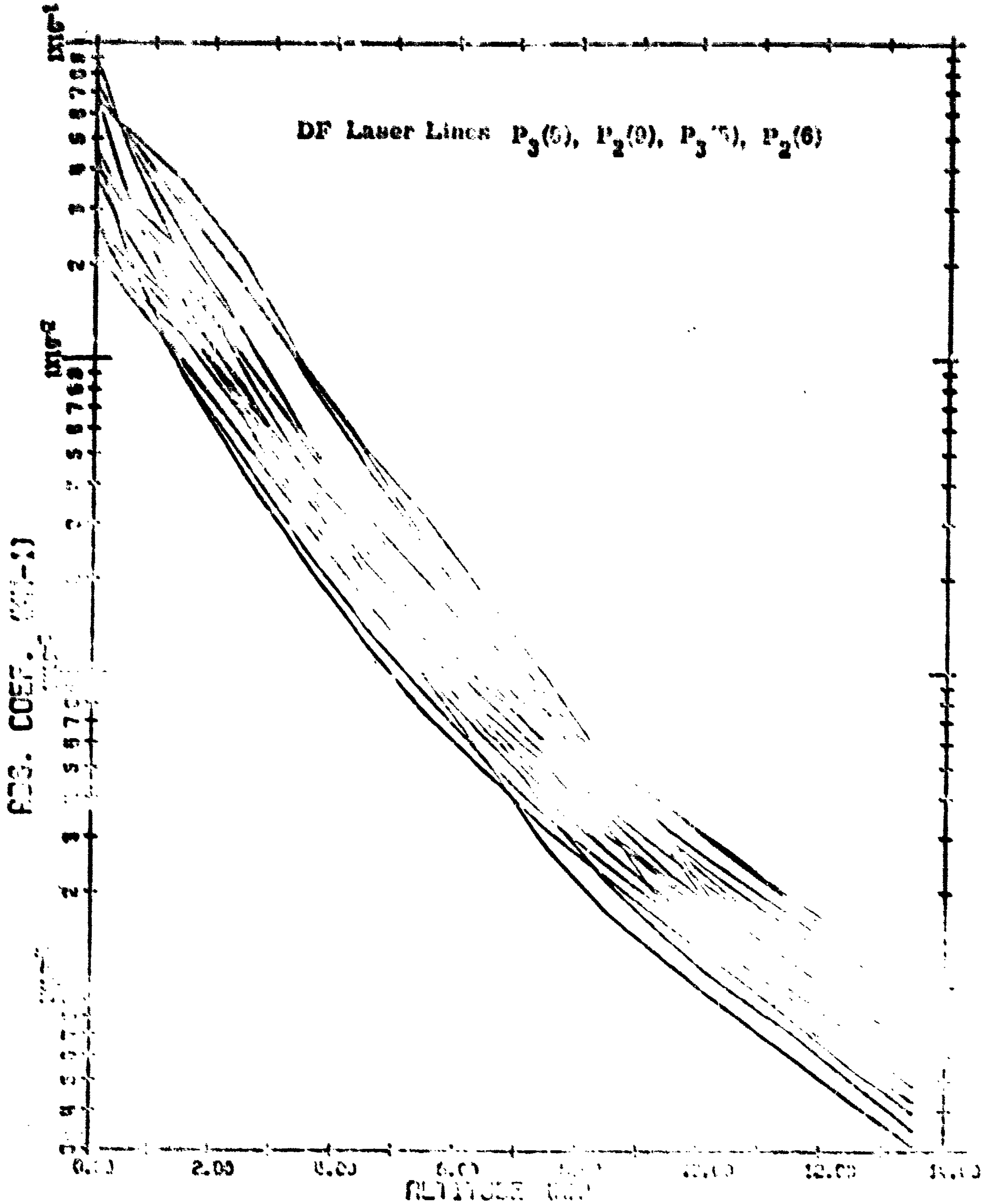


Figure A-4. Laser Propagation-Altitude Function Type B: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.

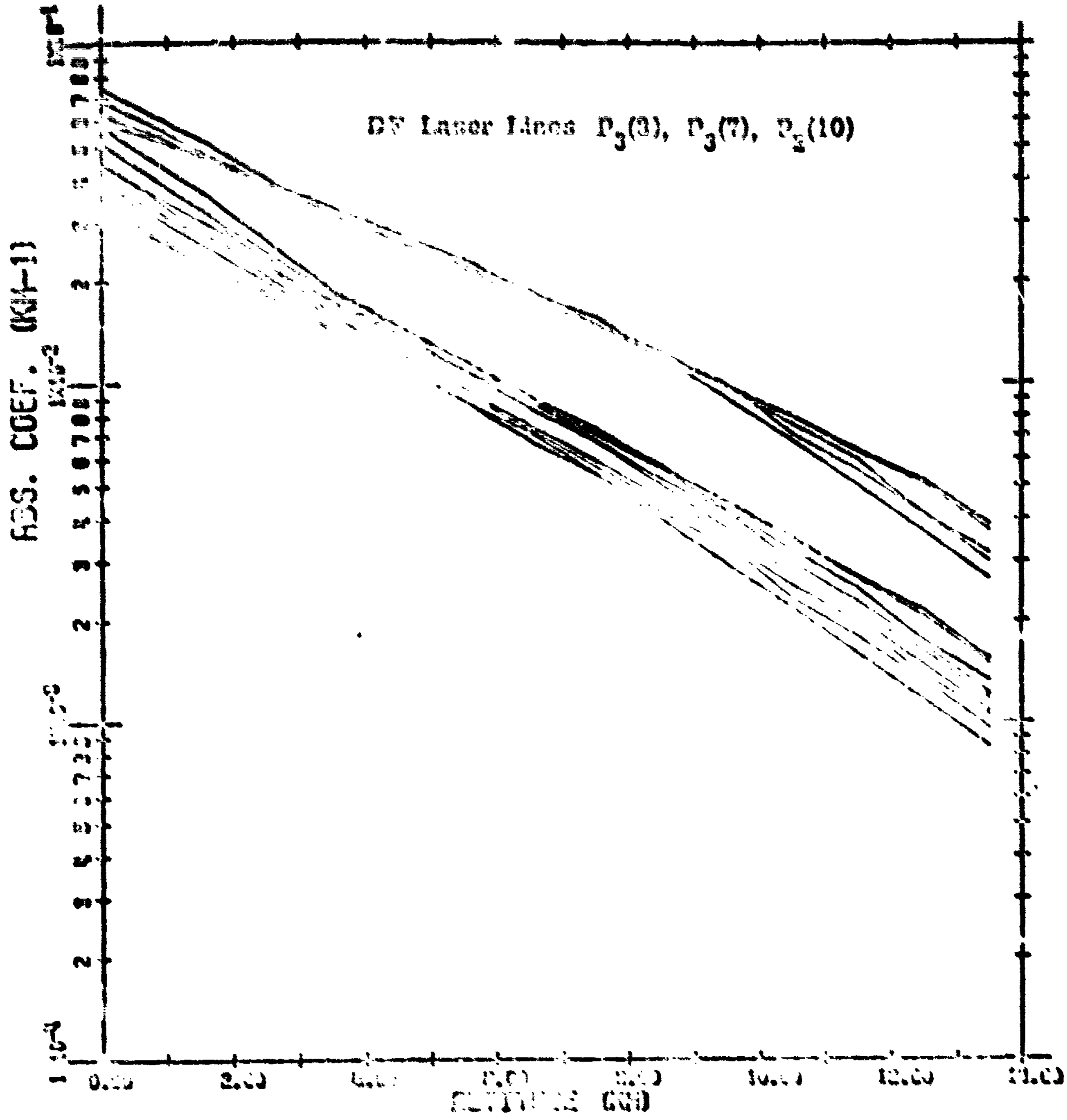


Figure A-5. Laser Propagation-Altitude Function Type C: Dominated by Water at Low Altitudes but with Underlying Absorption Lines which become Important at High Altitudes.

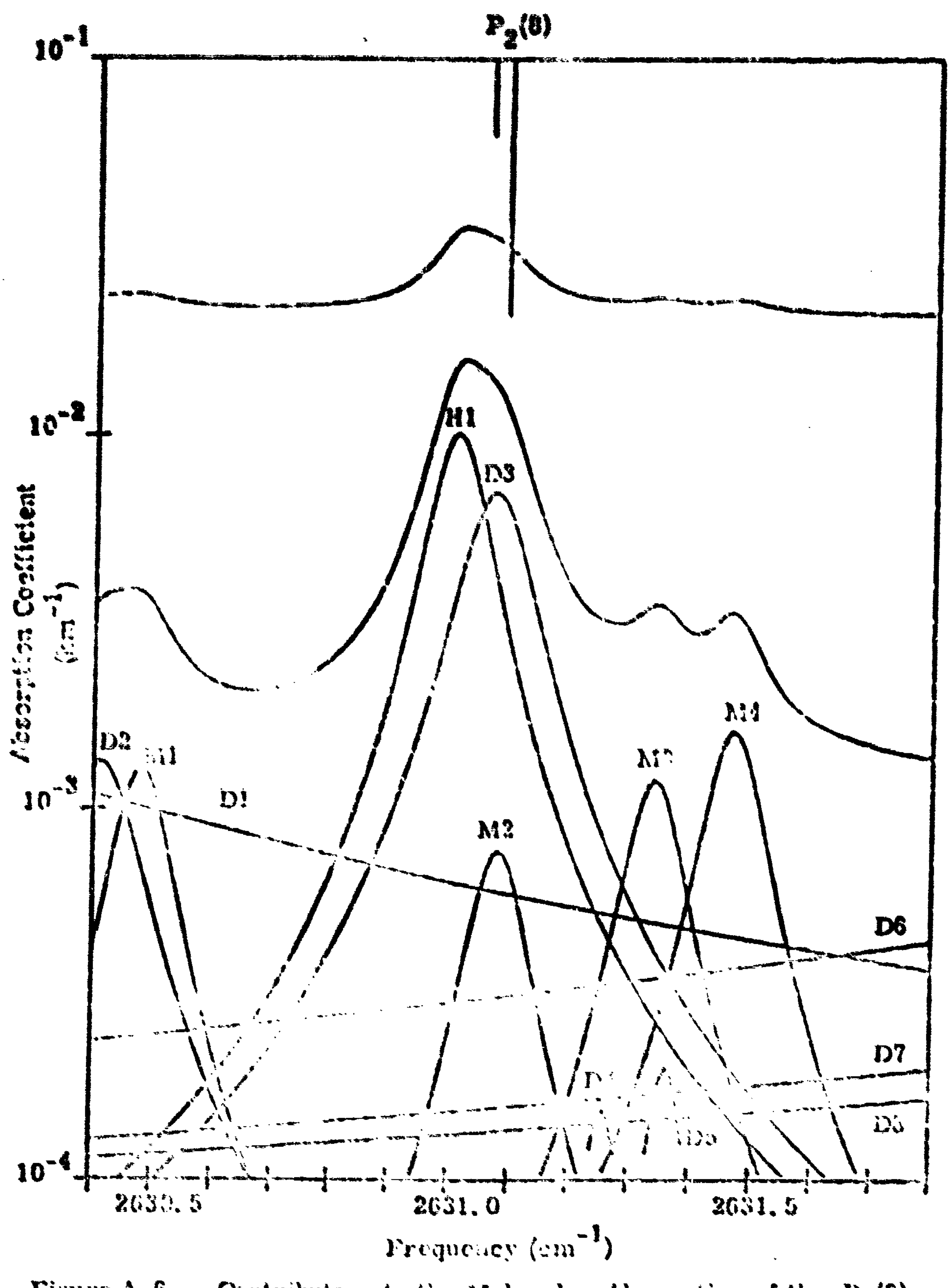


Figure A-6. Contributors to the Molecular Absorption of the $P_2(8)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type A Absorption, Extracted from Ref. A.4.

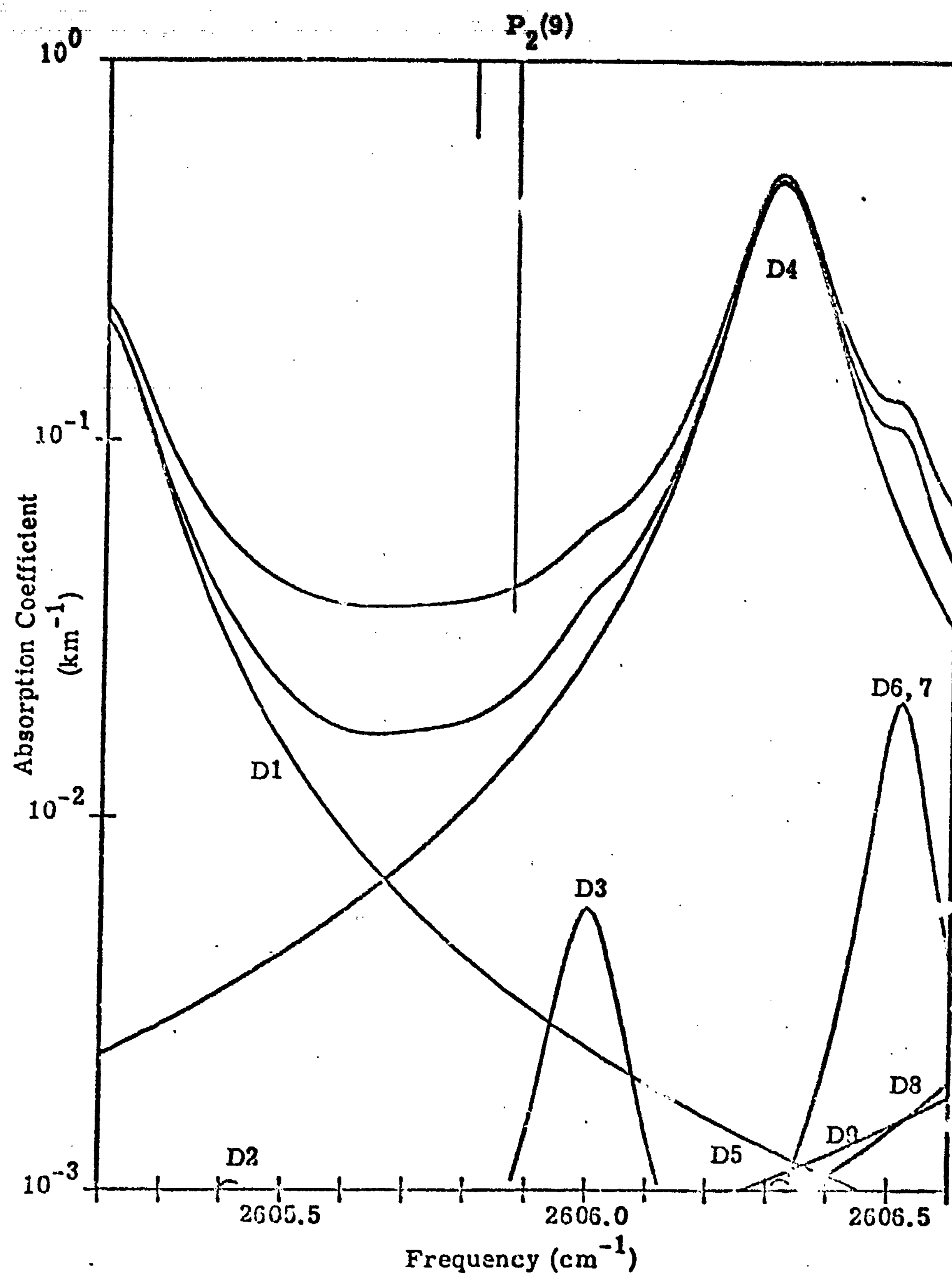


Figure A-7. Contribut rs to the Molecular Absorption of the $P_2(9)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type B Absorption, Extracted from Ref. A.4

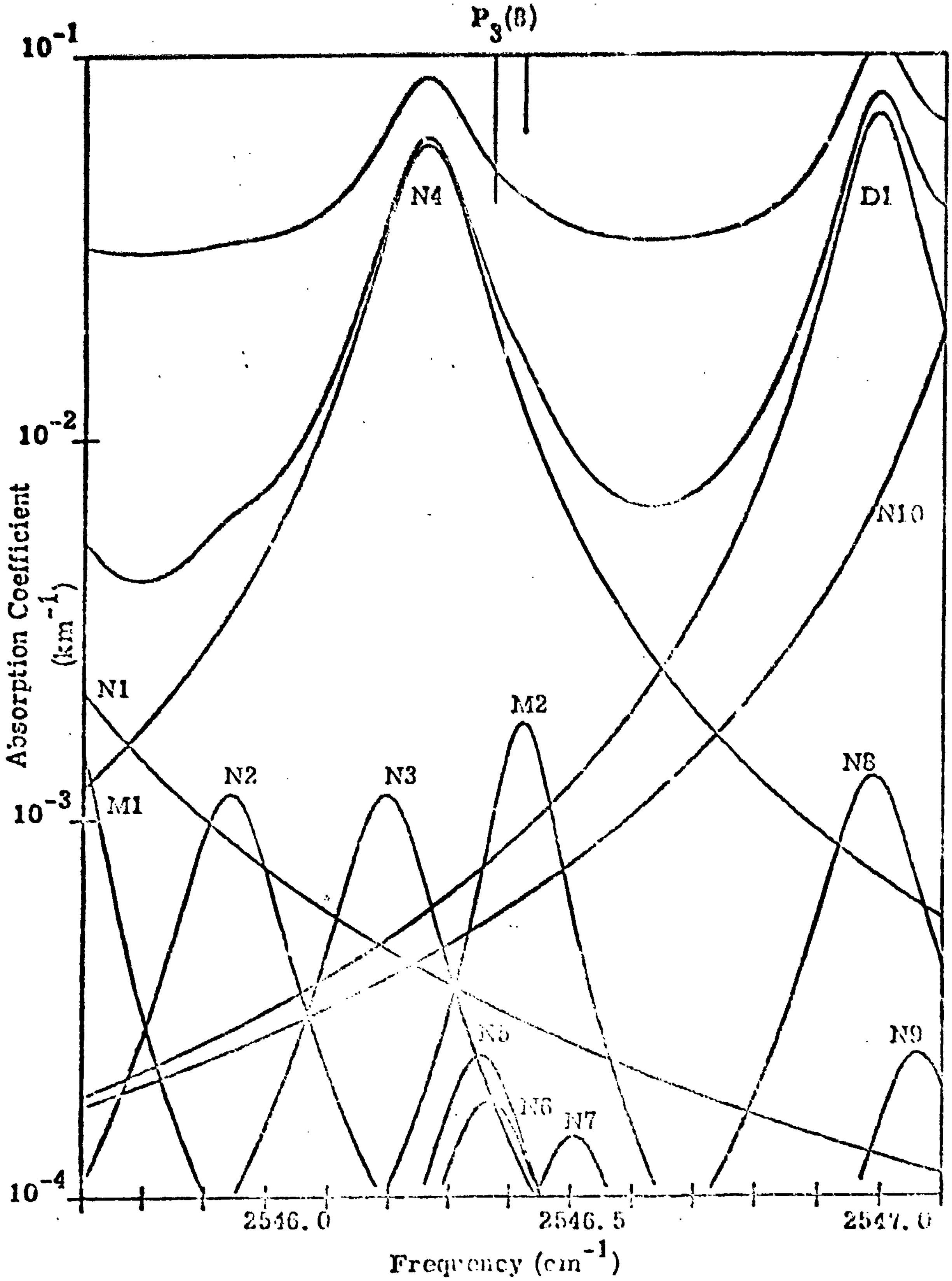


Figure A-8. Contributors to the Molecular Absorption of the $P_3(8)$ DF Line (Midlatitude Summer, Sea Level).

Example of Type C Absorption, Extracted from Ref. A.4

where k^* is the normalized absorption coefficient (km^{-1}) and h is the altitude (km). The results of this fit for each group are shown in Figures A-9 through A-11, and the determined coefficients (i.e., A_0, A_1, A_2) given in Table A-2.

Table A-2. Coefficients of Least Squares Fit

Type	DF Laser Lines	A_0	A_1	A_2
A	$P_2(8)$, $P_2(7)$, $P_1(10)$	-3.138	-0.6388	0.0225
B	$P_3(6)$, $P_2(9)$, $P_3(5)$, $P_2(6)$	-3.173	-0.6952	0.0155
C	$P_3(8)$, $P_3(7)$, $P_2(10)$	-3.039	-0.2199	-0.00196

For Type C laser lines this normalized coefficient k^* is identical to the un-normalized coefficient k (since water absorption is insignificant):

$k = k^*$ (for Type C)

Type A and B lines must be un-normalized by:

$k = \rho^* k^*$ (for Types A & B)

where $\rho^* \equiv 1 + (\rho_0^* - 1)\ 10^{R/2}$ and:

$R = C_1 h + C_2 h^2$

with $C_1 = 0.05875$ and $C_2 = 0.00835$.

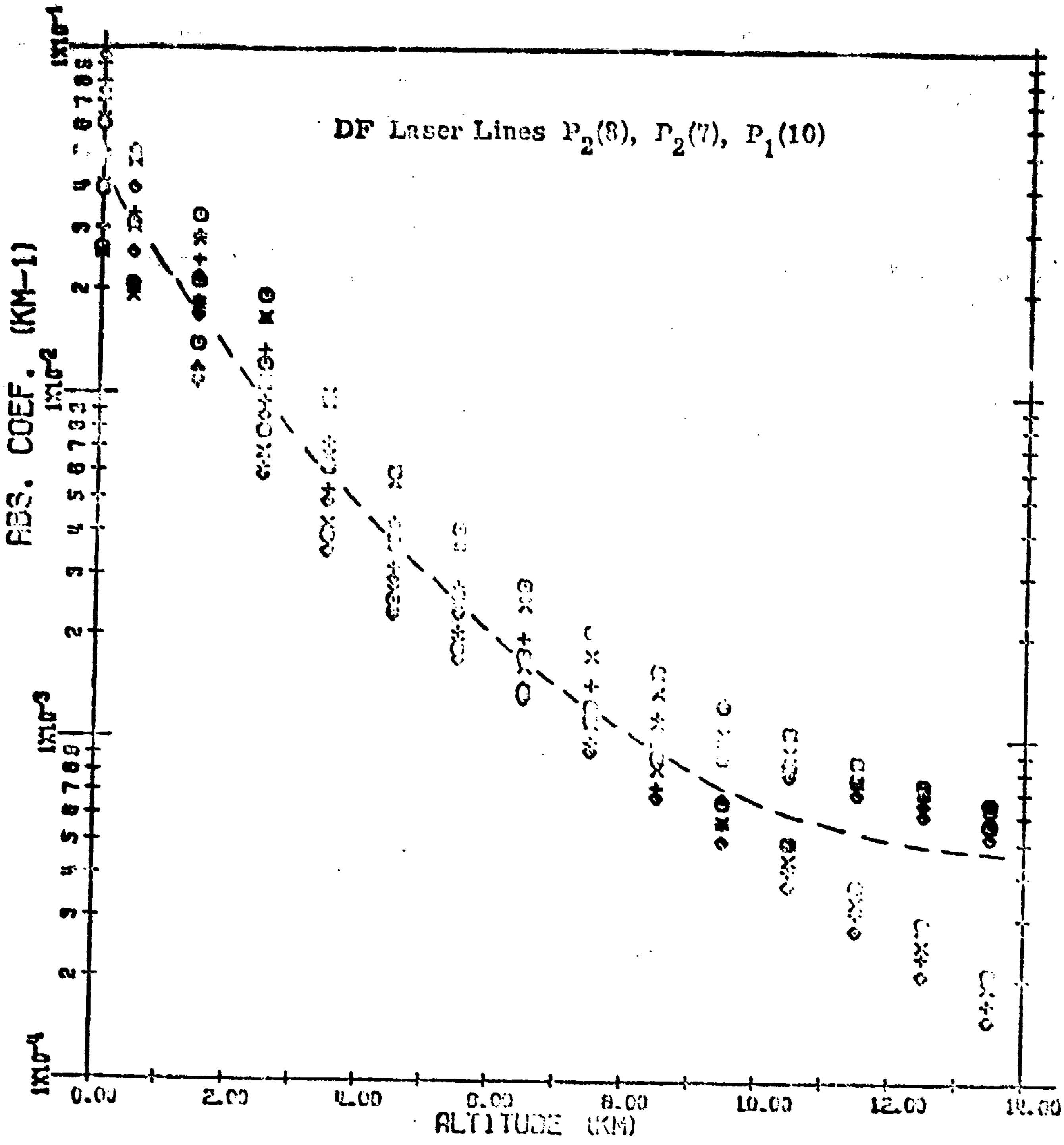


Figure A-9. Least Squares Fit to Type A Laser Lines

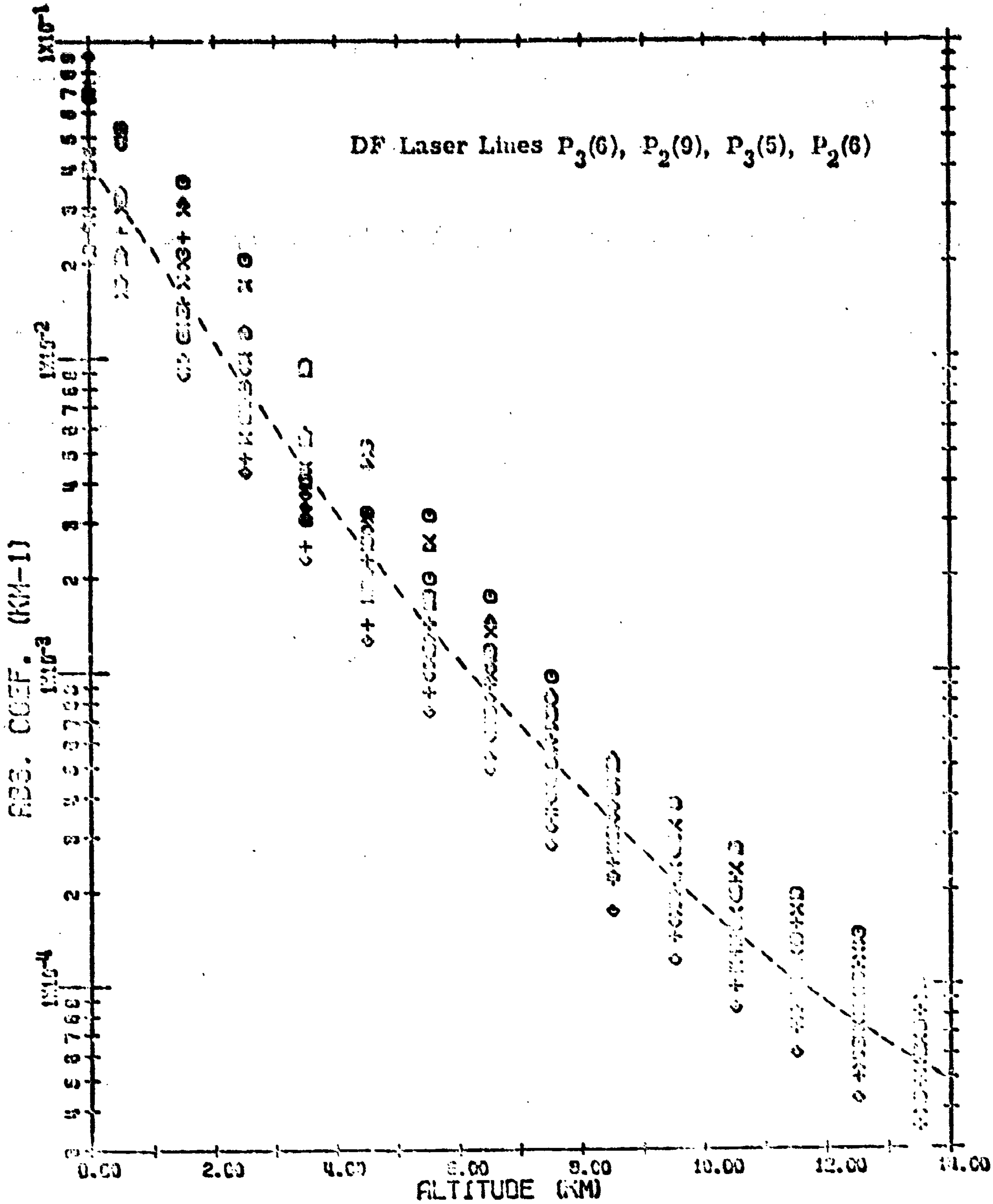


Figure A-10. Least Squares Fit to Type B Laser Lines

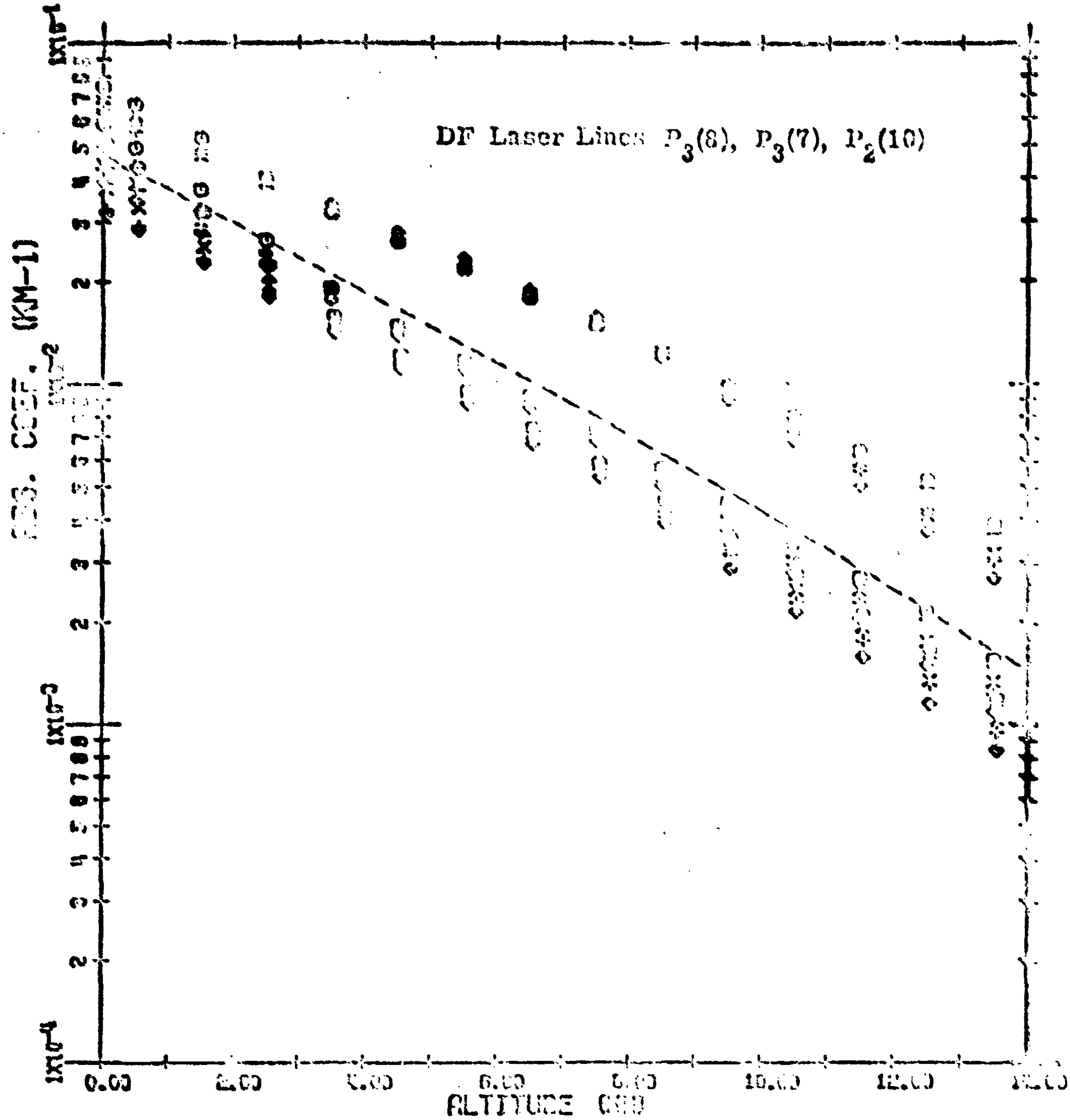


Figure A-11. Least Squares Fit to Type C Laser Lines

APPENDIX B

SAICOM

```
      PROGRAM SAICOM(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)               SIC     2
C                                                                         SIC     3
C     SAICOM IS THE EXECUTIVE ROUTINE WHICH READS THE INPUTS AND DEFINES  SIC     4
C     THE CONDITIONS AT EXIT OF THE TELESCOPE.                            SIC     5
C                                                                         SIC     6
      LOGICAL ERR                                                         SIC     7
      EQUIVALENCE (RO,R0)                                                 SIC     8
      EQUIVALENCE (HOM,HOM)                                               SIC     9
      INTEGER BEAM,BEAN,DEBUG,OUT,PROP,SPOT,TITLE(7),WTHR                 SIC    10
      REAL IBD,L,LAMDA,M,M1,M2                                            SIC    11
C                                                                         SIC    12
      COMMON /ERROR/ ERR                                                  SIC    13
      COMMON /ATMIN/ M,OI,PROP,SIGLF,SIGHF,WTHR,M1,M2                     SIC    14
      COMMON /ATMS/ BEAM,FL,GL,HTM,IBD,L,LAMDA,NSTEP,PHI                  SIC    15
      COMMON /IN/ COEFP,HOM,RI                                            SIC    16
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,R0                                  SIC    17
      COMMON /INT/ PD                                                     SIC    18
      COMMON /ALFA/ LAM,RH                                                SIC    19
      COMMON /OPTIN/ DB,PIN,WL,EPS,XNL,DT,XRI,THI,DIOVI,DLI,DELTAR,RREF,  SIC    20
     1XLC,DC,N,REFL,SFAR,ITYPEM,XLMIR,XMAG,DTR,ITYPEB,XLEA,BETA,ASAB,ITY  SIC    21
     2PEA,THTR,THRS,THAA,THSV,DIT,DELT,ITYPAW                             TCP     1
      COMMON /OPTOUT/ DBT,P,XM1,XM2,TH                                    SIC    23
      COMMON /X/ CHI,OMEGA,VP,VPSC,VXA                                    SIC    24
C                                                                         SIC    25
      DIMENSION IBEAM(2), IDEBUG(2), IIW(3), IJTYPE(4), IOUT(2), IPROP(3  SIC    26
     1)                                                                   SIC    27
C                                                                         SIC    28
      NAMELIST /INPUT/ BEAM,CHI,DEBUG,FL,GL,HTM,HOM,IBD,LAMDA,M,NSTEP,OM  SIC    29
     1EGA,OUT,PHI,PROP,RH,RI,RO,SIGHF,SIGLF,VP,VXS,WTHR                   SIC    30
      NAMELIST /CASE/ DB,EPS,DT,XRI,THI,DIOVI,DLI,DELTAR,RREF,XLC,DC,N,R  SIC    31
     1EFL,SFAR,ITYPEM,XLMIR,XMAG,THRE,ITYPEB,XLEA,BETA,ASAB,ITYPEA,THTR,  SIC    32
     2THRS,THAA,THSV,DELT,ITYPAW                                          TCP     2
C                                                                         SIC    34
      DATA IBEAM/10HCOLLIMATED,10HFOCUSED   /                             SIC    35
      DATA IDEBUG/10HOUT DEBUG ,10H DEBUG   /                             SIC    36
      DATA IIW/10HMILD      ,10HNORMAL    ,10HSEVERE    /                 SIC    37
      DATA IOUT/5HSHORT,5H LONG/                                          SIC    38
      DATA IPROP/10HGAUSSIAN  ,10HPLANE WAVE,10HIAF GAUSS /               SIC    39
C                                                                         SIC    40
      READ (5,7) NRUNS                                                    SIC    41
      DO 6 IRUNS=1,NRUNS                                                  SIC    42
C                                                                         SIC    43
C     READ REQUIRED INPUTS                                                SIC    44
      READ (5,8) TITLE                                                    SIC    45
      READ (5,9) ITYPE,PD,PT,OI,L                                         SIC    46
C                                                                         SIC    47
C     SET DEFAULT VALUES OF OPTIONAL PROPAGATION INPUTS                   SIC    48
      IF (OI.EQ.0.) OI=1.E7                                               SIC    49
      BEAM=1                                                              SIC    50
      CHI=.52                                                             SIC    51
      DEBUG=1                                                             SIC    52
      FL=L                                                                SIC    53
      GL=0.                                                               SIC    54
      HTM=10.                                                             SIC    55
      HOM=50.                                                             SIC    56
      IHD=1E12                                                            SIC    57
      LAMDA=3.8E-6                                                        SIC    58
```

```
      M=1.5                                                    SIC   59
      NSTEP=30                                                 SIC   60
      OMEGA=0.                                                 SIC   61
      OUT=1                                                    SIC   62
      PHI=-1.E-6                                               SIC   63
      PROP=1                                                   SIC   64
      RM=.5                                                    SIC   65
      RI=.08                                                   SIC   66
      RO=.35                                                   SIC   67
      SIGMF=5.E-6                                              SIC   68
      SIGLF=5.E-6                                              SIC   69
      VXM=0.                                                   SIC   70
      VP=15.                                                   SIC   71
      WTHR=0                                                   SIC   72
C                                                              SIC   73
      READ (5,INPUT)                                           SIC   74
C                                                              SIC   75
      BEAN=BEAM+1                                              SIC   76
      IW=WTHR+2                                                SIC   77
      ERR=.FALSE.                                              SIC   78
      IF (VXM.NE.0.) VP=0.0                                    SIC   79
C                                                              SIC   80
      IF (PD.EQ.0.) GO TO 1                                    SIC   81
C                                                              SIC   82
C     SET DEFAULT VALUES FOR OPTICAL TRAIN                     SIC   83
C                                                              SIC   84
      THI=SQRT(SIGMF*SIGMF+SIGLF*SIGLF)                        SIC   85
      WL=ABS(LAMDA)                                            SIC   86
      PIN=PC                                                   SIC   87
      XNL=M                                                    SIC   88
      OIT=2.*RI                                                SIC   89
      DIR=2.*RO                                                SIC   90
      DH=.15                                                   SIC   91
      EPS=.36                                                  SIC   92
      DT=2.0                                                   SIC   93
      XRI=1.E70                                                SIC   94
      DIOVI=0.5                                                SIC   95
      DLI=0.1                                                  SIC   96
      DELTAR=0.1                                               SIC   97
      RREF=2.5                                                 SIC   98
      XLC=50.                                                  SIC   99
      DC=.166                                                  SIC  100
      N=7                                                      SIC  101
      REFL=.986                                                SIC  102
      SFAR=1./8.                                               SIC  103
      ITYPEM=1                                                 SIC  104
      XLMIR=.15                                                SIC  105
      XMAG=4.375                                               SIC  106
      ITYPEH=1                                                 SIC  107
      ITYPEA=1                                                 SIC  108
      XLEA=.05                                                 SIC  109
      BETA=.01                                                 SIC  110
      ASAM=.05                                                 SIC  111
      THTP=5.E-6                                               SIC  112
      THHS=5.E-6                                               SIC  113
      THAA=5.E-6                                               SIC  114
      THSV=5.E-6                                               SIC  115
```

```
            DELT = 1.0                                                     TCP    3
            ITYPAW = 1                                                     TCP    4
      C                                                                    SIC  116
      1     READ (5,CASE)                                                  SIC  117
      C                                                                    SIC  118
      C     WRITE INPUTS                                                   SIC  119
      C                                                                    SIC  120
            IF (PMI.NE.-1.E-6) MTM=-0.0                                    SIC  121
            MOF=3.281*MOM                                                  SIC  122
            MTF=3.281*MTM                                                  SIC  123
            WRITE (6,10) TITLE                                             SIC  124
            IF (ITYPE.EQ.5) GO TO 2                                        SIC  125
            WRITE (6,11) IOUT(OUT),IDEBUG(DEBUG),CL,RO,FL,PT               SIC  126
            GO TO 3                                                        SIC  127
      2     WRITE (6,12) IOUT(OUT),IDEBUG(DEBUG),OI,PD,FL,PT               SIC  128
      3     WRITE (6,13) CL,LAMD*,HOM,SIGMF,MOF,SIGLF,MTM,OMEGA,MTF,RO,PMI,R2 SIC  129
            WRITE (6,14) CHI,IPROP(PROP),VP,IBEAM(BEAM),VXS,M,IIW(IW),NSTEP,RM SIC  130
      C                                                                    SIC  131
      C     OPTICAL TRAIN CALCULATIONS                                     SIC  132
      C                                                                    SIC  133
            IF (PD.EQ.0.) GO TO 4                                          SIC  134
            CALL OPTRAIN                                                   SIC  135
            RC=DRT/2.                                                      SIC  136
            PT=P                                                           SIC  137
            M1=XM1                                                         SIC  138
            M2=XM2                                                         SIC  139
            SIGMF=TM                                                       SIC  140
            SIGLF=0.                                                       SIC  141
            IF (PROP.EQ.2) GO TO 5                                         SIC  142
            M1=XM1/.89                                                     SIC  143
            IF (PROP.EQ.1) M2=1.092*XM2                                    SIC  144
            IF (PROP.EQ.3) M2=XM2/1.29                                     SIC  145
            GO TO 5                                                        SIC  146
      C                                                                    SIC  147
      C     SPECIFICATION OF BEAM QUALITY FOR PD = 0                       SIC  148
      C     (TRUNCATED GAUSSIAN)                                           SIC  149
      C                                                                    SIC  150
      4     M1=1.                                                          SIC  151
            M2=1.41*M                                                      SIC  152
            IF (PROP.EQ.1) GO TO 5                                         SIC  153
      C                                                                    SIC  154
      C     (INFINITE GAUSSIAN)                                            SIC  155
            M2=M                                                           SIC  156
            IF (PROP.EQ.3) GO TO 5                                         SIC  157
      C                                                                    SIC  158
      C     (PLANE WAVE)                                                   SIC  159
            M1=0.89                                                        SIC  160
            M2=1.29*M                                                      SIC  161
      C                                                                    SIC  162
      5     WRITE (6,15) M1,M2                                             SIC  163
      C                                                                    SIC  164
            CALL ATM                                                       SIC  165
      C                                                                    SIC  166
      6     CONTINUE                                                       SIC  167
            STOP 61                                                        SIC  168
      C                                                                    SIC  169
      C                                                                    SIC  170
```

```
      C                                                                      SIC   171
      7    FORMAT (I2)                                                       SIC   172
      8    FORMAT (7A10)                                                     SIC   173
      9    FORMAT (I2,8X,6E10.0)                                             SIC   174
      10   FORMAT (1H1,30X,7A10/)                                            SIC   175
      11   FORMAT(///,10X,A5,20H OUTPUT FORMAT, WITH,A10,//,10X,40HTARGET RAN SIC  176
          1GE (L) ----------------------,1PE10.3,* METERS*5X,34HDEVICE POWER SIC   177
          2 (PD) ---------------,E10.3,* WATTS*/,10X,40HFOCAL DISTANCE (FL)  SIC   178
          3------------------, E10.3,* METERS*,5X,*POWER OUT OF THE TELESCO SIC   179
          4PE (PT) --*, 1PE10.3,* WATTS*,//)                                 SIC   180
      12   FORMAT (///,10X,A5,20H OUTPUT FORMAT, WITH,A10,//,10X,40HDESIRED I SIC  181
          1NTENSITY (DI) ----------------,1PE9.2,* WATTS/M*,3H**22X34HDEVICE SIC   182
          2 POWER (PD) ----------------,E10.3,* WATTS*,/,10X,40HFOCAL DISTANC SIC  183
          3E (FL ------------------,0PF9.0,* METERS*,6X, 34HPOWER OUT OF TH SIC   184
          4E TELESCOPE (PT) --,1PE10.3,* WATTS*,//)                          SIC   185
      13   FORMAT (10X,40HGROUND LEVEL (GL) ---------------------,0PF5.0,*   SIC   186
          1  METERS*6X,34HWAVELENGTH (LAMDA) ---------------,1PE9.2,* METERS SIC   187
          2*,/10X,40HDEVICE ALTITUDE (HOM) -----------------,E9.2,* METERS*, SIC   188
          36X,*INPUT JITTER (HIGH FREQUENCY) ----*, 1PE9.2/,50X,1PE9.2,*  FE SIC   189
          4ET*,21X,        *(LOW FREQUENCY) ---*,1PE9.2/10X,40HTARGET ALTITU SIC   190
          5DE (HTM) -----------------,E9.2,* METERS*,6X,34HTRACKING RATE (OM SIC   191
          6EGA) ------------,0PF5.2,* RADIANS/SEC*/,53X,1PE9.2,*   FEET*,6X, SIC   192
          6*OPTICS RADIUS (R0) ----------------*,0PF6.2,* METERS*/10X,*VERTICA SIC  193
          7L ANGLE (PHI) -----------------*,F7.3,                            SIC   194
          8    *  RADIANS*,  6X,*OBSCURATION RADIUS (RI) ----------*,F6.2,   SIC   195
          9* METERS*,//)                                                     SIC   196
      14   FORMAT (10X, *AZIMUTH ANGLE (CHI) ------------------*,F7.3,       SIC   197
          1*  RADIANS*,6X,*BEAM TYPE (PROP) --------------- *,  A10,/,10X,   SIC   198
          2*PLATFORM VELOCITY (VP) ---------------*,F7.0,*METERS/SEC*,5X,    SIC   199
          3*TYPE OF PROPAGATION (BEAM) ------- *  ,A10,/,10X,*SPECIFIED CROSS SIC  200
          4 WIND (VXW) ------------*,F6.2,15X,  *BEAM QUALITY (M) ---------- SIC   201
          5-------* ,F6.2,/,10X,*SEVERITY OF TURBULENCE (WTWR) --------- *,  SIC   202
          6A6,15X,*NUMBER OF BEAMPATH INCREMENTS ----*,                      SIC   203
          6I3,/,10X,  *RELATIVE HUMIDITY (RH) ------------------*,F6.2//)    SIC   204
      15   FORMAT (10X,*RESULTANT BEAM QUALITY*,5X,*M1 = *,F5.3,5X,*M2 = *,  SIC   205
          1F5.3)                                                             SIC   206
           END                                                               SIC   207
```

```
      SUBROUTINE OPTRAIN                                                OPT       2
C                                                                       OPT       3
C     OPTRAIN CALCULATES THE POWER LOSSES,BEAM QUALITY DEGRADATIONS,AND OPT       4
C     JITTER INDUCED BY THE OPTICAL TRAIN EXTERNAL TO THE DEVICE.       OPT       5
C                                                                       OPT       6
      REAL IOPS,LC,LMIR,LBE,LEA,LT,M1,M2                                OPT       7
      REAL LM,MAG                                                       OPT       8
C                                                                       OPT       9
      COMMON /OPTIN/ DRA,PI,WL,EPSI,QUAL,DT,RI,THI,DIOVI,DL1,DELTAR,RREF OPT      10
     1,LC,DC,N,REFL,SFAB,ITYPEM,LMIR,MAG,DTR,ITYPEB,LEA,BETA,ASAB,ITYPEA OPT      11
     2,THTR,THBS,THAA,THSV,DIT,DELT,ITYPAW                               TCP       5
      COMMON /OPTOUT/ DB,P,M1,M2,TM                                     OPT      13
C                                                                       OPT      14
      DIMENSION HB(2),HA(2),HEA(2),HAW(2)                               TCP       6
C                                                                       OPT      16
      DATA HB/8HON-AXIS ,8HOFF-AXIS/                                    OPT      17
      DATA HM/8HCOOLED  ,8HUNCOOLED/                                    OPT      18
      DATA HEA/6HFIXED ,4HOPEN/                                         OPT      19
      DATA HAW/7HFOCUSED, 9HUNFOCUSED/                                  TCP       7
      DATA BLK/8H        /                                              OPT      20
C                                                                       OPT      21
      DBI=DRA                                                           OPT      22
      ZP=0.0                                                            OPT      23
      ONE=1.0                                                           OPT      24
      BIG=1.E70                                                         OPT      25
      WRITE (6,18)                                                      OPT      26
      WRITE (6,19) DBI,PI,WL,EPSI,QUAL,DT,RI,THI,DIOVI                  OPT      27
      WRITE(6,20) DL1,HAW(ITYPAW),DELTAR,RREF,LC,DC,N,REFL,SFAB,HM(ITYPE TCP       8
     AM)                                                                TCP       9
      WRITE(6,21) LMIR,MAG,DTR,HB(ITYPEB),HEA(ITYPEA),LEA,BETA,DELT,ASAB TCP      10
      WRITE (6,22) THTR,THBS,THSV,THAA                                  OPT      30
C     INPUT BEAM CALCULATIONS                                           OPT      31
      IOPS=4.*PI*DIOVI/(10.883*DBI*DBI)                                 OPT      32
      SI=0.                                                             OPT      33
      IF (QUAL.GT.1.0) SI=SQRT(-ALOG((1.-EXP(-4.9348/QUAL/QUAL))/.992508 OPT      34
     12))                                                               OPT      35
C                                                                       OPT      36
C     AERODYNAMIC WINDOW                                                OPT      37
      SAW=1.44523E-5*DBI*DELTAR*RREF/WL                                 OPT      38
      IF(ITYPAW .EQ. 1) SAW=0.0                                         TCP      11
C                                                                       OPT      39
C     BEAM CLIPPER                                                      OPT      40
      FN=DHI*DHI/(4.*WL*LC)                                             OPT      41
      A=.112/SQRT(FN)                                                   TCP      12
      DHO=DHI/(1.-A)                                                    OPT      43
      DBIN=DHI*(EPSI-A)                                                 OPT      44
      IF (DBIN.LT.0.) DBIN=0.                                           OPT      45
      TC=1.0                                                            OPT      46
      DHI=DBO                                                           OPT      47
      IF (DHO.LE.DC) GO TO 1                                            OPT      48
      TC=(DC/DHO)**2                                                    OPT      49
      DHI=DC                                                            OPT      50
    1 CONTINUE                                                          OPT      51
C                                                                       OPT      52
C     RELAY MIRRORS                                                     OPT      53
C     TRANSMISSION                                                      OPT      54
      TM=REFL**N                                                        OPT      55
```

```
      SFAP=6.28319*0.546E-6*SFAB/WL
      GO TO (2,3), ITYPEM
C
C     COOLED MIRRORS
2     CON=5.E-14*6.28319/WL
      SMI=CON*(1.0-REFL)*IRMS
      FINV=0.0
      GO TO 4
C
C     UNCOOLED MIRRORS
3     RHO=2.205E6
      CP=0.02
      COND=0.0138E2
      ALFA=3.E-8
      THK=.10
      F=1.E70
      IF (REFL.LT.1.0) F=.707*THK )61*DBI*SQRT(CP*RHO*COND/DT)/(2.24*PI*
     1ALFA*(1.-REFL))
      SMI=4.*3.14159*(1.0-REFL)*ALFA*DT*IRMS/(WL*CP*RHO)
      FINV=-1.0/F
4     SMSQ=N*(SFAP**2)+((N-1)*SMI+SMI/MAG/MAG)**2
      SM=SQRT(SMSQ)
      LM=0.
      IF (SMSQ.GT.0.) LM=DLI*N*N*SMI*SMI/SMSQ
      A=1.0
      B=LMIR
      C=FINV
      D=LMIR*FINV+1.0
      DO 5 K=2,N
      A=A+LMIR*C
      B=B+LMIR*D
      C=C+FINV*A
      D=D+FINV*B
5     CONTINUE
      F2=(A+B/R1)/(C+D/R1)
C
C     BEAM EXPANDER
      R2=MAG*F2
      DO=DIN/MAG
      DI=DII/MAG
      C=DMI**2-DMIN**2
      GO TO (6,10), ITYPEB
C
C     ON-AXIS
6     IF (DMI.LE.DO) GO TO 8
      IF (DMIN.LE.DI) GO TO 7
      TRE=(DO**2-DMIN**2)/C
      E=DMIN/DO
      DA=MAG*DO
      GO TO 12
7     TRE=(DO**2-DI**2)/C
      E=DI/DO
      DA=MAG*DO
      GO TO 12
8     IF (DMIN.LE.DI) GO TO 9
      TRE=1.0
      E=DMIN/DMI
```

```
      DB=MAG*DBI                                                        OPT   113
      GO TO 12                                                          OPT   114
    9 TBE=(DBI**2-DI**2)/C                                              OPT   115
      E=DI/DBI                                                          OPT   116
      DB=MAG*DBI                                                        OPT   117
      GO TO 12                                                          OPT   118
C                                                                       OPT   119
C     OFF-AXIS                                                          OPT   120
   10 IF (DBI.LE.DO) GO TO 11                                           OPT   121
      THE=(DO/DBI)**2                                                   OPT   122
      E=DOIN/DO                                                         OPT   123
      DB=MAG*DO                                                         OPT   124
      GO TO 12                                                          OPT   125
   11 TBE=1.0                                                           OPT   126
      E=DOIN/DBI                                                        OPT   127
      DB=MAG*DBI                                                        OPT   128
C                                                                       OPT   129
C     COMPUTE QUALITY LOSS DUE TO CENTRAL OBSCURATION                   OPT   130
   12 SBE=0.0                                                           OPT   131
      LBE=0.0                                                           OPT   132
      IF (E.LE.0.) GO TO 13                                             OPT   133
      A=.6561114881+.1884071484*E-.632167832*E*E+2.343434343*E*E*E      OPT   134
      B=2.297342657-3.116550116*E+36.78787879*E*E-26.75990676*E*E*E     OPT   135
      SBE=SQRT(A*A-.433111257)                                          OPT   136
      LBE=(A*A/B-.1962180453)/(SBE*SBE)                                 OPT   137
C                                                                       OPT   138
C     EXIT APERTURE                                                     OPT   139
   13 SST=SQRT(ASAH)                                                    OPT   140
      GO TO (14,15), ITYPEA                                             OPT   141
C                                                                       OPT   142
C     SOLID WINDOW                                                      OPT   143
   14 TEA=EXP(-BETA*LEA)*(1.0-ASAB)                                     OPT   144
      SEA=5.E-12*DT*BETA*LEA*IRMS*6.28319/WL                            OPT   145
      THE=0.                                                            TCP    14
      GO TO 16                                                          OPT   146
C     OPEN PORT                                                         OPT   147
   15 TEA=1.0-ASAB                                                      OPT   148
      SEA=0.0                                                           TCP    15
      THE=2.14E-7*(((LEA**3)*(DELT**6)/(WL*DB*DB))**.2)                 TCP    16
   16 CONTINUE                                                          OPT   150
C                                                                       OPT   151
C     COMPUTE TOTAL DISTORTION                                          OPT   152
      SQ=.43312*SI**2+SAW**2+SMSQ+SWE**2+SEA**2+SST**2                  OPT   153
      S=SQRT(SQ)                                                        OPT   154
      LT=(.144218*DLI*(((N-1)*SMI+SMI/MAG/MAG)**2)+LBE*SBE*SBE+DLI*SEA* TCP    17
     X SEA)/SQ                                                          TCP    18
      A=EXP(-SQ)                                                        OPT   156
      B=1.+2./(LT*LT)                                                   OPT   157
      P1=.864665*A+(1.-A)*(1.-EXP(-2./B))                               OPT   158
      P2=.997665*A+(1.-A)*(1.-EXP(-6./B))                               OPT   159
      X=2.                                                              OPT   160
      Y=P1/P2                                                           OPT   161
   17 T1=EXP(-2./X)                                                     OPT   162
      T2=1.-T1                                                          OPT   163
      T3=EXP(-6./X)                                                     OPT   164
      T4=1.-T3                                                          OPT   165
      T5=(-2.*T1*T4+6.*T3*T2)/(X*X*T4*T4)                               OPT   166
```

```
              T6=(T2/T4-Y)/T5                                                OPT    167
              X=X-T6                                                         OPT    168
              IF (ABS(T6).GT.1.E-5) GO TO 17                                 OPT    169
              M2=SQRT(X)                                                     OPT    170
              M1=P1/T2                                                       OPT    171
C                                                                            OPT    172
C             TRANSMISSION                                                   OPT    173
              T=TC*TM*TBE*TEA                                                OPT    174
              P=T*PI                                                         OPT    175
C                                                                            OPT    176
C             JITTER                                                         OPT    177
              TH=SQRT(THTR**2+THSV**2+THBS**2+THE**2+(THI**2+THAA**2)/(MAG**2))  TCP     19
              WRITE (6,23)                                                   OPT    179
              WRITE (6,24)                                                   OPT    180
              WRITE (6,25) BLK,ONE,SI,ZR,BLK,ONE,SAW,ZR,BLK,TC,ZR,ZR,HM(ITYPEM), OPT    181
             1TM,SM,LM,HB(ITYPEB),TBE,SBE,LBE,HEA(ITYPEA),TEA,SEA,DLI,BLK,T,S,LT OPT    182
              WR=1.+(3.14159*DB*DB/(4.*WL*R2))**2                            OPT    183
              WR=SQRT(WR)                                                    TCP     20
              XM2=M2                                                         OPT    184
              M2=WR*M2                                                       OPT    185
              WRITE (6,26) DB,P,M1,XM2,WR,M2                                 OPT    186
              WRITE (6,27) TH,R2                                             OPT    187
              RETURN                                                         OPT    188
C                                                                            OPT    189
   18         FORMAT(10X,30(1H*),*INPUT TO OPTICAL TRAIN*,30(1H*))           OPT    190
   19         FORMAT(20X,*LASER BEAM DIAMETER         *,   G12.4,* METERS*/   OPT    191
             1      20X,*LASER POWER                 *,0PG12.4,* WATTS    */ OPT    192
             2      20X,*WAVELENGTH                  *,   E12.4,* METERS*/   OPT    193
             3      20X,*OBSCURATION                 *,0PG12.4,*          */ OPT    194
             4      20X,*BEAM QUALITY                *,G12.4,*           */  OPT    195
             5      20X,*PULSE LENGTH                *,G12.4,* SECONDS   */  OPT    196
             6      20X,*PHASE FRONT CURVATURE       *,   G12.4,* METERS*/   OPT    197
             7      20X,*JITTER                      *,0PG12.4,* RADIANS  */ OPT    198
             8      20X,*INTENSITY FLUCTUATIONS      *,G12.4,* PEAK-TO-PEAK*) OPT   199
   20         FORMAT(20X,*SCALE SIZE OF FLUCTUATIONS  *,G12.4,* L/WT      */  OPT    200
             X      20X,*TYPE OF AEROWINDOW          *,A9/                    TCP     21
             1      20X,*AEROWINDOW DELTA RHO/RHO    *,G12.4,*           */  OPT    201
             2      20X,*RHO/RHO REF                 *,G12.4,*           */  OPT    202
             3      20X,*DISTANCE TO CLIPPER         *,   G12.4,* METERS*/   OPT    203
             4      20X,*CLIPPER DIAMETER            *,G12.4,* METERS*/      OPT    204
             5      20X,*NUMBER OF MIRRORS           *,   I2, *          */  OPT    205
             6      20X,*REFLECTIVITY                *,0PG12.4,*          */ OPT    206
             7      20X,*FABRICATION ERROR           *,G12.4,* VIS. LAMBDAS*/ OPT   207
             8      20X,*TYPE OF MIRRORS             *,A8)                    OPT    208
   21         FORMAT(20X,*DISTANCE BETWEEN MIRRORS    *,   G12.4,* METERS*/   OPT    209
             1      20X,*TELESCOPE MAGNIFICATION     *,0PG12.4,*          */ OPT    210
             3      20X,*TELESCOPE DIAMETER          *,   G12.4,* METERS*/   OPT    211
             4      20X,*TELESCOPE TYPE              *,A8,    *          */  OPT    212
             2      20X,*TYPE OF EXIT APERTURE       *,A8,    *          */  OPT    213
             5      20X,*EXIT APERTURE LENGTH        *,G12.4,* METERS    */  OPT    214
             6      20X,*ABSORPTION COEFFICIENT      *,0PG12.4,* METERS-1 */ OPT    215
             X      20X,*TEMPERATURE FLUCTUATION     *,G12.4,* DEG K      */ TCP     22
             7      20X,*STRUT AREA/ BEAM AREA       *,G12.4,*           *)  OPT    216
   22         FORMAT(20X,*TRACKER JITTER              *,G12.4,* RADIANS   */  OPT    217
             1      20X,*BORE-SIGHT JITTER           *,G12.4,* RADIANS   */  OPT    218
             2      20X,*SERVO JITTER                *,G12.4,* RADIANS   */  OPT    219
             3      20X,*AUTOALIGNMENT JITTER        *,G12.4,* RADIANS   *)  OPT    220
```

```
      23  FORMAT(1H1,10X,30(1H*),*OPTICAL TRAIN OUTPUT*,30(1H*)//)          OPT   221
      24  FORMAT(23X*SOURCE              *,8X,*TRANSMISSION  SIGMA   L/WT  *) OPT   222
      25  FORMAT(20X,*INPUT BEAM          *,A8,2X,F8.4,2X,2F8.4/             OPT   223
     1         20X,*AERODYNAMIC WINDOW *,A8,2X,F8.4,2X,2F8.4/                OPT   224
     2         20X,*BEAM CLIPPER       *,A8,2X,F8.4,2X,2F8.4/                OPT   225
     3         20X,*MIRRORS            *,A8,2X,F8.4,2X,2F8.4/                OPT   226
     4         20X,*BEAM EXPANDER      *,A8,2X,F8.4,2X,2F8.4/                OPT   227
     5         20X,*EXIT APERTURE      *,A8,2X,F8.4,2X,2F8.4/                OPT   228
     6         20X,*TOTALS             *,A8,2X,F8.4,2X,2F8.4)                OPT   229
      26  FORMAT(20X,*TRANSMITTED BEAM DIAMETER*,F8.4,* METERS*/             OPT   230
     1         20X,*TRANSMITTED POWER*,G12.4,* WATTS*/                       OPT   231
     2         20X,*BEAM QUALITY BEFORE ACCOUNTING FOR DIVERGENCE*/          OPT   232
     3          31X,*M1 =*,F8.4,4X,*M2 =*,F8.4/                              OPT   233
     4         20X,*EFFECT OF BEAM DIVERGENCE ON WAIST*,G12.4/               OPT   234
     X         20X,*FINAL BEAM SPREAD PARAMETER, M2*,G12.4)                  OPT   235
      27  FORMAT(20X,*TOTAL BEAM JITTER*,G12.4,* RADIANS*/                   OPT   236
     X         20X,*PHASE FRONT CURVATURE*,  G12.4,* METERS*,//)             OPT   237
          END                                                                OPT   238
```

```
      SUBROUTINE ATM
C
C     ATM SETS UP THE VARIABLES FOR THE FOUR MAIN PROPAGATION SUBROUTINE
C     IT CALCULATES THE INITIAL STEP OF ALL TYPES OF PROPAGATION AND
C     REFINES THE ESTIMATES FOR THE REVERSE CALCULATIONS UNTIL THEY ARE
C     WITHIN THE SPECIFIED RANGE.
C
      LOGICAL CPHI,EQUAL,ERR,PRINT
      INTEGER TYPED(4),TYPEE(4)
      INTEGER BEAM,DEBUG,FINAL,OUT,PQ,PROP,TYPE,WTHR
      REAL I,IBD,IOLD,KAS,KOL,KIP,L,LAMDA,LT2,LT2SO,M,MSQ,NBAR,NU
      REAL KI,IP,M2,M1
C
      COMMON /ERROR/ ERR
      COMMON /ATMIN/ M,OI,PROP,SIGLF,SIGHF,WTHR,M1,M2
      COMMON /MESH/ XPKAS,ZPREV,XN,AREA
      COMMON /ALFDTA/ DUMMY(4),PLINE(3),ABL,ABE,SCL,SCE
      COMMON /ATMS/ BEAM,FL,GL,HTM,IBD,L,LAMDA,NSTEP,PHI
      COMMON /IN/ COEFP,HOM,RI
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,R0
      COMMON /INT/ PD
      COMMON /SATM/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
     1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT2SO,MSQ,VSM1,PI,PQ,PRINT,ROSO,R
     210,SIGASQ,SIGHSQ,SIGMAT,SIGSQ,ROLD
      COMMON /ALFA/ LAM,RH
      COMMON /CNVW/ IW
      COMMON /X/ CHI,OMEGA,VP,VPSC,VXB
C
      EXTERNAL ALFAEX,CNSQ
      NAMELIST /USPEC/ PLINE,ABL,ABE,SCL,SCE
C
      DATA PI/3.14159/
      DATA TYPED/5HABOVE,5HBELOW,5HABOVE,5HBELOW/
      DATA TYPEE/5HABOVE,5HBELOW,5HBELOW,5HABOVE/
C
C     SELECT LAMS
      LAM=1
      PLINE(1)=.338
      PLINE(2)=.32
      PLINE(3)=.342
      ABL=ABE=SCL=SCE=0.
      IF (LAMDA.GT.0.) GO TO 2
      READ (5,USPEC)
      IF (ABL.NE.0.) LAM=4
      LAMDA=ABS(LAMDA)
      TEMP=1./(PLINE(1)+PLINE(2)+PLINE(3))
      DO 1 III=1,3
    1 PLINE(III)=PLINE(III)*TEMP
      WRITE (6,44) PLINE(1),PLINE(2),PLINE(3),ABL,ABE,SCL,SCE
      IF (LAM.EQ.4) GO TO 3
    2 IF (LAMDA.EQ.3.8E-6) LAM=2
      IF (LAMDA.EQ.5E-6) LAM=3
C
C     COLLIMATED OR FOCUSED BEAM
C     (FOCUSED)
    3 G4=0.
      G5=1.
```

```
            IF (REAM.EQ.1) GO TO 4                                   ATM      59
      C     (COLLIMATED)                                             ATM      60
            G5=0.                                                    ATM      61
            G4=1.                                                    ATM      62
      C                                                              ATM      63
      C     SET CONSTANTS AND VARIABLES                              ATM      64
      4     G3=1.-.865*M1                                            ATM      65
            COEF2=PT/PI                                              ATM      66
            COEF3=.865*M1*PT                                         ATM      67
            EXPKAS=1.                                                ATM      68
            FINAL=2                                                  ATM      69
            FIVE3=5./3.                                              ATM      70
            FIVE9=5./9.                                              ATM      71
            HOM=HOM+GL                                               ATM      72
            HTM=HTM+GL                                               ATM      73
            IFLAG=1                                                  ATM      74
            IW=WTHR+2                                                ATM      75
            KAS=0.                                                   ATM      76
            KOUNT=0                                                  ATM      77
            LCOUNT=0                                                 ATM      78
            M=M2                                                     ATM      79
            MSQ=M*M                                                  ATM      80
            OIH=1.05*OI                                              ATM      81
            OIL=.95*OI                                               ATM      82
            PO=1                                                     ATM      83
            ROSQ=RO*RO                                               ATM      84
            R10=RO*10.                                               ATM      85
            SIGSQ=SIGLF**2+SIGHF**2                                  ATM      86
            ZPREV=0.                                                 ATM      87
            SIGMAB=0.3183*M2*LAMDA/(RO*2.)                           ATM      88
            SIGBSQ=SIGMAB*SIGMAB                                     ATM      89
            SIGMA=SQRT(SIGBSQ+SIGSQ)                                 ATM      90
            SIGASQ=SIGMA*SIGMA                                       ATM      91
            SIGMAT=0.                                                ATM      92
            Z=0.                                                     ATM      93
            IF (ITYPE.NE.5) GO TO 5                                  ATM      94
      C                                                              ATM      95
      C     CALCULATE L FOR REVERSE PROPAGATION--OI AND PT KNOWN     ATM      96
            FL=L                                                     ATM      97
            IF (L.GT.0.) GO TO 5                                     ATM      98
            NU=.865*PT*M1-PI*G4*ROSQ*OI                              ATM      99
            L=SQRT(NU/(4.*PI*OI*SIGASQ))                             ATM     100
            IF (DEBUG.EQ.2) WRITE (6,33) NU,L                        ATM     101
            IF (L.LT.R10) L=100.                                     ATM     102
            FL=L                                                     ATM     103
      C                                                              ATM     104
      C     CALCULATE PHI OR HTM                                     ATM     105
      5     CPHI=.FALSE.                                             ATM     106
            IF (PHI.LT.0.) GO TO 6                                   ATM     107
            COSPHI=COS(PHI)                                          ATM     108
            HTM=HOM+L*COSPHI                                         ATM     109
            GO TO 7                                                  ATM     110
      6     CPHI=.TRUE.                                              ATM     111
            HD=HTM-HOM                                               ATM     112
            HDP=ABS(HD)                                              ATM     113
            NHD=1                                                    ATM     114
            IF (HDP.NE.HD) NHD=-1                                    ATM     115
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```
            IF (L.LT.HDP) HD=L*NHD                                  ATM    116
            COSPHI=HD/L                                             ATM    117
            PHI=ACOS(COSPHI)                                        ATM    118
    7       VPSC=VP*((SIN(PHI)*SIN(CHI))**2+COSPHI**2)              ATM    119
            IF (DEBUG.EQ.2) WRITE (6,34) HOM,HTM,PHI                ATM    120
            HTF=3.281*HTM                                           ATM    121
            LT2=L*2.                                                ATM    122
            LT2SO=LT2*LT2                                           ATM    123
            IF (HOM.GT.1E5.AND.HTM.GT.1E5) NSTEP=1                  ATM    124
            NSM1=NSTEP-1                                            ATM    125
    C                                                               ATM    126
    C                                                               ATM    127
    C       GAUSSIAN OR PLANE WAVE                                  ATM    128
            G2=6.54                                                 ATM    129
            IF (PROP.EQ.2) G2=3.58                                  ATM    130
            IF (PROP.EQ.3) G2=4.9                                   ATM    131
            IF (OUT .EQ. 2) WRITE (6,49)                            TCP     23
    C                                                               ATM    132
    C       DECIDE WHICH TYPE OF CALCULATIONS TO DO                 ATM    133
            IF (HOM.LT.1E5) GO TO 9                                 ATM    134
            IF (HTM.LT.1E5) GO TO 8                                 ATM    135
            TYPE=1                                                  ATM    136
            GO TO 11                                                ATM    137
    8       TYPE=3                                                  ATM    138
            GO TO 11                                                ATM    139
    9       IF (HTM.LT.1E5) GO TO 10                                ATM    140
            TYPE=4                                                  ATM    141
            GO TO 11                                                ATM    142
    10      TYPE=2                                                  ATM    143
    11      WRITE (6,35) TYPED(TYPE),TYPEE(TYPE)                    ATM    144
    C                                                               ATM    145
    C       PROPAGATION OR REVERSE PROPAGATION                      ATM    146
            IF (ITYPE.NE.5) GO TO 12                                ATM    147
    C       REVERSE PROPAGATION--OI AND PT KNOWN                    ATM    148
            FINAL=1                                                 ATM    149
    C                                                               ATM    150
    C       REGULAR PROPAGATION                                     ATM    151
    C                                                               ATM    152
    C       COMPUTE STARTING VALUES OF AREA AND INTENSITY           ATM    153
    12      AREA=PI*ROSQ                                            ATM    154
            I=PT/AREA                                               ATM    155
            IP=2.312*I                                              ATM    156
            EXPKAS=1.                                               ATM    157
            KAS=0.                                                  ATM    158
            SIGMAT=0.                                               ATM    159
            PRINT=.FALSE.                                           ATM    160
            IF (OUT.EQ.2.AND.(FINAL.EQ.2.OR.DEBUG.EQ.2)) PRINT=.TRUE.    ATM    161
            IF (PRINT) WRITE (6,36) Z,HOM,SIGMAT,SIGTST,EXPKAS,AREA,I,IP  ATM    162
    C                                                               ATM    163
            GO TO (13,14,15,16), TYPE                               ATM    164
    13      CALL AA (HOM)                                           ATM    165
            GO TO 48                                                ATM    166
    14      CALL HH (HOM)                                           ATM    167
            GO TO 48                                                ATM    168
    15      CALL AH (HOM)                                           ATM    169
            GO TO 48                                                ATM    170
    16      CALL HA (HOM)                                           ATM    171
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```
      C                                                                   ATM   172
      48    IF (ERR) RETURN                                               ATM   173
      C                                                                   ATM   174
            IF (XN.LT.1.E-8) RETURN                                       ATM   175
            IF (TYPE.EQ.1) RETURN                                         ATM   176
            IF (ITYPE.EQ.5) GO TO 22                                      ATM   177
      C                                                                   ATM   178
      C     COMPUTE AND PRINT DISPLACEMENT, ECCENTRICITY AND ISO-INTENSITY ATM  179
      C     CONTOUR DATA.                                                 ATM   180
      C                                                                   ATM   181
            AF=.70710678*ROLD                                             ATM   182
            PTOTAL=PT*XPKAS*(1.-G3)                                       ATM   183
            ETA=ROLD/RO                                                   ATM   184
            ANOM=3.1415926*AF*AF/KIP                                      ATM   185
            ECC=0.3+0.7*KIP                                               ATM   186
            DISP=(-0.692)+SQRT(0.478864-2.6666667*ALOG(KIP))              ATM   187
            DISP=AF*(ETA**(-.29))*DISP                                    ATM   188
            IF (PD .EQ. 0.) WRITE (6,49)                                  TCP    24
            WRITE (6,42) DISP,ECC                                         ATM   189
            GAMMA=1.0                                                     ATM   190
            DGAM=0.1                                                      ATM   191
            DO 17 KGAM=1,9                                                ATM   192
            GAMMA=GAMMA-DGAM                                              ATM   193
            AREA=(-ANOM)*ALOG(GAMMA)                                      ATM   194
            POWER=PTOTAL*(1.-GAMMA)                                       ATM   195
            AVGI=POWER/AREA                                               ATM   196
            WRITE (6,43) GAMMA,AREA,POWER,AVGI                            ATM   197
      17    CONTINUE                                                      ATM   198
      C                                                                   ATM   199
      C     BREAKDOWN POWER AND OPTIMUM POWER CALCULATIONS                ATM   200
      C                                                                   ATM   201
            IF (PD .NE. 0.)WRITE (6,49)                                   TCP    25
            PBD = IBD * PT * KIP / (2.312 * I)                            ATM   202
            PRINT 45, IBD,PBD                                             ATM   203
            PMAX=PT*5.54/XN                                               ATM   204
            XI=I*1.205/(XN*KIP)                                           ATM   205
            IF (PMAX.LE.PBD) GO TO 18                                     ATM   206
            PMAX=PBD                                                      ATM   207
            XI=IBD                                                        ATM   208
      18    PRINT 32, XI,PMAX                                             ATM   209
      C                                                                   ATM   210
      C     EFFECT OF POWER VARIATIONS                                    ATM   211
      C                                                                   ATM   212
            DP=PT*0.1                                                     ATM   213
            DN=XN*0.1                                                     ATM   214
            PP=0.                                                         ATM   215
            YN=0.                                                         ATM   216
            PTOT=I/(KIP*PT)                                               ATM   217
            DO 20 III=1,20                                                ATM   218
            PP=PP+DP                                                      ATM   219
            IF (PP.GT.PBD) GO TO 21                                       ATM   220
            YN=YN+DN                                                      ATM   221
            ZZ=KI(BEAM,YN)                                                ATM   222
            ZN=I*ZZ*YN/(XN*KIP)                                           ATM   223
            ZXXX=ZN*2.312                                                 ATM   224
            FACTOR=CI/ZXXX                                                ATM   225
            IF ((FACTOR.LT.1).AND.(FACTOR.GT.0.1)) GO TO 19               ATM   226
```

```
      PUSE=0.
      AUSE=0.
      GO TO 20
   19 PUSE=PTOT*PP*(1.-FACTOR)
      AUSE=-0.5*AREA*ALOG(FACTOR)/ZZ
   20 PRINT 46, PP,ZN,PUSE,AUSE
   21 PRINT 47, OI
      RETURN
C
C     REFINEMENT LOOP FOR ITYPE 5
C
   22 LCOUNT=LCOUNT+1
      IF (LCOUNT.GT.20) GO TO 31
      IF (FINAL.EQ.2) RETURN
C
C     SELECTION OF NEXT FOCAL LENGTH
      XK=0.7
      RAT=1/OI
      IF (RAT.LT.0.45.OR.RAT.GT.2.22) GO TO 26
      IF (RAT.LT.0.62.OR.RAT.GT.1.6) GO TO 25
      IF (RAT.LT.0.8.OR.RAT.GT.1.25) GO TO 24
      IF (RAT.LT.0.91.OR.RAT.GT.1.1) GO TO 23
      XK=1.0
      GO TO 26
   23 XK=0.95
      GO TO 26
   24 XK=0.9
      GO TO 26
   25 XK=0.8
   26 FL=FL*XK*SQRT(RAT)
      IF (FL.GE.R10) GO TO 27
      KOUNT=KOUNT+1
      IF (KOUNT.GT.2) GO TO 30
      FL=100.
   27 L=FL
      LT2=L*2
      LT2SQ=LT2*LT2
C
C     RECALCULATE PHI OR HTM
      IF (CPHI) GO TO 28
      HTM=HCM+L*COSPHI
      HTM=HTM+GL
      GO TO 29
   28 HD=HTM-HCM
      HDP=ABS(HD)
      NHD=1
      IF (HDP.NE.HD) NHD=-1
      IF (L.LT.HDP) HD=L*NHD
      COSPHI=HD/L
      PHI=ACOS(COSPHI)
   29 IF (DEBUG.EQ.2) WRITE (6,37) FL,HTM,PHI
      IF (I.LT.OIL.OR.I.GT.OIH) GO TO 12
      WRITE (6,38) L
      FINAL=2
      GO TO 12
C
C     RANGE TOO SMALL
```

```
 30     WRITE (6,39)                                                     ATM   284
        ERR=.TRUE.                                                       ATM   285
        RETURN                                                           ATM   286
 C                                                                       ATM   287
 C      TOO MANY TIMES THROUGH THE LOOP                                  ATM   288
 31     WRITE (6,40) LCOUNT,FL,I,OI                                      ATM   289
        ERR=.TRUE.                                                       ATM   290
        RETURN                                                           ATM   291
 C                                                                       ATM   292
 C                                                                       ATM   293
 C                                                                       ATM   294
 32     FORMAT (30X,*MAXIMUM INTENSITY ON TARGET =*,1PE10.2,10X,*ACHIEVED ATM   295
       1AT TELESCOPE POWER =*, E10.2,///,56X,*POWER RANGE AVAILABLE*,//, ATM   296
       2   T10,                                          *TELESCOPE PO ATM   297
       2WER*,T40,*INTENSITY*,T70,*USEFUL POWER*,T100,*OVER AREA*/T10,*(WAT ATM   298
       3TS)*,T40,*(WATTS/M*,4H**2),T70,*(WATTS)*,T1(0,6H(M**2))          ATM   299
 33     FORMAT (//10X,*FOR ITYPE 5,  NU = *,1PE12.5,*, L = *,E12.5)      ATM   300
 34     FORMAT (//10X,6HMOM = ,E12.5,8H, MTM = ,E12.5,8H, PHI = ,E12.5)  ATM   301
 35     FORMAT (//10X,24HCALCULATIONS FOR ORIGIN ,A5,19H 100 KM AND TARGET ATM 302
       1 ,A5,8H 100 KM,)                                                 ATM   303
 36     FORMAT (/,7X,*DISTANCE*,8X,*HEIGHT*,7X,*SIGMAT-LT*,6X,*SIGMAT-ST*, ATM 304
       18X,   *EXPKAS*, 10X,*AREA*,8X,*INTENSITY*,8X,*IPEAK*,/,8X,*METERS* ATM 305
       2,9X,*METERS*,8X,*RADIANS*,8X,*RADIANS*,23X,  *METERS*,3H**2,5X,  ATM   306
       3  *WATTS/M*,3H**2, 5X,*WATTS/M*,3H**2,//,1X,1PHE15.4)            ATM   307
 37     FORMAT (//10X,13HREFINED FL = ,E12.5,8H, HTM = ,E12.5,8H, PHI = ,E ATM 308
       112.5)                                                            ATM   309
 38     FORMAT (10X,19HTARGET RANGE (L) --,1PE10.3,7H METERS/)           ATM   310
 39     FORMAT (//10X,23HREFINED RANGE TOO SMALL)                        ATM   311
 40     FORMAT (//10X,*ITYPE 5 HAS NOT CONVERGED AFTER*,I3,       11H I ATM   312
       1TERATIONS/10X,5HFL = ,E12.5,6H, I = ,E12.5,7H, OI = ,E12.5)      ATM   313
 42     FORMAT(/10X,*DISPLACEMENT = *,F6.3,* METERS*,10X,*ECCENTRICITY = * ATM 314
       1,F6.3,//,37X,*I/IPEAK*,10X,   *AREA*,8X,*CUMULATIVE*,7X,   *AVERAG ATM 315
       1E*,/,37X,  *CONTOUR*,7X,*(METER*,4H**2),7X,   *POWER*,9X,*INTENSIT ATM 316
       2Y*,/)                                                            ATM   317
 43     FORMAT (35X,F6.1,4X,1P3E15.3)                                    ATM   318
 44     FORMAT(/,10X,*PLINE (1) = *,1PE10.2,3X,*PLINE (2) = *,E10.2,3X,  ATM   319
       1*PLINE (3) = *,E10.2,/,10X,*ABL = *,E10.2,9X,*ABE = *,E10.2,9X,  ATM   320
       2*SCL = *,E10.2,9X,*SCE = *,E10.2,//)                             ATM   321
 45     FORMAT(//30X,*BREAKDOWN INTENSITY        =*,1PE10.2,10X,  *ACHIEV TCP   26
       1ED AT TELESCOPE POWER =*,E10.2)                                  ATM   323
 46     FORMAT (T10,1PE10.3,T40,E10.3,T70,E10.3,T100,E10.3)              ATM   324
 47     FORMAT (/,10X, *USEFUL INTENSITY =*,1PE10.3,*WATTS/M*,3H**2)     ATM   325
 49     FORMAT (1H1)                                                     TCP   27
        END                                                              ATM   326
```

```
      SUBROUTINE AA (HOM)
C
C     CALCULATIONS FOR ORIGIN AND TARGET ABOVE 100 KM
C
      LOGICAL EQUAL,ERR,PRINT
      INTEGER BEAM,DEBUG,FINAL,OUT,PO
      REAL I,IRO,KAS,KIP,L,LAMDA,LT2,LT2SQ,MSQ
C
      COMMON /MESH/ XTRA(3),AREA
      COMMON /ERROR/ ERR
      COMMON /ATMS/ BEAM,FL,GL,HTM,IRO,L,LAMDA,NSTEP,PHI
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,RO
      COMMON /SAIM/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
     1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT2SQ,MSQ,NSM1,PI,PO,PRINT,R0SQ,R
     2O,SIGASQ,SIGHSQ,SIGMAT,SIGSQ,ROLD
C
C     CALCULATE RADIUS, AREA, AND INTENSITY
      RSQ=LT2SQ*SIGASQ
      R=SQRT(RSQ)
      AREA=PI*RSQ
      I=COEF3/AREA
      IF (FINAL.NE.2.AND.DEBUG.EQ.1) RETURN
C
C     WRITE RESULTS
      ROLD=R
      IF (OUT.EQ.1) GO TO 1
      WRITE (6,2) L,HOM,I,AREA,R
      RETURN
C
    1 WRITE (6,3) HTM,HTF,L,R,AREA,I
      RETURN
C
C
C
    2 FORMAT (10X,12HABOVE 100 KM/1X,1P2E15.4,5X,2H0.,8X,3E15.4,5X,10H1.
     10000E-00/)
    3 FORMAT (//10X,23HTARGET ALTITUDE (HTM) =,1PE10.3,9H METERS (,E10.3
     1,6H FEET)/10X,42HTARGET RANGE (L)                         =,E9.2,7
     2H METERS,12X,29HRADIUS WITHOUT BLOOMING (R) =,0PF7.2,7H METERS/10X
     3,42HAREA WITHOUT BLOOMING (AREA)            =,1PE10.3,10H METERS*
     4*2,8X,29HTARGET PLANE INTENSITY (I)  =,E11.4,11H WATTS/M**2/)
      END
```

```
      SUBROUTINE AB (HOM)
C
C     CALCULATIONS FOR ORIGIN ABOVE 100 KM AND TARGET BELOW 100 KM
C
      REAL I,L,L1,L2
      REAL IP
      LOGICAL PRINT
      COMMON /ATMS/ BEAM,FL,GL,HTM,IRD,L,LAMDA,NSTEP,PHI
      COMMON /INS/ DEMUG,ITYPE,OUT,PT,RO
      COMMON /SATM/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
     1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT2SO,MSO,NSM1,PI,PO,PRINT,ROSO,R
     210,SIGASO,SIGBSO,SIGMAT,SIGSO,ROLD
      COMMON /MESH/ EXPKAS,L1,NI,AREA
      L1=(1E5-HOM)/COSPHI
      L2=L-L1
C
C     ABOVE 100 KM
C
      RSO=ROSO
      IF (BEAM.EQ.1) RSO=(RO*L2/L)**2
      RSO=RSO+4.*L1*L1*SIGASO
      R=SQRT(RSO)
      AREA=PI*RSO
      L1=(1E5-HOM)/COSPHI
      L2=L-L1
C
C     ABOVE 100 KM
C
      RSO=ROSO
      IF (BEAM.EQ.1) RSO=(RO*L2/L)**2
      RSO=RSO+4.*L1*L1*SIGASO
      R=SQRT(RSO)
      AREA=PI*RSO
      I=PT/AREA
      IP=I*2.312
      IF (PRINT) WRITE (6,1) L1,AREA,I,IP
      HOLD1=FL
      HOLD2=ROSO
      HOLD3=L
      FL=L2
      L=L2
      ROSO=RSO
C
      CALL BB (1.E5)
      FL=HOLD1
C
      ROSO=HOLD2
      L=HOLD3
      RETURN
C
C
C
    1 FORMAT (6X,*ABOVE 100 KM*,/,1X,1PE15.4,5X,*1.0000E+05*,5X,*0.*,13X
     1*0.*,13X,*1.0000E+00*,3E15.4,/)
      END
```

```
      SUBROUTINE RA (HOM)                                                BA    2
C                                                                        BA    3
C     CALCULATIONS FOR ORIGIN BELOW 100 KM, AND TARGET ABOVE 100 KM      BA    4
C                                                                        BA    5
      COMMON /XY/ SIGTST                                                 BA    6
      COMMON /MESH/ EXPKAS,ZPREV,NI,AREA                                 BA    7
      INTEGER DEBUG,FINAL,OUT                                            BA    8
      REAL I,KIP,L,LT2,L1,L2                                             BA    9
      REAL IP                                                            BA   10
      COMMON /ATMS/ REAM,FL,GL,HTM,IRD,L,LANDA,NSTEP,PHI                 BA   11
      COMMON /INS/ DEBUG,ITYPE,OUT,PT,PO                                 BA   12
      COMMON /SAT/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,  BA   13
     1G3,G4,G5,HIF,I,IFLAG,KAS,KIP,LT2,LT2SQ,MSQ,NSM1,PI,PO,PRINT,ROSQ,R BA   14
     2IO,SIGASQ,SIGHSQ,SIGMAT,SIGSQ,ROLD                                 BA   15
C                                                                        BA   16
C                                                                        BA   17
      L1=(1E5-HOM)/COSPHI                                                BA   18
      L2=L-L1                                                            BA   19
C                                                                        BA   20
C     BELOW 100 KM                                                       BA   21
C                                                                        BA   22
      HOLD1=L                                                            BA   23
      HOLD2=HTM                                                          BA   24
      L=L1                                                               BA   25
      HTM=1.E5                                                           BA   26
      WRITE (6,3)                                                        BA   27
C                                                                        BA   28
      CALL RB (HOM)                                                      BA   29
      L=HOLD1                                                            BA   30
C                                                                        BA   31
      HTM=HOLD2                                                          BA   32
C                                                                        BA   33
C     ABOVE 100 KM                                                       BA   34
C                                                                        BA   35
      R=LT2*SQRT(SIGASQ+SIGTSQ)                                          BA   36
      AREA=PI*R*R                                                        BA   37
      BLAREA=AREA/KIP                                                    BA   38
      I=COEF3*EXPKAS*KIP/AREA                                            BA   39
      IF (FINAL.NE.2.AND.DEBUG.EQ.1) RETURN                              BA   40
      IP=I*2.312                                                         BA   41
      WRITE (6,4)                                                        TCP  28
      IF (OUT.EQ.1) GO TO 1                                              TCP  29
      WRITE (6,2) L,HTM,SIGMAT,SIGTST,EXPKAS,BLAREA,I,IP                 BA   44
      RETURN                                                             BA   45
C                                                                        BA   46
    1 WRITE (6,5) HTM,HIF,SIGMAT,L,SIGTST,EXPKAS,R,KIP,I,AREA,IP,BLAREA  BA   47
      RETURN                                                             BA   48
C                                                                        BA   49
C                                                                        BA   50
C                                                                        BA   51
    2 FORMAT (/,1X,1P8E15.4)                                             TCP  30
    3 FORMAT (//,10X,*BELOW  100  KM*)                                   BA   53
    4 FORMAT (//,10X,*ABOVE 100 KM*)                                     BA   54
    5 FORMAT (//,10X,*TARGET ALTITUDE (HTM) =*,1PE10.3,* METERS (*,      BA   55
     1E10.3,* FEET)*,9X,*LONG-TERM TURBULENCE (SIGMAT) =*,E10.3,         BA   56
     2*    RADIANS*,/,10X,*TARGET RANGE (L)                      =*,     BA   57
     3[illegible] *,*LONG-TERM TURBULENCE (SIGTST)=*, E10.3,             BA   58
```

```
      4*     RADIANS*,/,19X,*LINEAR EFFECTS ON TRANSMISSION (EXPKAS)  =*, BA        59
      50PF6.3,19X,*RADIUS WITHOUT BLOOMING (R)   =* ,F7.3,               BA        60
      5*       METERS*,/,10X,                    *NON-LINEAR EFFECTS BA        61
      3ON TRANSMISSION (KIP)  =*,F6.3,19X,*AVERAGE INTENSITY (I)         BA        62
      4=*,1PE11.4,*  WATTS/M*,3H**2/10X,*AREA WITHOUT BLOOMING (AREA)     BA        63
      5          =*,E10.3,* METERS*,3H**2,5X*PEAK INTENSITY (IP)          BA        64
      6 =*,E11.4,*  WATTS/M*,3H**2/10X*AREA WITH BLOOMING (BLAREA)        BA        65
      7        =*,E10.3,* METERS*,3H**2,/)                                BA        66
       END                                                                BA        67
```

```
      SUBROUTINE BB (HOM)
C
C     CALCULATIONS FOR ORIGIN AND TARGET BELOW 100 KM
C
      LOGICAL CNVGGO,ENDED,UNIFRM
      LOGICAL EQUAL,ERR,LESS,PRINT
C
      INTEGER MEAN,DEBUG,FINAL,OUT,PO,ST
      REAL I,IHD,KAS,KI,KIP,L,LAMDA,LT2,LT2SQ,MSQ,N,NAJ,NI,IP,MI,M2,M
C
      COMMON /MESH/ EXPKAS,ZPHFV,NI,AREA
      COMMON /ERROR/ EPR
      COMMON /ATMS/ MEAN,FL,GL,HTM,IHD,L,LAMDA,NSTEP,PHI
      COMMON /INS/ DEBUG,ITYPE,OUT,PI,RO
      COMMON /SATM/ COEF1,COEF2,COEF3,COSPHI,EQUAL,FINAL,FIVE3,FIVE9,G2,
     1G3,G4,G5,HTF,I,IFLAG,KAS,KIP,LT2,LT2SQ,MSQ,NSM1,PI,PC,PRINT,R0SQ,R
     210,SIGASQ,SIGMSQ,SIGMAT,SIGSQ,HOLD
      COMMON /ATMIN/ M,DI,PROP,SIGLF,SIGMF,WTHR,MI,M2
      COMMON /AY/ SIGIST
C
      LOGICAL OK
C
      DIMENSION UG10P(5), OG10W(5)
      DIMENSION SVSTSQ(50)
C
      DATA UG10P/.4859533,.4325317,.3397048,.2166977,.07443717/
      DATA OG10W/.03333567,.07472567,.1095432,.1346334,.14773717/
      DELTAZ=L/NSTEP
C
C     COMPARE STARTING Z WITH R0*10
      DO 1 K=1,NSM1
      KJ=K
      Z=DELTAZ*K
      IF (Z.GE.R10) GO TO 2
    1 CONTINUE
      WRITE (6,22) Z,R10
      ERR=.TRUE.
      RETURN
C
    2 LESS=.FALSE.
      IF (HTM.LT.HOM) LESS=.TRUE.
      Y=0.
      RHOINT=0.
      OK=.TRUE.
      CALL ALFSET (NLAM,LAM)
      DZ=DELTAZ*0.1
      DH=DZ*COSPHI
      HH=DH-DH*0.5
      TEMP2=1./FLOAT(NSTEP)
      TEMPK=6.495/LAMDA**0.4
      TEMP7=1.439*(LAMDA/6.28319)**1.2
C
C     LINEAR LOOP
C
      DO 4 J=KJ,NSTEP
      NAJ=FLOAT(NSTEP-J)*TEMP2
      TEMP1=NAJ+0.5*TEMP2
```

```
      Z=DELTAZ*J
      Z1=DELTAZ*(J-1)
      IF (LESS) GO TO 3
C
C     SHOOTING UP
      HL=Z1*COSPHI+HOM
      HU=Z*COSPHI+HOM
      HO=HU
      GO TO 4
C
C     SHOOTING DOWN
3     HL=Z*COSPHI+HOM
      HU=Z1*COSPHI+HOM
      HO=HL
C
C     TURBULENCE CALCULATIONS
C
4     ZJL=Z/L
      CG10A=0.5*(HL+HU)-GL
      DG10B=HL-HU
      DO 5 IDG10=1,5
      TEMP3=DG10P(IDG10)
      DG10C=TEMP3*DG10B
      TEMP3=TEMP3*TEMP2
      TEMP6=WG10*(IDG10)*DELTAZ
      TEMP4=CHSQ(DG10A+DG10C)*TEMP6
      TEMP5=CHSQ(DG10A-DG10C)*TEMP6
      RHOINT=RHOINT+TEMP4+TEMP5
5     Y=Y+TEMP4*(TEMP1-TEMP3)**FIVE3+TEMP5*(TEMP1+TEMP3)**FIVE3
      RHOTT=(1./RHOINT)**.6
      FAC=1.-0.37*(TEMP7*RHOTT/(RO*RO))**0.3333333333
      SIGTSQ=TEMPX*Y**1.2
      SYSTSQ(J)=SIGTSQ*(FAC*FAC)**2
      SIGTST=SQRT(SYSTSQ(J))/2.
      IF (PRINT) SIGMAT=SQRT(SIGTSQ)
C
      RC=ABS(FL-Z)/FL
      RCSQ=RC*RC*ROSQ
      Z4=4.*(Z*ZH+EV)**2
      P=SQRT(G4*RCSQ+G5*RCSQ+Z4*(SIGGSQ+SIGTSQ+SIGSQ))
      PSQ=P*P
      DO 6 JJ=1,10
      HH=HH+DH
6     EAPKAS=ALFKAS(DZ,HH,DK)
      COEF=COEF2*(1.-G3*ZJL)
      I=COEF*EAPKAS/RSQ
      IP=2.312*I
      IF (IP.LT.1.0) GO TO 7
C
C     I GREATER THAN I BREAKDOWN, WRITE AND RETURN
      WRITE (6,23) Z,IPD
      ERR=.TRUE.
      RETURN
C
7     AREA=PI*RSQ
C
C     WRITE OUTPUT
```

```
      IF (PRINT) WRITE (6,24) Z,HO,SIGMAT,SIGTST,EXPKAS,AREA,I,IP
    8 CONTINUE
C
      ROLD=R
      FINDTO=1./DELTAZ
C
C     START COMPUTATION OF BLOOMING LOSSES
C
      ENDED=.FALSE.
      CNVRGD=.FALSE.
      HOM=HOM
      SIGMAT=SQRT(SIGTSQ)
      CALL ALFSET (NLAM,LAM)
      TEMP3=(SIGHF+SIGHF)**2+4.*SIGBSQ
      TEMP4=G4*ROSQ
      TEMP5=G5*ROSQ
      UNIFRM=.FALSE.
      RSQ=TEMP4+TEMP5+TEMP3*ZPREV**2
C
C     CALCULATIONS FOR Z = R * 10
C
      DZ=R10
      HDZ=DZ*0.5
      TFDZ=DZ*0.0416666666667
      DZFL=DZ/FL
      TEMP1=DZ*COSPHI
      DZSQ=DZ*DZ
      TEMP6=G3*DZ/L
      GPREV=GALTIN(HOM)*ALFFAC(0.,HOM,OK)/(VX(GL,HOM,HOM,PHI,0.)*RSQ)
      Z=DZ
      H=HOM+TEMP1
      G3TRM=1.-TEMP6
      RC=1.-DZFL
      RSQ=TEMP4+TEMP5*RC**2+(TEMP3+SVSTSQ(KJ))*(Z+ZPREV)**2
      GCURR=GALTIN(H)*ALFFAC(DZ,H,OK)*G3TRM/(VX(GL,H,HOM,PHI,Z)*RSQ)
      XCURR=DZSQ*(-0.5*GPREV-(GPREV-GCURR)*0.0416666666667)/SQRT(RSQ)
      NI=XCURR
      G=(GCURR+GPREV)*HDZ
      GUESS=GCURR+GCURR-GPREV
C
C     CALCULATIONS FOR NEXT INTERVAL
C
    9 Z=Z+DZ
      IF (Z.GE.L) GO TO 16
   10 H=H+TEMP1
      G3TRM=G3TRM-TEMP6
      RC=RC-DZFL
      TOIND=Z*FINDTO+1.
      INDTO=TOIND
      IF (INDTO.GE.NSTEP) INDTO=NSTEP-1
      SIGTSQ=SVSTSQ(INDTO)
      SIGTSQ=SIGTSQ+(TOIND-FLOAT(INDTO))*(SVSTSQ(INDTO+1)-SIGTSQ)
      RSQ=TEMP4+TEMP5*RC**2+(TEMP3+SIGTSQ)*(Z+ZPREV)**2
      GNEW=GALTIN(H)*ALFFAC(DZ,H,OK)*G3TRM/(VX(GL,H,HOM,PHI,Z)*RSQ)
      IF (ABS(GNEW).LT.1.E-40) GO TO 12
      OK=.FALSE.
C
```

```
C     CHECK ACCURACY OF LINEAR EXTRAPOLATION
C
      DEVIAT=ABS((GNEW-GUESS)/GUESS)
      IF (DEVIAT.GT.0.05) GO TO 15
      OK=.TRUE.
      RSOHLD=RSQ
      G=G+GNEW*DZ
      XPREV=XCURR
      XCURR=DZ*((HDZ*GNEW-G)-(GCURR-GNEW)*TFDZ)/SQRT(RSQ)
      NI=NI+XCURR
      IF (ENDED) GO TO 17
      IF (DEVIAT.LT.0.01) GO TO 12
   11 GPREV=GCURR
      GCURR=GNEW
      GUESS=GCURR+GCURR-GPREV
      UNIFRM=.TRUE.
      GO TO 9
   12 IF (CNVRGD) GO TO 11
C
C     INCREASE SIZE OF INTERVAL
C
   13 CONTINUE
      HDZ=DZ
      DZ=DZ+DZ
      UNIFRM=.FALSE.
      IF ((Z+DZ).GE.L) GO TO 14
      TFDZ=TFDZ+TFDZ
      DZFL=DZFL+DZFL
      TEMP1=TEMP1+TEMP1
      TEMP6=TEMP6+TEMP6
      GCURR=GNEW
      GUESS=GCURR+GCURR-GPREV
      GO TO 9
C
C     FINAL INTERVAL
C
   14 CNVRGD=.TRUE.
      FRACT=(L-Z)/DZ
      IF (FRACT.LT.5.E-4) GO TO 17
      DZ=(L-Z)*0.5
      HDZ=DZ*0.5
      TFDZ=DZ*0.0416666666667
      DZFL=DZFL*FRACT
      TEMP1=TEMP1*FRACT
      TEMP6=TEMP6*FRACT
      GUESS=(GNEW-GCURR)*FRACT+GNEW
      GPREV=GNEW+GNEW-GUESS
      GCURR=GNEW
      GO TO 9
C
C     TRY EXPONENTIAL EXTRAPOLATION
C
   15 DEVIAT=ABS(GCURR**2/(GPREV*GNEW)-1.)
      IF (DEVIAT.LT.0.05) GO TO 19
      IF (DZ.LT.0.01) GO TO 19
      CNVRGD=.FALSE.
      ENDED=.FALSE.
```

```
C
C     INTERVAL MUST BE REDUCED
C
      H=H-TEMP1
      G3TRM=G3TRM+TEMP6
      RC=RC+DZFL
      Z=Z-DZ
      DZ=HDZ
      HDZ=DZ*0.5
      TFDZ=DZ*0.0416666666667
      DZFL=DZFL*0.5
      TEMP1=TEMP1*0.5
      TEMP6=TEMP6*0.5
      GPREV=(GCURR+GPREV)*0.5
      GUESS=GCURR+GCURR-GPREV
      GO TO 9
C
   16 FRACT=(L-Z+DZ)/DZ
      IF (FRACT.LT.1.E-3) GO TO 17
      IF (ABS(FRACT-1.).LE.1.E-3) GO TO 10
      UNIFRM=.FALSE.
      DZ=L-Z+DZ
      HDZ=DZ*0.5
      TFDZ=DZ*0.0416666666667
      DZFL=DZFL*FRACT
      TEMP1=TEMP1*FRACT
      TEMP6=TEMP6*FRACT
      GUESS=(GCURR-GPREV)*FRACT+GCURR
      GPREV=GCURR+GCURR-GUESS
      ENDED=.TRUE.
      CNVPGD=.TRUE.
      Z=L
      GO TO 10
   17 IF (UNIFRM) NI=NI-0.5*XCURR-(XCURR-XPREV)*0.04166666667
      NI=G2*COEF2*ABS(NI)
      NI=NI*(77.6+5.84E-13/LAMDA**2)/(77.6+5.84E-13/1.1236E-10)
      SIGTSQ=SIGMAT**2
C
C     CALCULATION OF INTENSITY WITH BLOOMING
      KIP=KI(BEAM,ABS(NI))
      I=I*KIP
      IP=2.312*I
      ROLDSQ=ROLD*ROLD
      BLAREA=PI*ROLDSQ/KIP
      IF (FINAL.NE.2.AND.DEBUG.EQ.1) RETURN
      IF (OUT.EQ.1) GO TO 18
      WRITE (6,25) NI,KIP,BLAREA,I,IP
      RETURN
C
   18 WRITE (6,26) HTM,HTF,SIGMAT,L,SIGTST,EXPKAS,R,KIP,I,AREA,IP,BLAREA
      RETURN
   19 UNIFRM=.FALSE.
      OK=.TRUE.
      GOLD=G/SQRT(RSQHLD)
      RSQHLD=RSQ
      G=G+(GNEW-GCURR)*DZ/ALOG(GNEW/GCURR)
      TEMP=G/SQRT(RSQ)
```

```
      XPREV=XCURR
      XCURR=D7*(GOLD-TEMP)/ALOG(TEMP/GOLD)
      NI=NI+XCURR
      IF (ENDED) GO TO 17
      IF (DEVIAT.LT.0.01) GO TO 21
   20 GPREV=GCURR
      GCURR=GNEW
      GUESS=GCURR+GCURR-GPREV
      GO TO 9
   21 IF (CNVRGD) GO TO 20
      GO TO 13
C
C
C
   22 FORMAT (59H THE LENGTH OF THE BEAM PATH IS LESS THAN 10 TIMES R0,
     1Z = 1PE10.3,7H R10 = E10.3)
   23 FORMAT(/10X*INTENSITY HAS REACHED BREAKDOWN, Z(J) = *,1PE10.3,* IB
     1D = *,E10.3)
   24 FORMAT (1X,1P8E15.4)
   25 FORMAT (///,* NI = *,1PE12.5,8X,*KIP = *,E12.5,8X,*BLAREA = *,
     1E12.5,8X,*IAVL = *,E12.5,8X,*IPEAK = *,E12.5,/)
   26 FORMAT (//,10X,*TARGET ALTITUDE (HTM) =*,1PE10.3,* METERS (*,
     1E10.3,* FEET)*,9X,*LONG-TERM TURBULENCE (SIGMAT) =*,E10.3,
     2*     RADIANS*,/,10X,*TARGET RANGE (L)                        =*,
     3E9.2,* METERS*,9X,*SHORT-TERM TURBULENCE (SIGTST)=*, E10.3,
     4*     RADIANS*,/,10X,*LINEAR EFFECTS ON TRANSMISSION (EXPKAS)  =*,
     50PF6.3,19X,*RADIUS WITHOUT BLOOMING (R)   =* ,F7.3,
     5*          METERS*,/,10X,                     *NON-LINEAR EFFECTS
     3 ON TRANSMISSION (KIP) =*,F6.3,19X,*AVERAGE INTENSITY (I)
     4=*,1PE11.4,*  WATTS/M*,3H**2/10X,*AREA WITHOUT BLOOMING (AREA)
     5        =*,E10.3,* METERS*,3H**2,5X*PEAK INTENSITY (IP)
     6 =*,E11.4,*  WATTS/M*,3H**2/10X*AREA WITH BLOOMING (BLAREA)
     7        =*,E10.3,* METERS*,3H**2,/)
      END
```

```
      SUBROUTINE ALFSET (NL,IL)                                   SET     2
C                                                                 SET     3
C     POWER RATIOS FOR MULTILINE PROPAGATION                      SET     4
C                                                                 SET     5
      COMMON /ALFDTA/ P(3),RHOFAC,PLINE(3)                        SET     6
      COMMON /ALFA/ LAM,RH                                        SET     7
C                                                                 SET     8
      IF (LAM.EQ.2) GO TO 1                                       SET     9
      P(1)=1.                                                     SET    10
      RETURN                                                      SET    11
1     DO 2 I=1,3                                                  SET    12
2     P(I)=PLINE(I)                                               SET    13
      IF (RH.EQ.0.) RH=1.E-6                                      SET    14
      RHOFAC=0.9446*RH-1.                                         SET    15
      RETURN                                                      SET    16
      END                                                         SET    17
```

```
      FUNCTION ALFFAC (DZ,H,OK)                                         FAC    2
C                                                                       FAC    3
C     MULTI-LINE POWER LOSSES                                           FAC    4
C                                                                       FAC    5
      LOGICAL OK                                                        FAC    6
      COMMON /ALFDTA/ P(3),RHOFAC                                       FAC    7
      COMMON /ALFA/ LAM,RH                                              FAC    8
      DIMENSION POLD(3)                                                 FAC    9
C                                                                       FAC   10
      IF (LAM.EQ.2) GO TO 3                                             FAC   11
      IF (OK) GO TO 1                                                   FAC   12
      P(1)=POLD(1)                                                      FAC   13
      GO TO 2                                                           FAC   14
    1 POLD(1)=P(1)                                                      FAC   15
    2 TEMP=P(1)*EXP(-ALFAEX(H)*DZ)                                      FAC   16
      P(1)=TEMP                                                         FAC   17
      ALFFAC=ALFAAB(H)*TEMP                                             FAC   18
      RETURN                                                            FAC   19
C                                                                       FAC   20
    3 IF (OK) GO TO 5                                                   FAC   21
      DO 4 I=1,3                                                        FAC   22
    4 P(I)=POLD(I)                                                      FAC   23
      GO TO 7                                                           FAC   24
    5 DO 6 I=1,3                                                        FAC   25
    6 POLD(I)=P(I)                                                      FAC   26
C                                                                       FAC   27
    7 ASSIGN 17 TO J1                                                   FAC   28
      ASSIGN 20 TO J2                                                   FAC   29
      ASSIGN 23 TO J3                                                   FAC   30
      ASSIGN 12 TO J4                                                   FAC   31
    8 SUM=0.                                                            FAC   32
C                                                                       FAC   33
      IF (H.GT.13500.) GO TO 11                                         FAC   34
      IF (H.GT.9500.) GO TO 10                                          FAC   35
      IF (H.GT.5000.) GO TO 9                                           FAC   36
      ALFAS=3.6E-6*EXP(4.1056*RH-H*0.83333333333333E-3)                 FAC   37
      GO TO 16                                                          FAC   38
    9 ALFAS=9.3096E-6*EXP(4.1056*RH-H*1.031E-3)                         FAC   39
      GO TO 16                                                          FAC   40
   10 ALFAS=4.32E-10*EXP(4.1056*RH)                                     FAC   41
      GO TO 16                                                          FAC   42
C                                                                       FAC   43
C     CALCULATIONS FOR H GREATER THAN 13500 METERS                      FAC   44
   11 XTRA=EXP(-ALFAEX(H)*DZ)                                           FAC   45
      GO TO J4(12,14)                                                   FAC   46
   12 AS=ALFAAH(H)                                                      FAC   47
      DO 13 I=1,3                                                       FAC   48
      TEMP=P(I)*XTRA                                                    FAC   49
      P(I)=TEMP                                                         FAC   50
   13 SUM=SUM+TEMP*AS                                                   FAC   51
      ALFFAC=SUM                                                        FAC   52
      RETURN                                                            FAC   53
C                                                                       FAC   54
   14 DO 15 I=1,3                                                       FAC   55
      TEMP=P(I)*XTRA                                                    FAC   56
      P(I)=TEMP                                                         FAC   57
   15 SUM=SUM+TEMP                                                      FAC   58
```

```
          ALFFAC=SUM                                                     FAC   59
          RETURN                                                         FAC   60
C                                                                        FAC   61
16        RHOSTR=1.+RHOFAC*EXP(-H*(6.738E-5+9.61E-9*H))                 FAC   62
          AS=RHOSTR*EXP(-10.047+H*(-6.388E-4+H*2.25E-8))                 FAC   63
          IF (H .GT. 8000) AS = EXP(-(((RH*.9471)+ 10.37917)+((4.6303E-4-(RH TCP   32
         1*1.62515E-4))*H)))                                              TCP   33
          AB3 = AS                                                       TCP   34
          AS3 = ALFAS                                                    TCP   35
          TEMP=P(1)*EXP(-(AS+ALFAS)*DZ)                                  FAC   64
          P(1)=TEMP                                                      FAC   65
C                                                                        FAC   66
          GO TO J1(17,18)                                                FAC   67
17        SUM=SUM+AS*TEMP                                                FAC   68
          GO TO 19                                                       FAC   69
18        SUM=SUM+TEMP                                                   FAC   70
19        AS=RHOSTR*EXP(-10.082+H*(-6.952E-4+H*1.55E-8))                 FAC   71
          IF (H .GT. 8000) AS = EXP (-(((RH*.9474)+12.6721)+((2.9317E-4-(RH* TCP   36
         11.62515E-4))*H)))                                               TCP   37
          AB4 = AS                                                       TCP   38
          AS4 = ALFAS                                                    TCP   39
          TEMP=P(2)*EXP(-(AS+ALFAS)*DZ)                                  FAC   72
          P(2)=TEMP                                                      FAC   73
C                                                                        FAC   74
          GO TO J2(20,21)                                                FAC   75
20        SUM=SUM+AS*TEMP                                                FAC   76
          GO TO 22                                                       FAC   77
21        SUM=SUM+TEMP                                                   FAC   78
22        AS=EXP(-9.948+H*(-2.199E-4-H*1.96E-9))                         FAC   79
          IF(H .GT. 8000) AS=EXP(-(((RH*1.813)+4.8547)+((8.7225E-4-(RH*2.266 TCP   40
         17E-4))*H)))                                                     TCP   41
          AB2 = AS                                                       TCP   42
          AS2 = ALFAS                                                    TCP   43
          TEMP=P(3)*EXP(-(AS+ALFAS)*DZ)                                  FAC   80
          P(3)=TEMP                                                      FAC   81
C                                                                        FAC   82
          GO TO J3(23,24)                                                FAC   83
23        ALFFAC=SUM+AS*TEMP                                             FAC   84
          RETURN                                                         FAC   85
24        ALFFAC=SUM+TEMP                                                FAC   86
          RETURN                                                         FAC   87
C                                                                        FAC   88
          ENTRY ALFKAS                                                   FAC   89
C                                                                        FAC   90
          IF (LAM.EQ.2) GO TO 25                                         FAC   91
          TEMP=P(1)*EXP(-ALFAEX(H)*DZ)                                   FAC   92
          P(1)=TEMP                                                      FAC   93
          ALFFAC=TEMP                                                    FAC   94
          RETURN                                                         FAC   95
C                                                                        FAC   96
25        ASSIGN 18 TO J1                                                FAC   97
          ASSIGN 21 TO J2                                                FAC   98
          ASSIGN 24 TO J3                                                FAC   99
          ASSIGN 14 TO J4                                                FAC  100
          GO TO 8                                                        FAC  101
C                                                                        FAC  102
          END                                                            FAC  103
```

```
      FUNCTION ALFAAB (H)
C
C     SINGLE LINE ABSORPTION COEFFICIENTS IN 1/M
C
      COMMON /ALFA/ LAM,RH
      COMMON /ALFDTA/ DUMMY(7),ABL,ABE
C
      HF=3.281*H
      CALL MEGAIR (HF,TR,PMB,[illegible])
      P=0.359*PMB/0.476802[illegible]
      T=TR*5.0/9.0
      PW=6.0724E-10*RH*P*EXP(0.0[illegible]
      GO TO (1,5,8,11), LAM
C
C     LA[illegible]DA IS 10.6
C
    1 IF ([illegible]H.GT.16000.0) GO TO [illegible]
      ALF[illegible]O2=7.99577416E-5-2.10[illegible]62795E-9*H-3.57576007E-12*H*H+1.07366914
     1E-15*H**3-1.69645494E-19*H**4+1.50364450E-23*H**5-7.16578722E-28*H
     2*[illegible]+1.61586924E-32*H**7-1.13662124E-37*H**8
      G[illegible] 4
C
    2 IF [illegible].GT.55000.0) GO TO 3
      ALFCO2=7.67462668E-[illegible]-1.89713935E-7*H+1.98650379E-11*H*H-1.14976017
     1E-15*H**3+4.04716134E-20*H**4-8.90401506E-25*H**5+1.19826061E-29*H
     2**6-9.03345045E-35*H**7+2.92529072E-40*H**8
      GO TO 4
C
    3 ALFCO2=1.0E-7*EXP(-1.74E-4*H+12.18)
C
    4 ALFH2O=4.32E-9*PW*(P+193.0*PW)
      ALFAAB=ALFCO2+ALFH2O
      RETURN
C
C     LAMDA IS 3.8
C
    5 ALFH2O=5.4E-6*PW
      IF (PW.GE.0.2) ALFH2O=-5.923E-7+8.3633E-6*PW+3.1184E-8*PW*PW
C
      IF (H.GT.7500.0) GO TO 6
      ALFCO2=1.848E-6*EXP(-2.272E-4*H)
      GO TO 7
C
    6 ALFCO2=4.25E-6*EXP(-3.36E-4*H)
C
    7 ALFA[illegible]=ALFH2O+ALFCO2
      RETURN
C
C     LAMDA IS 5.0
C
    8 IF (PW.GT.4.5E-4) GO TO 9
      AAA=1.9222
      BBB=1.4032
      GO TO 10
    9 AAA=1.14256
      BBB=-4.6052
   10 ALFAAB=(1.E-3)*EXP(AAA*ALOG(PW)+BBB)
```

```
                RETURN
           C
60         C    INSERT EQUATIONS FOR OTHER WAVELENGTHS HERE
           C
           11   ALFAAB=ABL*EXP(-ABE*H)
                RETURN
                END
```

```
      FUNCTION ALFAEX (H)                                              AEX    2
C                                                                      AEX    3
C     THIS ROUTINE CALCULATES THE EXTINCTION COEFFICIENT IN 1/M       AEX    4
C                                                                      AEX    5
      COMMON /ALFA/ LAM,RH                                             AEX    6
      COMMON /ALFDTA/ DUMMY(7),ABL,ABE,SCL,SCE                         AEX    7
C                                                                      AEX    8
      GO TO (1,2,3,10), LAM                                            AEX    9
C                                                                      AEX   10
C     LAMDA IS 10.6                                                    AEX   11
C                                                                      AEX   12
    1 ALFAS0=1.0E-6*EXP(4.75*RH)                                       AEX   13
      GO TO 4                                                          AEX   14
C                                                                      AEX   15
C     LAMDA IS 3.8                                                     AEX   16
C                                                                      AEX   17
    2 ALFAS0=3.6E-6*EXP(4.1056*RH)                                     AEX   18
      GO TO 4                                                          AEX   19
C                                                                      AEX   20
C     INSERT EQUATIONS FOR OTHER WAVELENGTHS HERE                      AEX   21
C                                                                      AEX   22
C                                                                      AEX   23
C     LAMDA IS 5.0                                                     AEX   24
C                                                                      AEX   25
    3 ALFAS0=3.E-6*EXP(4.2*RH)                                         AEX   26
C                                                                      AEX   27
C     THE REST OF THE FUNCTION IS INDEPENDENT OF LAMDA                 AEX   28
C                                                                      AEX   29
    4 IF (H.GT.13500.0) GO TO 7                                        AEX   30
      IF (H.GT.9500.0) GO TO 6                                         AEX   31
      IF (H.GT.5000.0) GO TO 5                                         AEX   32
      ALFAS=ALFAS0*EXP(-H/1.2E+3)                                      AEX   33
      GO TO 9                                                          AEX   34
C                                                                      AEX   35
    5 ALFAS=ALFAS0*2.586*EXP(-H*1.031E-3)                              AEX   36
      GO TO 9                                                          AEX   37
C                                                                      AEX   38
    6 ALFAS=ALFAS0*1.2E-4                                              AEX   39
      GO TO 9                                                          AEX   40
C                                                                      AEX   41
    7 IF (H.GT.25000.0) GO TO 8                                        AEX   42
      ALFAS=ALFAS0*(-3.251E-3+3.738E-7*H-9.4557E-12*H*H)               AEX   43
      GO TO 9                                                          AEX   44
C                                                                      AEX   45
    8 ALFAS=ALFAS0*1.8E-3*EXP(-1.535E-4*(H-25000.))                    AEX   46
      ALFAS = ALFAS/9.7725                                             TCP   44
    9 ALFAEX=ALFAS+ALFAAR(H)                                           AEX   47
      RETURN                                                           AEX   48
C                                                                      AEX   49
C     USER SPECIFIED COMPUTATION                                       AEX   50
   10 ALFAEX=ABL*EXP(-ABE*H)+SCL*EXP(-SCE*H)                           AEX   51
      RETURN                                                           AEX   52
      END                                                              AEX   53
```

```
      FUNCTION CNSO (H)
C
C     ATMOSPHERIC STRUCTURE CONSTANT IN M**(2/3)
C
      COMMON /CNVW/ IW
C
      IF (H.GE.1.0) GO TO 4
C
C     SET CNSO FOR ALTITUDES LESS THAN 1 METER
C
      GO TO (1,2,3), IW
C
C     BAD WEATHER CONDITIONS
1     CNSO=2.85E-13
      RETURN
C
C     NOMINAL WEATHER CONDITIONS
2     CNSO=1.0E-13
      RETURN
C
C     GOOD WEATHER CONDITIONS
3     CNSO=8.5E-15
      RETURN
C
C     CALCULATE CNSO FOR ALTITUDES AT OR ABOVE 1 METER
C
4     GO TO (5,9,10), IW
C
C     BAD WEATHER CONDITIONS
5     IF (H.GT.100.0) GO TO 7
      IF (H.GT.10.0) GO TO 6
      CNSO=2.9E-13*H**(-0.6993)
      RETURN
C
6     CNSO=9.496E-13*H**(-1.214)
      RETURN
C
7     IF (H.GT.1.0E4) GO TO 8
      CNSO=2.56E-12*H**(-1.4386)
      RETURN
C
8     IF (H.GT.1.5E4) GO TO 9
      CNSO=2.0E-16
      RETURN
C
C     NOMINAL WEATHER CONDITIONS
9     CNSO=2.0E-16
      IF (H.LE.11600..OR.H.GE.12600.) CNSO=1E-13*H**(-1.07535)
      RETURN
C
C     GOOD WEATHER CONDITIONS
10    IF (H.GT.2.5E3) GO TO 12
      IF (H.GT.20.0) GO TO 11
      CNSO=8.580E-15*H**(-0.4444)
      RETURN
C
11    CNSO=1.51E-13*H**(-1.396)
```

```
          RETURN                                CN2   59
C                                               CN2   60
12        IF (M.GT.1.5E4) GO TO 9               CN2   61
          CNSO=3.0E-18                          CN2   62
          RETURN                                CN2   63
          END                                   CN2   64
```

```
      REAL FUNCTIONKI(BEAM,X)
C
C     COMPUTES THE INTENSITY RATIO
C
      IF (X.GT.0.1) GO TO 1
      KI=1.0
      RETURN
C
    1 X2=X*X
      IF (BEAM.EQ.0) GO TO 5
C
C     FOCUSED BEAM
C
      X32=X**1.5
      X15=X**.2
      IF (X.GT.1.0) GO TO 2
      KI=.176*X32+.169/X15+.733*EXP(-X2)
      RETURN
C
    2 IF (X.GT.2.0) GO TO 3
      KI=-.176*X+.793
      RETURN
C
    3 IF (X.GT.100.0) GO TO 4
      X5=X2*X2*X
      X34=X**.75
      KI=-1.67/X5+6.3/X32+2.42/X34-12.9/(X2+1)-1.71*ALOG(X)/X
      RETURN
C
    4 KI=EXP(-2.445*ALOG(X)+5.378)
      RETURN
C
C     COLLIMATED BEAM
C
    5 X4=X2*X2
      IF (X.GE.5.0) GO TO 6
      X12=X**.5
      X13=X**(1./3.)
      X34=X**.75
      KI=-4.14E-4*X4-2.99E-5/X4+.598*X13-.385/X12+.4/X34
      RETURN
C
    6 KI=EXP(-2.163*ALOG(X)+3.145)
      RETURN
      END
```

```
      FUNCTION GALTIN (H)
C
C     ALTITUDE DEPENDENT PARAMETERS FOR THE BLOOMING CALCULATION--CHANGE
C     IN REFRACTIVE INDEX FOR A GIVEN TEMPERATURE CHANGE DIVIDED BY THE
C     REFRACTIVE INDEX,DENSITY,AND SPECIFIC HEAT.
C
      DIMENSION FAC(101)
      DATA FAC/-.772408,-.791416,-.811310,-.832196,-.854079,-.877084,-.9
     101245,-.926778,-.953667,-.982071,-1.012121,-1.043965,-1.044585,-1.
     2044595,-1.044604,-1.044612,-1.044619,-1.044624,-1.044629,-1.044633
     3,-1.044637,-1.039437,-1.034973,-1.030055,-1.025163,-1.020354,-1.01
     45573,-1.010834,-1.006138,-1.001465,-.996875,-.992306,-.987774,-.97
     55583,-.964385,-.952478,-.940852,-.929446,-.918402,-.907560,-.89696
     62,-.886650,-.876466,-.866553,-.856854,-.847361,-.838069,-.829971,-
     7.825851,-.825851,-.825851,-.825851,-.825851,-.829522,-.833576,-.84
     82564,-.849220,-.855941,-.862854,-.869820,-.876492,-.884077,-.89440
     99,-.909420,-.924922,-.940929,-.957444,-.974563,-.992244,-1.010561,
     $-1.029425,-1.044112,-1.069470,-1.090583,-1.112507,-1.135271,-1.154
     5946,-1.183577,-1.209224,-1.235951,-1.263549,-1.263549,-1.263549,-1
     $.263549,-1.263549,-1.263549,-1.263549,-1.263549,-1.263549,-1.26354
     $9,-1.263458,-1.242521,-1.221822,-1.202361,-1.183508,-1.165236,-1.1
     $47517,-1.130327,-1.113643,-1.097443,-1.081111/
C
      IF (H.GE.1.E5) GO TO 1
      IH=H*1.E-3
      DH=(H-FLOAT(IH)*1.E3)*1.E-3
      IH=IH+1
      IF (IH.LE.1) IH=2
      GALTIN=(FAC(IH)+(FAC(IH+1)-FAC(IH))*DH)*1.E-9
      RETURN
C
    1 GALTIN=FAC(101)*1.E-9
      RETURN
C
      END
```

```
      SUBROUTINE MEGAIR (H,TM,PMB,D,G)                                  MEG       2
C                                                                       MEG       3
C     ************************************************************      MEG       4
C     *                                                          *      MEG       5
C     *  *     *  *****  *****  *****  *****  *****   ***      *      MEG       6
C     *  **   **  *      *      *   *    *    *   *  *   *     *      MEG       7
C     *  * * * *  *      *      *   *    *    *   *     *     *      MEG       8
C     *  *  *  *  *      *      *   *    *    *   *    *      *      MEG       9
C     *  *     *  ****   * ***  *****    *    *****   *       *      MEG      10
C     *  *     *  *      *   *  *   *    *    * *    *        *      MEG      11
C     *  *     *  *      *   *  *   *    *    *  *  *         *      MEG      12
C     *  *     *  *****  *****  *   *  *****  *   * *****     *      MEG      13
C     *                                                          *      MEG      14
C     ************************************************************      MEG      15
C                                                                       MEG      16
C        MEGAIR2 CALCULATES ATMOSPHERE PARAMETERS (SPECIFICALLY         MEG      17
C     GEOPOTENTIAL HEIGHT, TEMPERATURE, PRESSURE, DENSITY,              MEG      18
C     GRAVITATIONAL ACCELERATION, AND THE SPEED OF SOUND) FROM          MEG      19
C     GEOMETRIC HEIGHT.                                                 MEG      20
C        MEGAIR2 ACCEPTS HEIGHTS IN ANY ORDER AND WORKS EQUALLY WELL    MEG      21
C     WITH ORDERED OR RANDOM VALUES.                                    MEG      22
C        MEGAIR2 ACCEPTS VALUES OF H FROM -16500 FEET TO 320000 FEET.   MEG      23
C     ACCURACY OF VALUES WHEN H IS LESS THAN 300000 FEET IS BETTER      MEG      24
C     THAN .05 PERCENT.   ACCURACY OF VALUES WHEN H IS GREATER THAN     MEG      25
C     300000 FEET IS BETTER THAN .1 PERCENT.                            MEG      26
C        MEGAIR2 IS BASED ON U.S. STANDARD ATMOSPHERE 1962.             MEG      27
C                                                                       MEG      28
C     DEFINE CONSTANTS                                                  MEG      29
C                                                                       MEG      30
C     ENGLISH UNITS ARE USED THROUGHOUT MEGAIR2.                        MEG      31
C     DLO = DENSITY AT SEA LEVEL  LB/FT**3                              MEG      32
C     GAMMA = CONSTANT                                                  MEG      33
C     GO = GRAVITATIONAL ACCELERATION AT SEA LEVEL  FT/SEC/SEC          MEG      34
C     MWO = MOLECULAR WEIGHT OF AIR AT SEA LEVEL  LB/LB MOL             MEG      35
C     PLO = SEA LEVEL PRESSURE  LB/FT**2                                MEG      36
C     R = GAS CONSTANT  (LB FT)**2/(SEC**2(LB MOL)(DEGREE R))           MEG      37
C     RO = RADIUS OF EARTH  FEET                                        MEG      38
C                                                                       MEG      39
      REAL L,MW,MWO                                                     MEG      40
C                                                                       MEG      41
      DIMENSION DELTAH(22), DELTAT(22), DELTAP(22), DELTAL(22)          MEG      42
      DIMENSION COEFF1(22), COEFF2(22), COEFF3(22)                      MEG      43
C                                                                       MEG      44
      DATA R,RO,GO,MWO/49719.,20851586.369,32.174049,28.9644/           MEG      45
C                                                                       MEG      46
C     DEFINE CONVERSION FACTORS                                         MEG      47
C     XMB CONVERTS LB/FT**2 TO MILLIBARS.                               MEG      48
      DATA XMB/.478802597/                                              MEG049
C                                                                       MEG      50
C     DEFINE LAYER BOUNDRY HEIGHTS AND THEIR ASSOCIATED TEMPERATURES,   MEG      51
C     PRESSURES, AND GRADIENTS.                                         MEG      52
      DATA (DELTAH(I),I=1,22)/0.,36152.,65823.,105518.,155348.,172011.,2MEG      53
     1102070.,262447.,295276.,328084.,360892.,393701.,492126.,524934.,557MEG      54
     2743.,623360.,754593.,984252.,1312336.,1640420.,1968504.,2296588./ MEG      55
      DATA (DELTAT(I),I=1,22)/518.67,389.97,389.97,411.57,487.17,487.17,MEG      56
     1454.77,325.17,325.17,379.17,469.17,649.17,1729.17,1999.17,2179.17,MEG      57
     22431.17,2791.17,3295.17,3889.17,4357.17,4663.17,4861.17/          MEG      58
```

```
      DATA (DELTAP(I),I=1,22)/7.657387,6.1584186,4.7392202,2.8975073,.83 MEG      59
     199754,.20884176,-.96573964,-3.8316926,-5.674318,-7.3727634,-8.7811 MEG      60
     2522,-9.85154047,-11.4573394,-11.7722702,-12.052080,-12.557160,-13. MEG      61
     344139853,-14.7483118,-16.2904,-17.59286,-18.74840,-19.81142/       MEG      62
      DATA (DELTAL(I),I=1,22)/-.00356616,0.,.00054864,.001536192,0.,-.00 MEG      63
     1109728,-.00219456,0.,.00164592,.0027432,.0054864,.0109728,.0082296 MEG      64
     2,.0054864,.00384048,.0027432,.00219456,.001810512,.001426464,.0009 MEG      65
     332688,.000603504,.000603504/                                       MEG      66
C                                                                        MEG      67
C     DEFINE MOLECULAR WEIGHT EQUATION COEFFICIENTS.                     MEG      68
      DATA (COEFF1(I),I=1,22)/0.,0.,0.,0.,0.,0.,0.,0.,29.74,32.15,33.90, MEG      69
     141.98,30.64,30.84,31.55,31.37,31.35,33.36,36.4973,34.8002,20.82470 MEG      70
     26,20.824706/                                                       MEG      71
      DATA (COEFF2(I),I=1,22)/0.,0.,0.,0.,0.,0.,0.,0.,.0000259740,.0000  MEG      72
     10992126,.0000148,.0000542400,.0000796875,.0000796875,.0000091666  MEG      73
     26,.000008857143,.000008833333,.000012796875,.0000178743,.000016046H MEG      74
     38,.000002029412,.000002029412/                                     MEG      75
      DATA (COEFF3(I),I=1,22)/0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,4.8E-11,0 MEG      76
     1.,0.,0.,0.,0.,1.953125E-12,4.0E-12,3.5156E-12,0.,0./               MEG      77
C                                                                        MEG      78
C     MAKE AN INDEX APPROXIMATION USING A STRAIGHT LINE APPROXIMATION TO MEG      79
C     GRAPH OF H VERSUS I.                                               MEG      80
      IF (H.LT.-16500.) GO TO 9                                          MEG      81
      IF (H.GT.300000.) GO TO 5                                          MEG      82
      I=.0000257384*H+1.88                                               MEG      83
      IF (ABS(H).GE.DELTAH(I)) GO TO 1                                   MEG      84
      IF (ABS(H).GE.DELTAH(I-1)) I=I-1                                   MEG      85
C                                                                        MEG      86
C     ESTABLISH BASE VALUES OF PRESSURE, TEMPERATURE, AND GRADIENT.      MEG      87
    1 HI=DELTAH(I)                                                       MEG      88
      HPB=HI/(1.+HI/RO)                                                  MEG      89
      TB=DELTAT(I)                                                       MEG      90
      PB=DELTAP(I)                                                       MEG      91
      L=DELTAL(I)                                                        MEG      92
C                                                                        MEG      93
C     PERFORM CALCULATIONS FOR H LESS THAN 300000 FEET.                  MEG      94
C                                                                        MEG      95
C     GEOPOTENTIAL HEIGHT                                                MEG      96
      HP=H/(1.+H/RO)                                                     MEG      97
C                                                                        MEG      98
C     TEMPERATURE                                                        MEG      99
C     UP TO 300000 FEET, MOLECULAR SCALE TEMPERATURE EQUALS KINETIC      MEG     100
C     TEMPERATURE.                                                       MEG     101
      TM=TB+L*(HP-HPB)                                                   MEG     102
C                                                                        MEG     103
C     PRESSURE (P), IN LB/FT**2.                                         MEG     104
      IF (L) 2,3,2                                                       MEG     105
    2 P=EXP(PB-(GO*MWO/(L*R))*ALOG(TM/TB))                               MEG     106
      GO TO 4                                                            MEG     107
C                                                                        MEG     108
    3 P=EXP(PB-(GO*MWO/R)*((HP-HPB)/TB))                                 MEG     109
    4 PMB=P*XMB                                                          MEG     110
C                                                                        MEG     111
C     DENSITY                                                            MEG     112
      D=(MWO*P*GO)/(R*TM)                                                MEG     113
C                                                                        MEG     114
C     GRAVITATIONAL ACCELERATION                                         MEG     115
```

```
      G=GO*(RO/(RO+H))**2
      RETURN
C
C     PERFORM CALCULATIONS FOR H GREATER THAN 300000 FEET.
C
C     SINCE MOLECULAR WEIGHT IS NO LONGER CONSTANT, MOLECULAR SCALE
C     TEMPERATURE IS NO LONGER EQUAL TO KINETIC TEMPERATURE.
C     THREE INDEX EQUATIONS ARE REQUIRED IN THE REGION ABOVE 300000 FEET
C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 300000
C     FEET BUT LESS THAN 492126 FEET.
C
    5 IF (H.GT.492126.) GO TO 7
      I=.00002573H4*H+1.88
      IF (I.GT.12) I=12
      IF (H.GE.DELTAH(I)) GO TO 6
      IF (H.GE.DELTAH(I-1)) I=I-1
C
C     ESTABLISH BASE VALUES OF TEMPERATURE, PRESSURE, AND GRADIENT.
    6 HB=DELTAH(I)
      TB=DELTAT(I)
      PB=DELTAP(I)
      L=DELTAL(I)
C
C     CALCULATE MOLECULAR WEIGHTS FROM EMPIRICAL, GRAPHICALLY DERIVED,
C     EQUATIONS.
      MW=COEFF1(I)-COEFF2(I)*H+COEFF3(I)*H*H
      HP=H/(1.+H/RO)
C
C     CALCULATE MOLECULAR SCALE TEMPERATURE AND CONVERT TO KINETIC
C     TEMPERATURE.
      TM=((TB+L*(H-HB))*MW)/MWO
C
C     PRESSURE (P), IN LB/FT**2.
      X=RO+HB-TB/L
      Y=1./(X*(RO+H))-1./(X*(RO+HB))+(1./(X*X))*ALOG(((H-HB+TB/L)*(RO+HB
     1)*L)/((RO+H)*TB))
      B=(GO*MWO*RO*RO)/(L*R)
      P=EXP(PB-B*Y)
      PMR=P*XMB
C
C     DENSITY
      D=(MW*P*GO)/(R*TM)
C
C     GRAVITATIONAL ACCELERATION
      G=GO*(RO/(RO+H))**2
      RETURN
C
C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 492126
C     FEET BUT LESS THAN 984252 FEET.
C
    7 IF (H.GT.984252.) GO TO 8
      Z=(H-740000.)/50000.
      I=17.5+.5048*Z-.04348*Z*Z
      IF (H.GE.DELTAH(I)) GO TO 6
      IF (H.GE.DELTAH(I-1)) I=I-1
      GO TO 6
C
```

```
      C     MAKE AN INDEX APPROXIMATION FOR VALUES OF H GREATER THAN 984252    MEG     173
      C     FEET.                                                              MEG     174
      C                                                                        MEG     175
      8     IF (H.GT.2320000.) GO TO 9                                         MEG     176
            I=.000003048*H+15.                                                 MEG     177
            IF (H.GE.DELTAH(I)) GO TO 6                                        MEG     178
            IF (H.GE.DELTAH(I-1)) I=I-1                                        MEG     179
            GO TO 6                                                            MEG     180
      C                                                                        MEG     181
      9     WRITE (6,10) H                                                     MEG     182
            RETURN                                                             MEG     183
      C                                                                        MEG     184
      C                                                                        MEG     185
      C                                                                        MEG     186
      10    FORMAT (1H ,20X,22H**ERROR FROM MEGAIR2**,5H H = ,E12.5)           MEG     187
            END                                                                MEG     188
```

```
      FUNCTION VX (GL,H,HOM,PHI,ZJ)
C
C     CROSS WIND VELOCITY PLUS SLEW VELOCITY IN METERS/SECOND
C
      COMMON /MESH/ XTRA,ZPREV
      COMMON /CNVW/ IW
      COMMON /X/ CHI,OMEGA,VP,VPSC,VXB
C
      VX=VXB
      IF (VXB.NE.0.) RETURN
C
      VS=OMEGA*(ZJ-ZPREV)
      VX=13.6
      IF (H.GE.5.E4) GO TO 6
      IF (H.GE.2.44E4) GO TO 2
      IF (H.GE.1.22E4) GO TO 1
      VX=3.42E-3*H+8.75
      GO TO 3
    1 VX=82.4-2.53E-3*H
      GO TO 3
    2 VX=27.2-2.72E-4*H
    3 IF (IW-2) 4,5,6
    4 VX=VX*0.27
      GO TO 6
    5 VX=VX*0.5
    6 IF ((HOM-GL).GT.10.) VX=VX*0.2
      IF (VPSC.GE.VX) VX=VPSC
      VX=VX+VS
      RETURN
      END
```

CASE 1 BELOW-BELOW,PD

SHORT OUTPUT FORMAT, WITHOUT DEBUG

```
TARGET RANGE (L) --------------------- 1.000E+03 METERS     DEVICE POWER (PD) --------------- 1.000E+06 WATTS
FOCAL DISTANCE (FL) ------------------ 1.000E+03 METERS     POWER OUT OF THE TELESCOPE (PT) ---0.        WATTS

GROUND LEVEL (GL) --------------------  0.       METERS     WAVELENGTH (LAMDA) -------------- 3.80E-06 METERS
DEVICE ALTITUDE (HOM) ---------------- 1.00E+02 METERS      INPUT JITTER (HIGH FREQUENCY) ---- 5.00E-06
                                       3.28E+02   FEET                   (LOW FREQUENCY) --- 5.00E-06
TARGET ALTITUDE (HTM) ---------------- 0.        METERS     TRACKING RATE (OMEGA) ----------- 0.00 RADIANS/SEC
                                       0.          FEET     OPTICS RADIUS (RO) -------------  .35 METERS
VERTICAL ANGLE (PHI) -----------------  -.000  RADIANS      OBSCURATION RADIUS -------------  .08 METERS

AZIMUTH ANGLE (CHI) ------------------  .520  RADIANS       BEAM TYPE (PROP) ---------------- GAUSSIAN
PLATFORM VELOCITY (VP) ---------------    0.METERS/SEC      TYPE OF PROPAGATION (BEAM) ------- FOCUSED
SPECIFIED CROSS WIND (VXB) ----------- 10.00                BEAM QUALITY (M) ---------------- 1.50
SEVERITY OF TURBULENCE (WTHR) -------- NORMAL               NUMBER OF BEAMPATH INCREMENTS ---- 30
RELATIVE HUMIDITY (RH) --------------- .50

*******************************INPUT TO OPTICAL TRAIN*******************************
          LASER BEAM DIAMETER               .1600      METERS
          LASER POWER                       .1000E+07  WATTS
          WAVELENGTH                        .3800E-05  METERS
          OBSCURATION                       .3600
          BEAM QUALITY                      1.500
          PULSE LENGTH                      2.000      SECONDS
          PHASE FRONT CURVATURE             .1000E+71  METERS
          JITTER                            .7071E-05  RADIANS
          INTENSITY FLUCTUATIONS            .5000      PEAK-TO-PEAK
          SCALE SIZE OF FLUCTUATIONS        .1000      L/AT
          TYPE OF AEROWINDOW              FOCUSED
          AEROWINDOW DELTA RHO/RHO          .1000
          RHO/RHO REF                       2.500
          DISTANCE TO CLIPPER               50.00      METERS
          CLIPPER DIAMETER                  .1660      METERS
          NUMBER OF MIRRORS               7
          REFLECTIVITY                      .9860
          FABRICATION ERROR                 .1250      VIS. LAMBDAS
          TYPE OF MIRRORS                 COOLED
          DISTANCE BETWEEN MIRRORS          .1500      METERS
          TELESCOPE MAGNIFICATION           4.375
          TELESCOPE DIAMETER                .7000      METERS
          TELESCOPE TYPE                  ON-AXIS
          TYPE OF EXIT APERTURE           WINDOW
          EXIT APERTURE LENGTH              .5000E-01  METERS
          ABSORPTION COEFFICIENT            .1000E-01  METERS-1
          TEMPERATURE FLUCTUATION           1.000      DEG K
          STRUT AREA/ BEAM AREA             .5000E-01
          TRACKER JITTER                    .5000E-05  RADIANS
          BORE-SIGHT JITTER                 .5000E-05  RADIANS
          SERVO JITTER                      .5000E-05  RADIANS
          AUTOALIGNMENT JITTER              .5000E-05  RADIANS
```

*******************************OPTICAL TRAIN OUTPUT*******************************

SOURCE		TRANSMISSION	SIGMA	L/WT
INPUT BEAM		1.0000	.3333	0.0000
AERODYNAMIC WINDOW		1.0000	0.0000	0.0000
BEAM CLIPPER		1.0000	0.0000	0.0000
MIRRORS	COOLED	.9060	.3028	.0007
BEAM EXPANDER	ON-AXIS	.9570	.3418	-.5901
EXIT APERTURE	WINDOW	.9495	.0593	.1000
TOTALS		.8233	.8979	.1573

TRANSMITTED BEAM DIAMETER .7000 METERS
TRANSMITTED POWER .8233E+05 WATTS
BEAM QUALITY BEFORE ACCOUNTING FOR DIVERGENCE
M1 = .4987 M2 = 1.1130
EFFECT OF BEAM DIVERGENCE ON WAIST 1.000
FINAL BEAM SPREAD PARAMETER, M2 1.113
TOTAL BEAM JITTER .6884E-05 RADIANS
PHASE FRONT CURVATURE .4375E+71 METERS

RESULTANT BEAM QUALITY M1 = .560 M2 = 1.215

CALCULATIONS FOR ORIGIN BELOW 100 KM AND TARGET BELOW 100 KM.

TARGET ALTITUDE (HTH) = 0. METERS (0. FEET)
TARGET RANGE (L) = 1.00E+03 METERS
LINEAR EFFECTS ON TRANSMISSION (EXPKAS) = .946
NON-LINEAR EFFECTS ON TRANSMISSION (KIP) = .500
AREA WITHOUT BLOOMING (AREA) = 1.065E-03 METERS**2
AREA WITH BLOOMING (BLAREA) = 2.131E-03 METERS**2

LONG-TERM TURBULENCE (SIGMAT) = 1.159E-06 RADIANS
SHORT-TERM TURBULENCE (SIGTST)= 8.633E-07 RADIANS
RADIUS WITHOUT BLOOMING (R) = .018 METERS
AVERAGE INTENSITY (I) = 1.7712E+08 WATTS/M**2
PEAK INTENSITY (IP) = 4.0950E+08 WATTS/M**2

DISPLACEMENT = .025 METERS ECCENTRICITY = .650

I/IPEAK CONTOUR	AREA (METER**2)	CUMULATIVE POWER	AVERAGE INTENSITY
.9	1.122E-04	3.774E+04	3.362E+08
.8	2.377E-04	7.547E+04	3.175E+08
.7	3.800E-04	1.132E+05	2.979E+08
.6	5.442E-04	1.509E+05	2.774E+08
.5	7.384E-04	1.887E+05	2.555E+08
.4	9.761E-04	2.264E+05	2.320E+08
.3	1.283E-03	2.642E+05	2.060E+08
.2	1.715E-03	3.019E+05	1.761E+08
.1	2.453E-03	3.396E+05	1.[illegible]

BREAKDOWN INTENSITY = 1.00E+12 ACHIEVED AT TELESCOPE POWER = 1.01E+09
MAXIMUM INTENSITY ON TARGET = 2.56E+08 ACHIEVED AT TELESCOPE POWER = 2.74E+06

POWER RANGE AVAILABLE

TELESCOPE POWER (WATTS)	INTENSITY (WATTS/M**2)	USEFUL POWER (WATTS)	OVER AREA (M**2)
8.233E+04	3.426E+07	3.542E+07	1.139E-02
1.647E+05	6.383E+07	7.085E+07	1.307E-02
2.470E+05	8.607E+07	1.063E+08	1.469E-02
3.293E+05	1.063E+08	1.417E+08	1.652E-02
4.116E+05	1.199E+08	1.771E+08	1.853E-02
4.940E+05	1.311E+08	2.126E+08	2.031E-02
5.763E+05	1.456E+08	2.4[illegible]E+08	2.175E-02
6.585E+05	1.593E+08	2.834E+08	2.307E-02
7.409E+05	1.687E+08	3.188E+08	2.450E-02
8.233E+05	1.771E+08	3.543E+08	2.605E-02
9.056E+05	1.834E+08	3.697E+08	2.777E-02
9.879E+05	1.876E+08	4.751E+08	2.967E-02
1.070E+06	1.935E+08	4.605E+08	3.128E-02
1.153E+06	1.998E+08	4.960E+08	3.270E-02
1.235E+06	2.062E+08	5.314E+08	3.403E-02
1.317E+06	2.128E+08	5.668E+08	3.534E-02
1.400E+06	2.184E+08	6.022E+08	3.662E-02
1.482E+06	2.239E+08	6.377E+08	3.791E-02
1.564E+06	2.290E+08	6.731E+08	3.922E-02
1.647E+06	2.335E+08	7.085E+08	4.055E-02

USEFUL INTENSITY = 1.000E+04WATTS/M**2

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