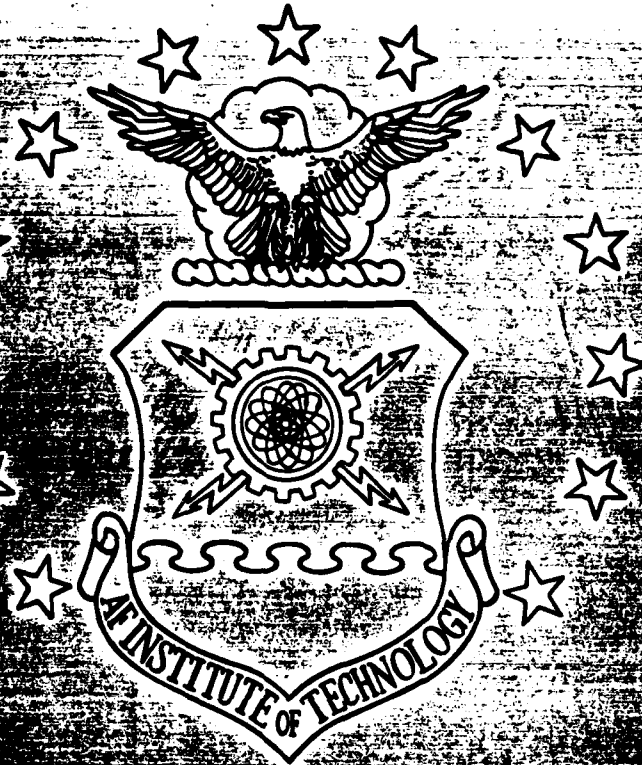


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VISIBILITY IN AN ATMOSPHERIC NUCLEAR
DUST CLOUD

THESIS

Thomas J. Wuchte
Captain, USAF

AFIT/GNE/ENP/89M-9

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Nuclear Engineering

Thomas J. Wuchte, B.S.
Captain, USAF

March 1989

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Preface

The purpose of this study was to determine the optical thickness in a nuclear dust cloud as it settles to the ground. This has been done before by other experimenters but only from the surface to the upper atmosphere. My model was to incorporate some of the previous work into one model. This model would be able to calculate the optical thickness as a function of particle-size distribution, altitude, total mass lofted, wavelength of the signal, and location of the sender and receiver within the dust cloud at times shortly after the burst. This new model would give more flexibility to the user when different parameters need to be examined.

I need to thank all the people who filled in the gaps of my understanding during the developmental portion of my research. Major Jim Lange, for getting me off on the right foot. My advisor, Professor C. J. Bridgman, for all of the education I received in my first twelve months at AFIT and guidance during my thesis quarter. To my wife - who without a doubt had every reason to be disgusted with me during this time - I am eternally grateful for all her support. Last of all I would like to thank my son - born in August of this year - who may now have a full-time father.

Thomas J. Wuchte

Table of Contents

	Page
Preface	ii
List of Figures	v
List of Tables	vi
Abstract	vii
I. Introduction	1
Background	1
Purpose	2
Approach	3
Objectives	4
Overview	4
II. Theory	6
Stabilized Cloud Model	6
Mass and Number of Particles Lofted.	6
Shape.	8
Distribution of Particle Groups.	10
Fall Mechanics.	13
Optical Properties of the Cloud Model	13
Extinction Efficiency - Q_x	13
Extinction Coefficient - β_x	16
Optical Thickness - OT.	18
III. Computational Methods	19
Assumptions in the Model	19
Cloud Model	20
Group Extinction Efficiencies - $Q_x(g)$	21
Signal Wavelengths	22
Signal Orientation to that of the Dust Cloud	22
IV. Results	24
Mean Radii and Extinction Efficiencies ...	24
Verification of the Model	27
Demonstrative Samples	29

	Page
V. Discussion and Conclusions	37
VI. Future Considerations	39
Appendix A - OPTHICK Source Code	40
Appendix B - The Lognormal Distribution	56
Bibliography	59
Vita	61

List of Figures

Figure	Page
1. Dust Mass Lofted into the Stabilized Cloud	7
2. Shape of the Gaussian Dust Cloud	8
3. Extinction Efficiencies for Three Wavelengths of Light	15
4. One Megaton Surface Burst - .55 Micron Signal	31
5. One Megaton Surface Burst - 2 Micron Signal	32
6. One Megaton Surface Burst - 7.9 Micron Signal	33
7. 100 Kiloton Surface Burst - .55 Micron Signal	34
8. 100 Kiloton Surface Burst - 2 Micron Signal	35
9. 100 Kiloton Surface Burst - 7.9 Micron Signal	36

List of Tables

Table	Page
1. Indices of Refraction: Dust-like Particles	16
2. Signal Wavelengths and Uses	22
3. Group Mean Radii	25
4. Group Extinction Efficiencies	26
5. Optical Thickness Calculations	29

Abstract

The purpose of this study was to examine the optical properties of a localized dust cloud created by a nuclear surface burst. The primary objectives were: (1) Model the dust cloud created by the burst. (2) Determine the number and size distribution of particles lofted. (3) Evaluate the extinction efficiency of each of the particles based on radius of the particle and signal wavelength. (4) Compute the optical thickness at any location within the cloud as it settles to the ground.

The technique used to calculate these values was based on calculating the extinction coefficient at 100 points along a line-of-sight through the dust cloud. The optical thickness at each point was then computed using the product of pathlength traveled and extinction coefficient at each point.

The results of the study demonstrated that the optical thickness generated by smaller, more localized bursts, was much greater than bursts that create global dust clouds. The localized dust cloud was also modeled to simulate global dust

clouds of other models. The optical thickness of these dust clouds were within one percent of the optical thickness predicted by other experimenters.

VISIBILITY IN AN ATMOSPHERIC NUCLEAR DUST CLOUD

I. Introduction

Background

Many studies have examined the long-term sunlight attenuation of atmospheric nuclear exchanges that involve gigaton yields and cover the majority of the northern hemisphere. The primary concern of these studies were attenuation of sunlight between the upper atmosphere and persons on the ground. This attenuation was due to both smoke from wide-spread fires and dust raised by nuclear surface bursts. Of these two attenuators smoke is of far more concern than dust.

One aspect that has not been specifically investigated is the effect on electromagnetic radiation (EMR) propagating through the dust clouds of much smaller, localized bursts. These signals - particularly in the visible and infrared bands - are of great importance at early times when radiation dose levels become tolerable. The degradation of these signals plays a major role in answering the question "when and where can I properly communicate through the dust cloud at these wavelengths"?

Evaluation of these effects requires that the properties of the dust cloud created by the burst be known and modeled

to simulate cloud rise and fall. The important parameters that define the cloud are the composition of the dust, the dust size and number distribution, total dust lofted, frequency of the signal being transmitted, and locations of the signal transmission and reception points relative to the dust cloud center.

The dust cloud used in this study is comprised of the local size distribution suggested by Baker (1:100-119) divided into a 100 particle groups that are lofted into the local atmosphere following a nuclear surface burst. Each particle group is tracked until it falls to the ground. Optical thickness calculations are achieved at several points in time based on the size and altitudes of these particles.

Purpose

The purpose of this study is to determine the optical thickness (OT) of a dust cloud generated by a nuclear burst. The determination is made at various altitudes, signal frequencies, and times after burst. This is done to evaluate the signal attenuation experienced by EMR in the visible and infrared ranges of the electromagnetic spectrum (EMS).

This study will aid in evaluation of communications, visibility, and other post-attack functions that are necessary following a nuclear surface burst.

Approach

Each dust cloud used in this study is modeled as if it were produced by a surface burst. The model assumes the cloud to be comprised of 100 particle group sizes, lognormally distributed using the second moment properties of lognormal distribution (see Appendix B). These groups are defined so that each contains one percent of the total cross sectional area and is represented by the mean radius of the group. The initial altitude attained by each group is determined using Hopkins' (8:14-15) or Pugh's (15:51) fit and the mean radius of each group. Yields up to 68 megatons are fit by Hopkins' method and yields of 69 megatons or greater are fit using Pugh's empirical equation. This is done to confine the dust cloud to the parameters used in models of the U.S. Standard Atmosphere (3).

The different particle groups are then allowed to fall for a fixed time interval. After each time step, fall mechanics - developed by McDonald (10:463-465) and Davies (6:259-270) - determine the altitudes of the 100 particles that represent each particle group (see Fall Mechanics). Extinction efficiencies, Q_x (see Extinction Efficiency - Q_x), for each particle group still airborne are then calculated based on mean radius of the group and the wavelength of the signal to be transmitted

through the cloud. The extinction coefficients, β_x (see Extinction Coefficient - β_x), along the vector of signal transmission are then used to calculate the optical thickness, OT (see Optical Thickness - OT), at each point along the vector. In this way, the signal attenuation can be computed along the line of sight between any two points in space relative to ground zero.

Specific Objectives

The objectives of this study are two-fold:

1. Determine the optical thickness within a nuclear dust cloud as a function time and space for a given set of parameters.
2. Develop a code that will compute the optical thickness within a nuclear dust cloud as a function of time and space for any yield, particle size distribution or signal wavelength.

Overview

The makeup, shape, and distribution of the particles within the cloud are contained in the Theory section. The Theory section also explains how the components of optical thickness are computed. The Computational Method section discusses how the signal is propagated through the dust cloud. Results of

various yields and signals are contained in the Results section followed by some observations and conclusions in the Discussion and Conclusions and Future Considerations sections.

II. Theory

Stabilized Cloud Model

Mass and Number of Particles Lofted. The total mass lofted is based on studies done by Carpenter - as reported by Baker (1:117) - that show a maximum dust mass loading of 0.3 tons of dust per ton of yield for a contact surface burst. See Figure 1. This nominal setting was used throughout the model.

The total number of particles can now be calculated using the 3rd moment property of the lognormal distribution (see APPENDIX B).

$$N_T = \frac{3e^{-\frac{3}{2}\beta^2} M_T}{4\pi\rho r_m^3} \quad (1)$$

where

N_T = total number of particles

M_T = total mass lofted (kilograms)

β = natural log of the slope of the distribution

r_m = mean radius of the distribution (meters) and

ρ = density of the dust particles (kg/m³).

The dust particles are modeled to be spherical in shape with a density of 2,600 (12:360-380) kg/m³.

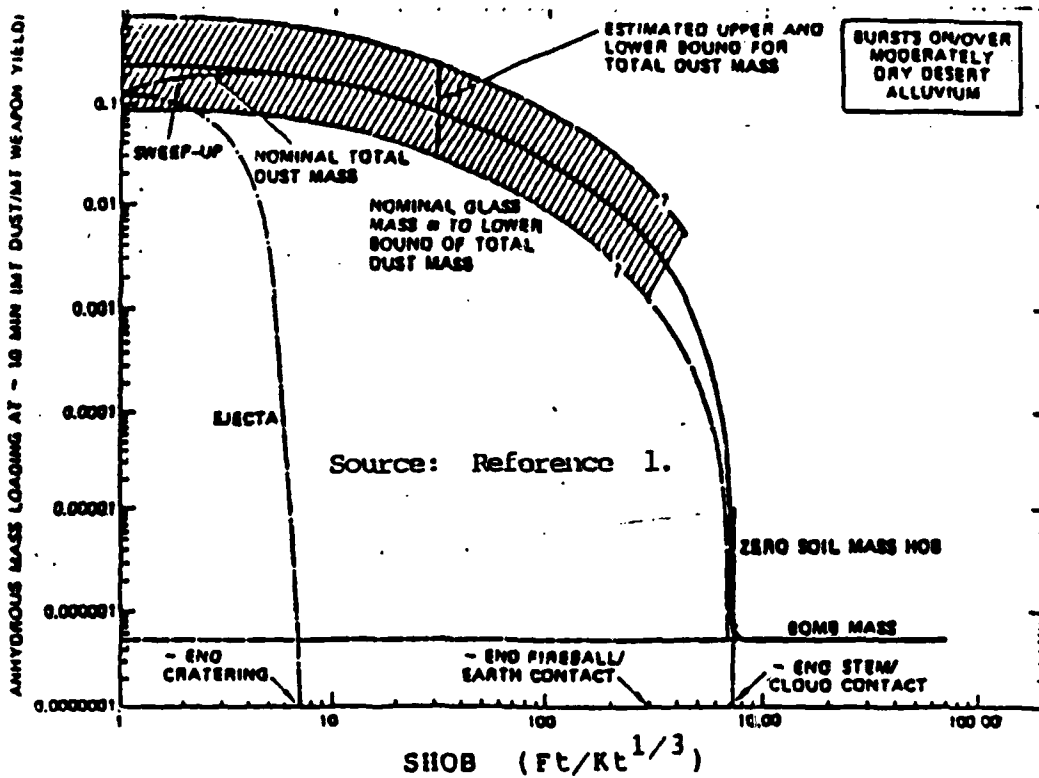


Figure 1. Dust Mass Lofted into the Stabilized Dust Cloud as a Function of Scaled Height-of-Burst

Shape. The shape of the stabilized cloud is modeled as a three dimensional gaussian comprised of 100 particle groups. See Figure 2. Each size group is centered at a different altitude.

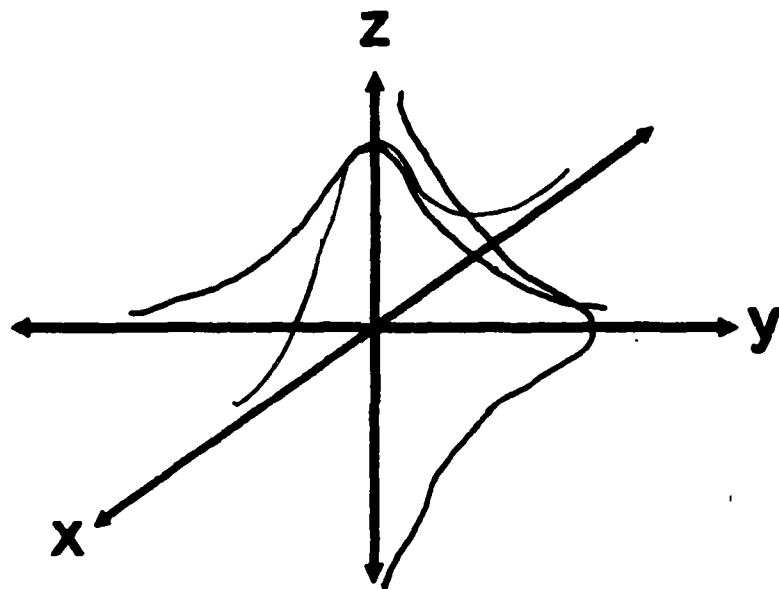


Figure 2. Shape of the Gaussian Dust Cloud

Hopkins (8:14-15) determined that the altitude (z) of a particle with radius r injected into the atmosphere can be modeled by

$$z_g = C_2 - 2C_1 r_g \quad (2)$$

where

r_g is the mean radius (microns) of group g.

$C_{1,2}$ are coefficients determined from

$$C_1 = \exp\{1.574 - .01197 \ln Y_k + .03636 (\ln Y_k)^2 - .0041 (\ln Y_k)^3 + .0001965 (\ln Y_k)^4\} \quad (3)$$

$$C_2 = \exp\{7.889 - .34 \ln Y_k + .001226 (\ln Y_k)^2 - .005227 (\ln Y_k)^3 + .000417 (\ln Y_k)^4\} \quad (4)$$

where Y_k is the yield of the burst in kilotons. This initial altitude model is used for yields up to 68 megatons.

All particle groups that originate from yields that exceed 68 megatons, are placed at an altitude determined from Pugh's (15:51) empirical equation. The height of the center (H_c) of the stabilized cloud is given as

$$H_c = 44 + 6.1 \ln(Y_M) - .205 \{ \ln(Y_M) + 2.42 \} | \ln(Y_M) + 2.42 | \quad (5)$$

where

Y_M is the yield of the burst (megatons) and

H_c is the height of the stabilized cloud's center (kilofeet).

The standard deviation (15:51) of the gaussian cloud in the x and y directions are defined by

$$\sigma_{x,y} = 1609 \exp \left\{ .7 + \frac{1}{3} (\ln Y_M) - \frac{3.25}{(4 + (\ln Y_M + 5.4)^2)} \right\} \quad (6)$$

The cloud's standard deviation in altitude is given by

$$\sigma_z = .18 H_c \quad (7)$$

The parameters $\sigma_{x,y}$ are in meters, σ_z is in kilofeet and Y_M is the yield in megatons.

Distribution of Particle Groups. The distribution of particulates occurring from the detonation of a nuclear surface burst has been examined by Baker (1:100-119) and determined to be a sum of two lognormal distributions. One distribution is made up of small particles (N_1) with a mean radius of .1 μ and a slope of 2, the other (N_2) is made up of larger particles with a mean radius of .204 μ and a slope of 4 - the DELFIC (13) nominal distribution. Baker (1:113) suggested a number density ratio of

$$\frac{N_1}{N_2} = 2.2 \quad (8)$$

where N_1 and N_2 represent the total number of particles in their respective distributions. Therefore, the number of particles in the larger size distribution make up just 31.25% of the total number.

Since the extinction coefficient is dependent on the cross sectional area of the particle, it is now convenient to convert from a number distribution to a distribution based on cross sectional area. The cross sectional area distribution is defined as

$$CS(r) = \frac{CS_{TOT}}{\sqrt{2\pi\beta}} e^{-\frac{1}{2}\left[\frac{\ln(r)-\alpha_2}{\beta}\right]^2} \quad (9)$$

where

$CS(r)$ is the cross sectional area per unit radius of all particles with radius r

CS_{TOT} is the total cross sectional area

β is the logarithmic slope of the distribution and

α_2 is defined as $\alpha_0 + 2\beta^2$.

The second moment property (see Appendix B) of the distribution is

$$\langle r_l^2 \rangle = r_{m,l}^2 e^{2\beta_l^2} \quad (10)$$

where β_l and $r_{m,l}$ are the natural log of the slope and mean radius of the l -th distribution as defined in the section Mass

and Number of Particles Lofted.

The respective cross sectional area fractions, CS_1 and CS_2 , of the two distributions can now also be computed by

$$CS_2 = CS_1 \frac{N_2 \langle r_{m2}^2 \rangle}{N_1 \langle r_{m1}^2 \rangle} \quad (11)$$

where it can be shown that the larger particle distribution now contains 97% of the total cross sectional area in the two distributions.

Previous studies and codes - like Baker's (1) and DELFIC - have modeled the size distribution of dust particles in the cloud. The range of mean radii have been from .1 to .2 μ with logarithmic slopes of 2 to 6. DELFIC uses a default lognormal distribution around a mean radius of .2 μ with a logarithmic slope of 4.

The distribution of particles used in the testing of this cloud model was also made up entirely of Baker's larger particle size distribution, i.e., mean radius .2 μ and slope of 4 (which is also the nominal DELFIC distribution). The reason for this is that the smaller particle distribution contributes only a small amount to the calculations necessary to determine extinction coefficients. There are provisions in the computer code OPTHICK - contained in Appendix A of this report - that

allows for two distributions to be used. To incorporate this option the number fraction, mean radii, and slopes of the two distributions must be known.

Fall Mechanics. Fall mechanics based on air density and viscosity, particle radii and density, and Reynolds number developed by Davies (6:259-270) and McDonald (10:463-465) are used to calculate terminal velocities of the falling particle groups. The distance a particle falls can then be calculated for the specified time increment. Particle groups that fall to the ground during this time are no longer included in the calculations since they no longer contribute to the optical thickness of the atmosphere.

Optical Properties of the Cloud Model

Extinction Efficiency - Q_x . The extinction efficiency of a sphere is the ratio of extinction cross section and the geometric cross section. That is

$$Q_x(x, \lambda) = \frac{\sigma_x}{\pi r^2} \quad (12)$$

where

Q_x is the extinction coefficient (no units)

σ_x is the extinction cross section (square microns)

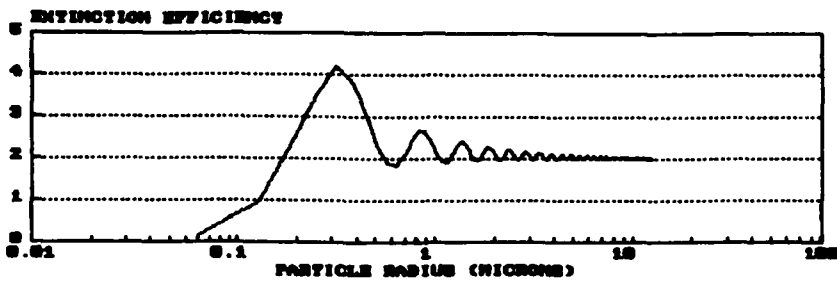
r is the radius of the spherical particle (microns)

λ is the wavelength (microns) of the signal and

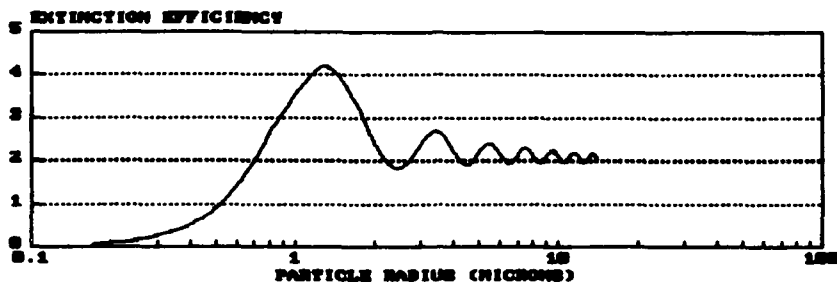
x is a parameter defined by $\frac{2\pi}{\lambda}$.

The extinction cross section, σ_x , of a sphere is a measure of the amount of energy removed from an incoming beam of EMR by scatter and absorption (9:49). Mie (11:377) developed the complete set of equations necessary to calculate these cross sections for various size spheres and wavelengths. Once the extinction cross section is known the extinction efficiency for that particle size is readily determined.

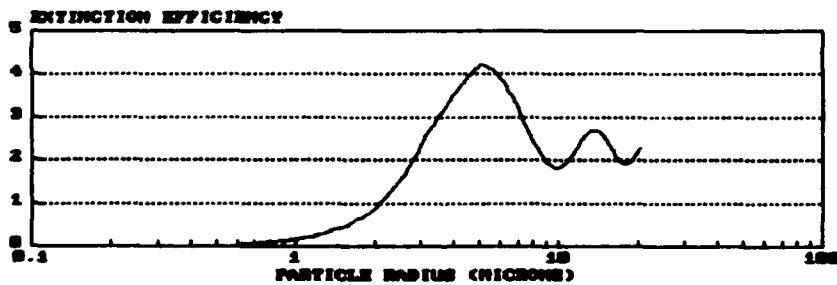
Diermendjian (7:371-381) developed a set of parametric equations that can be used to approximate extinction efficiencies of particles for monochromatic light. The values obtained from his fit correspond to the efficiencies and the general behavior of the full Mie calculations. Figure 3 shows the extinction efficiencies for three different wavelengths of light using the Diermendjian approximation equations. He notes that his values are accurate to within 4% of the values calculated by Mie in the range $1 < n \leq 1.5$ and $0 \leq n' \leq .25$. The symbols n and n' represent the scatter (real) and absorption (imaginary) parts of the index of refraction, m , where $m = n - in'$.



0.05 MICRON SIGNAL



0.25 MICRON SIGNAL



1 MICRON SIGNAL

FIGURE 3. Extinction Efficiencies as a Function of Particle Radius as Computed by the Diermendjian Approximation Equations

The values of these indices for the wavelengths examined in this study are listed in the following table (16:18).

Table 1. - Indices of Refraction: Dust-like Particles	
WAVELENGTH (MICRONS)	INDEX OF REFRACTION
.55	1.53-.0061
2	1.26-.0081
8	1.15-.041

Dust, as opposed to soot, has a very small absorption index of refraction (small absorption). Pontier (14:18) used a value of $m = 1.5 - .0011$ for his dust model and that value is used as a default index of refraction in OPTHICK (See APPENDIX A for program listing). Caution is to be used when using indices outside the ranges stated above. Broyles (5:323-332) states that for a wavelength of 0.55 microns and $m = 1$, Diermendjian's fit is within 15% of the full Mie calculations at the first maximum.

Extinction Coefficient - β_x . In general, the extinction coefficient of identical spherical particles in monochromatic light is defined by Van de Hulst (17:129) as

$$\beta_x = N_{vT} \pi r^2 Q_x(r, \lambda) \quad (13)$$

where

β_x is the extinction coefficient (m^{-1})

N_{vT} is the total number of particles per unit volume (m^{-3})

r is the particle radius (meters) and

Q_x is the extinction efficiency for that radius and wavelength.

If there is a distribution of particles present then the expression that defines the extinction coefficient is

$$\beta_x = \int_0^{\infty} Q_x(r)_g N(r) \pi r^2 dr \quad (14)$$

where $n(r)dr$ represents a lognormal distribution of particles per unit volume normalized to one. Since the signal is being treated as monochromatic and there is no longer a dependence on the wavelength of the signal.

After employing the second moment property of the lognormal distribution and treating the integral as a summation over 100 groups, the extinction coefficient can now be calculated by

$$\beta_x = .01 N_{vT} \pi \langle r^2 \rangle \sum_{g=1}^{100} Q_{xg} \quad (15)$$

where

N_{vT} is now the total number of particles per volume in the distribution as described above and

$\langle r^2 \rangle$ is the mean cross sectional area in square meters as defined in the Distribution of Particle Groups section.

Optical Thickness - OT. The optical thickness of a medium - given a monochrome wavelength of light and identical size dust particles - is the product of the extinction coefficient, β_x , and the distance traveled in the medium.

$$OT = \beta_x \times \text{pathlength traveled} \quad (16)$$

where

pathlength traveled is the distance (meters) traveled in the medium with extinction coefficient β_x .

The attenuation of a signal traveling in this medium is then calculated by

$$S = S_0 e^{(-OT)} \quad (17)$$

where S_0 and S denote the incident and resulting intensity of the signal.

III. Computational Methods

Assumptions in the Model

1. The signal transmitted through the dust cloud is monochromatic.
2. There is no multiple scatter. Photons scattered out of the incident signal are lost and no longer contribute to the signal at the receiver. This will tend to underestimate the resultant signal.
3. The dust cloud consists of 100 particle group sizes lognormally distributed.
4. The density distribution of the dust cloud is gaussian in x, y, and for each particle size in z. The x and y distributions are centered about the vertical centerline of the cloud.
5. Particle groups whose vertical distribution median radius reaches the ground within a time interval are no longer considered to contribute to optical thickness calculations. This tends to underestimate the optical thickness because the tail of the distribution is still aloft and is ignored.
6. The standard deviation in altitude (z) is constant throughout the model.

7. The signal is not refracted inside the cloud as is the case with other light transmittance models.

8. The extinction coefficient, β_x , is constant within each of the 100 spatial steps that the signal propagates through the cloud.

Cloud Model

The yield of a surface burst determines the stabilized cloud height and the amount of mass lofted into the atmosphere. To show how yield affects signal attenuation, two yields are used. The mass lofted by each burst is calculated for one distribution - Baker's large distribution. As the cloud settles and particles groups fall to the ground, the altitudes of particle group centers still aloft determine the optical thickness.

Since the cloud is modeled as 100 particle groups - all gaussian in shape - the spatial and temporal contribution factors from each group to the extinction coefficient can be calculated by

$$f(x,t) = \frac{e^{-\left(\frac{x-x_t}{\sigma_x}\right)^2}}{\sqrt{2\pi}\sigma_x} \quad (18)$$

$$f(y) = \frac{e^{-\left(\frac{y}{\sigma_y}\right)^2}}{\sqrt{2\pi}\sigma_y} \quad (19)$$

$$f(z) = \frac{e^{-\left(\frac{z-z_g}{\sigma_z}\right)^2}}{\sqrt{2\pi}\sigma_z} \quad (20)$$

where

$f(x,t)$, $f(y)$, and $f(z)$ are in meters⁻¹

x , y , and z are the distances (meters) in 3-D space referenced from the center of the stabilized cloud to the point where the optical thickness is being calculated,

z_g is the altitude (meters) of the mean of each group

v_x is the wind velocity (meters/second) in the x-direction

(wind is neglected in the sample calculations but can be introduced when OPTHICK is run),

t is the time (seconds) after cloud stabilization and all other parameters are as previously defined.

The product of these three factors and N_T result in a number density of particles (particles/meter³) at the location (x,y,z) at time t .

Group Extinction Efficiencies - $Q_x(g)$

The extinction efficiency of each of the 100 particle groups is computed using the mean radius of each group and Diermendjian's fit. Extinction efficiency also varies with signal wavelength, therefore each time a new wavelength is transmitted,

the extinction efficiencies are recomputed.

Signal Wavelengths

Three different wavelengths are used to demonstrate the changes in optical thickness as signal wavelength is altered. See Table 1. The three wavelengths chosen are representative of signals in the visible and infrared regions of the EMS. These are particularly important to those who must communicate and see in the post-burst environment.

WAVELENGTH (MICRONS)	EM BAND	GENERAL USES (2)
0.55	VISIBLE	Flying, driving, shooting, etc.
2 & 8	INFRARED	Lasers & guided missiles, rangefinders and designators, thermal sights, incandescent & fluorescent lights

Signal Orientation to that of the Dust Cloud

The point of origin and receipt of the signal must be known relative to the center of the stabilized cloud height and

ground zero. The optical thickness encountered along the signal path is done by determining the vector from origin to receipt. This vector is segmented into 100 steps and the extinction efficiency at each step is computed. The optical thickness for each segment is then the product of extinction coefficient and step-size.

IV. Results

Mean Radii and Extinction Efficiencies

The mean radii and extinction efficiencies - for a signal wavelength of 0.55 microns - of the 100 particle groups used in this study are listed in the Tables 3 and 4. The distribution was generated using Baker's large distribution parameters, $\alpha_0 = .204$, $\beta = \ln(4)$, and $\alpha_2 = \alpha_0 + 2\beta^2$. The tables were generated using the procedures outlined in the Approach section. The extinction efficiencies were calculated using these mean radii and Diermendjian's fit as described in the Extinction Efficiency - Q_x section.

Table 3. - Group Mean Radii (Microns)

0.27	0.47	0.63	0.77	0.91
1.04	1.17	1.29	1.42	1.55
1.68	1.80	1.93	2.06	2.20
2.33	2.47	2.61	2.75	2.89
3.04	3.19	3.34	3.50	3.66
3.82	3.99	4.16	4.34	4.52
4.70	4.89	5.08	5.28	5.48
5.69	5.91	6.13	6.36	6.59
6.83	7.08	7.33	7.60	7.87
8.15	8.44	8.73	9.04	9.36
9.69	10.03	10.39	10.76	11.14
11.53	11.95	12.37	12.82	13.29
13.77	14.28	14.81	15.36	15.94
16.55	17.19	17.86	18.56	19.31
20.09	20.93	21.81	22.74	23.73
24.79	25.92	27.14	28.44	29.84
31.36	33.00	34.80	36.76	38.91
41.30	43.96	46.94	50.31	54.16
58.62	63.85	70.10	77.74	87.36
99.97	117.50	144.27	193.06	338.80

Table 4. - Group Extinction Efficiencies

(Wavelength=0.55 μ)

3.66	2.98	1.88	2.36	2.65
2.22	1.96	2.20	2.38	2.17
1.98	2.12	2.26	2.13	2.00
2.10	2.19	2.08	2.01	2.12
2.13	2.02	2.05	2.12	2.05
2.03	2.10	2.05	2.02	2.09
2.04	2.03	2.08	2.02	2.05
2.05	2.02	2.06	2.02	2.05
2.02	2.05	2.02	2.04	2.02
2.04	2.02	2.04	2.02	2.02
2.03	2.02	2.02	2.03	2.02
2.01	2.02	2.02	2.02	2.02
2.02	2.02	2.02	2.02	2.02
2.01	2.01	2.01	2.01	2.01
2.01	2.01	2.01	2.01	2.01
2.01	2.01	2.01	2.01	2.01
2.01	2.01	2.01	2.01	2.01
2.01	2.01	2.01	2.01	2.01
2.01	2.01	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00

Verification of the Model

Two separate methods were used to determine the validity of the results in the previous section. The first method used was a direct substitution of the rural dust in the standard atmosphere in LOWTRAN for the dust cloud model. The atmospheric model and distribution of particles used were developed by Shettle (16:11-14,22,50). He lists attenuation coefficients for extinction, scatter and absorption for incident light from .2 to 40 microns.

Shettle normalized the number density to $1.5E10$ particles/ m^3 everywhere. A signal passing through the cloud model described in the Cloud Model section would be spatially and temporally dependent on the number density of particles, therefore the number density in OPTHICK was set to Shettle's default value. Although the source and values of his extinction, scatter, and absorption cross sections are not listed, the method proved very useful as a first-order test. However, no direct correlation between Shettle's extinction coefficient and OPTHICK was found.

The second method used to test the validity of the model revolves around an approximation for optical thickness developed by Bridgman (4:167-170). He suggests that the optical thickness of a cloud can be represented by

$$OT = \frac{3M_T Q_e \pi r_e^2}{4\pi r_m^3 \rho A_c} \quad (21)$$

where

M_T is the total mass lofted (kg)

Q_e is the extinction efficiency

$$r_e = r_m e^{\frac{\alpha}{\beta}}$$

r_m is the mean radius of the distribution (meters)

ρ is the density of the particles (kg/m³) and

A_c is area of the cloud (m²).

He states that a mono-size particle distribution, with a radius of r_e , would produce the same optical thickness as a lognormal particle distribution with the specified α and β . The parameters α and β are the natural logs of the mean radius and slope of the particle number distribution.

The following table lists the results of this validation test. The parameters used in Eq. 21 are

$$A_c = 2.5 \times 10^{14} \text{ meters}^2$$

$$Q_e = 2$$

$$r_m = .204 \text{ microns}$$

$$\beta = \ln(4) \text{ and}$$

$$\rho = 2600 \frac{\text{kg}}{\text{m}^3}.$$

The wavelength of light used in OPTHICK is monochromatic light at 0.55 microns. The optical thickness listed in Table 6 are calculated for pathways from the ground to the upper atmosphere through the entire dust cloud.

Table 5. - Optical Thickness Calculations		
YIELD (MT)	EQ (19)	'OPTHICK'
1	2.58E-5	2.56E-5
500	1.29E-2	1.30E-2
2400	6.29E-2	6.24E-2

It can be seen here that the computer code 'OPTHICK' closely follows the predicted optical thickness from Bridgman's effective optical thickness equation. All the calculations in Table 6 assume a cloud totally covering the northern hemisphere that is about $2.5E14$ meters² in area.

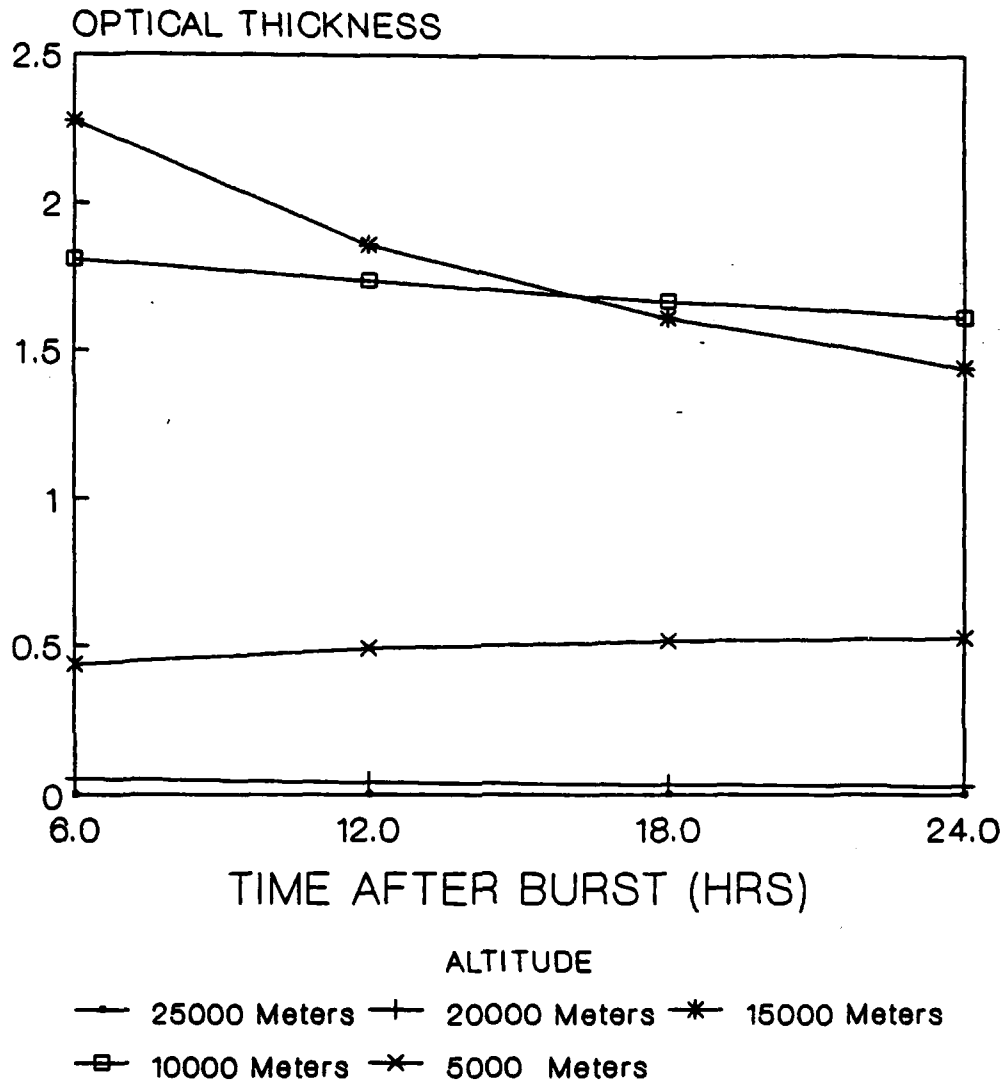
Demonstrative Samples

The ability to see straight up is not always as important as seeing directly ahead of you. For this reason the following six examples demonstrate the optical thickness created by two different sizes of surface bursts against three wavelengths of light. The area that the cloud covers in these examples

is much smaller than the area used in the Verification of the Model section. (This area is defined in the Shape section of the Stabilized Cloud Model of this report.) All of these samples are calculated using the DELFIC default distribution. The total optical thickness represented in Figures 4-9 are for a horizontal path through the entire cloud at the given time and altitude. (For example, in Figure 4 the total optical thickness at 15,000 meters - resulting from dust alone - from a one megaton burst, 24 hours after stabilization, with no wind present is about 1.5.)

OPTICAL THICKNESS

HORIZONTAL PATH THROUGH CLOUD CENTERLINE

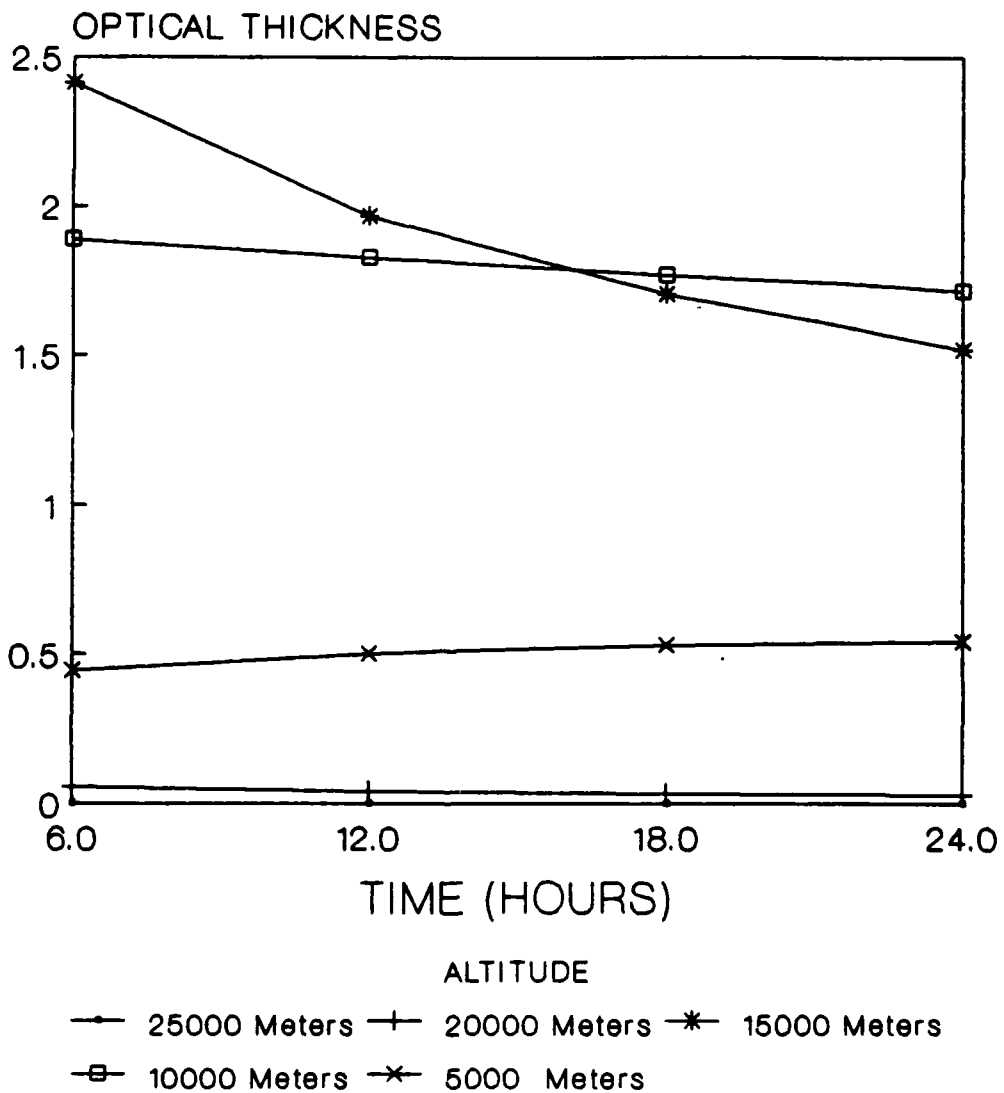


1 MT-.55 MICRON SIGNAL-.204/4

Figure 4. One Megaton Surface Burst - .55 Micron Signal

OPTICAL THICKNESS

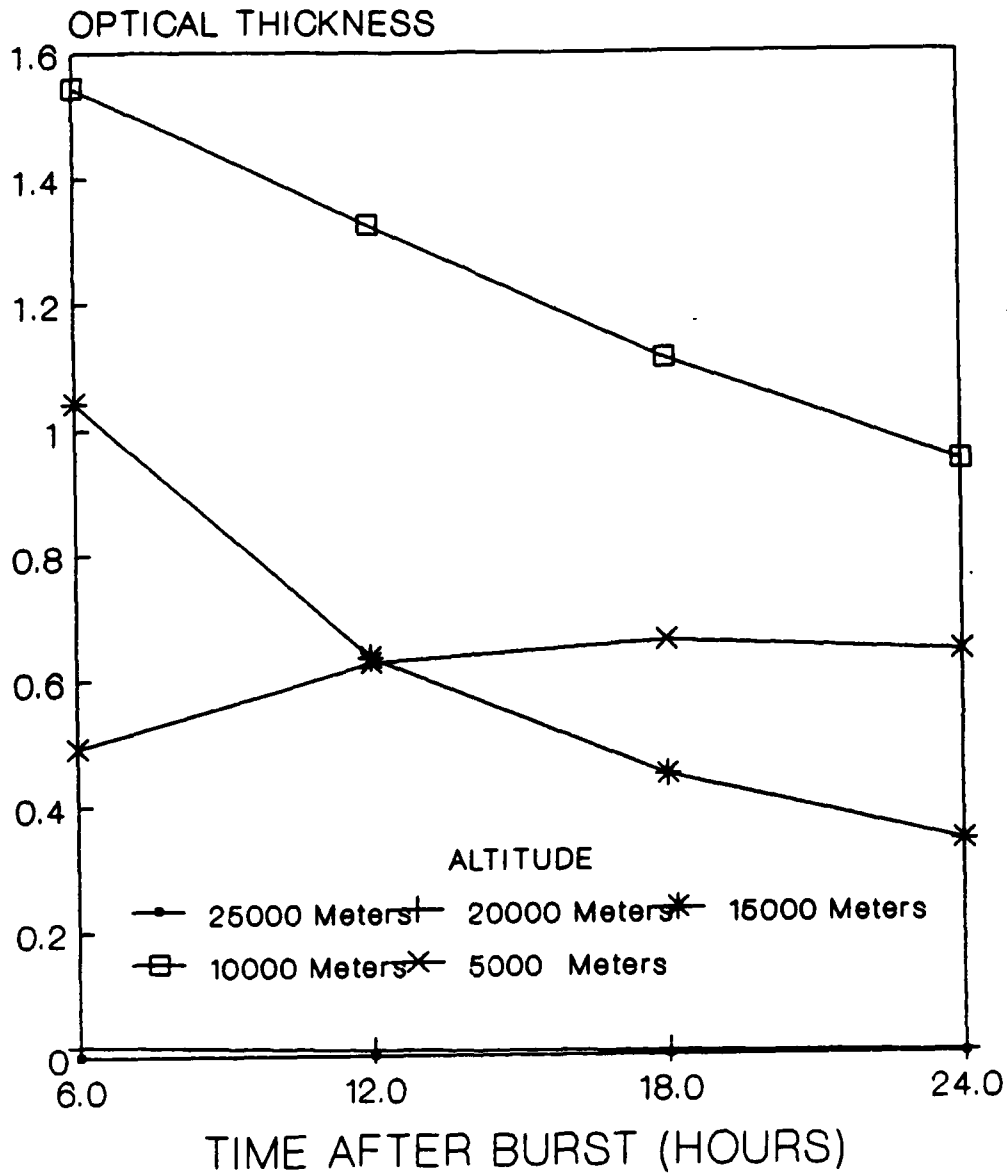
HORIZONTAL PATH THROUGH CLOUD CENTERLINE



1 MT-2 MICRONS-.204/4

Figure 5. One Megaton Surface Burst - 2 Micron Signal

OPTICAL THICKNESS HORIZONTAL PATH THROUGH CLOUD CENTERLINE

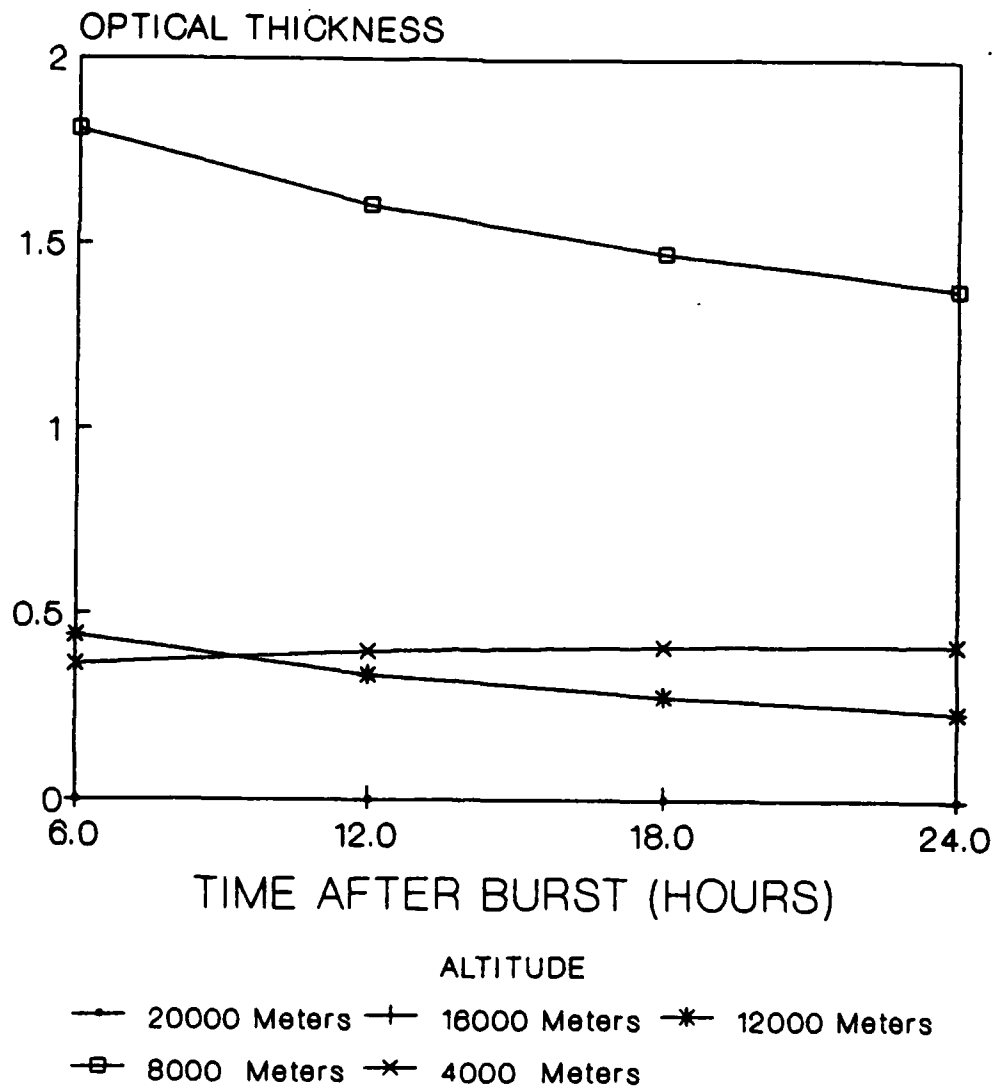


1 MT-7.9 MICRONS-.204/4

Figure 6. One Megaton Surface Burst - 7.9 Micron Signal

OPTICAL THICKNESS

HORIZONTAL PATH THROUGH CLOUD CENTERLINE

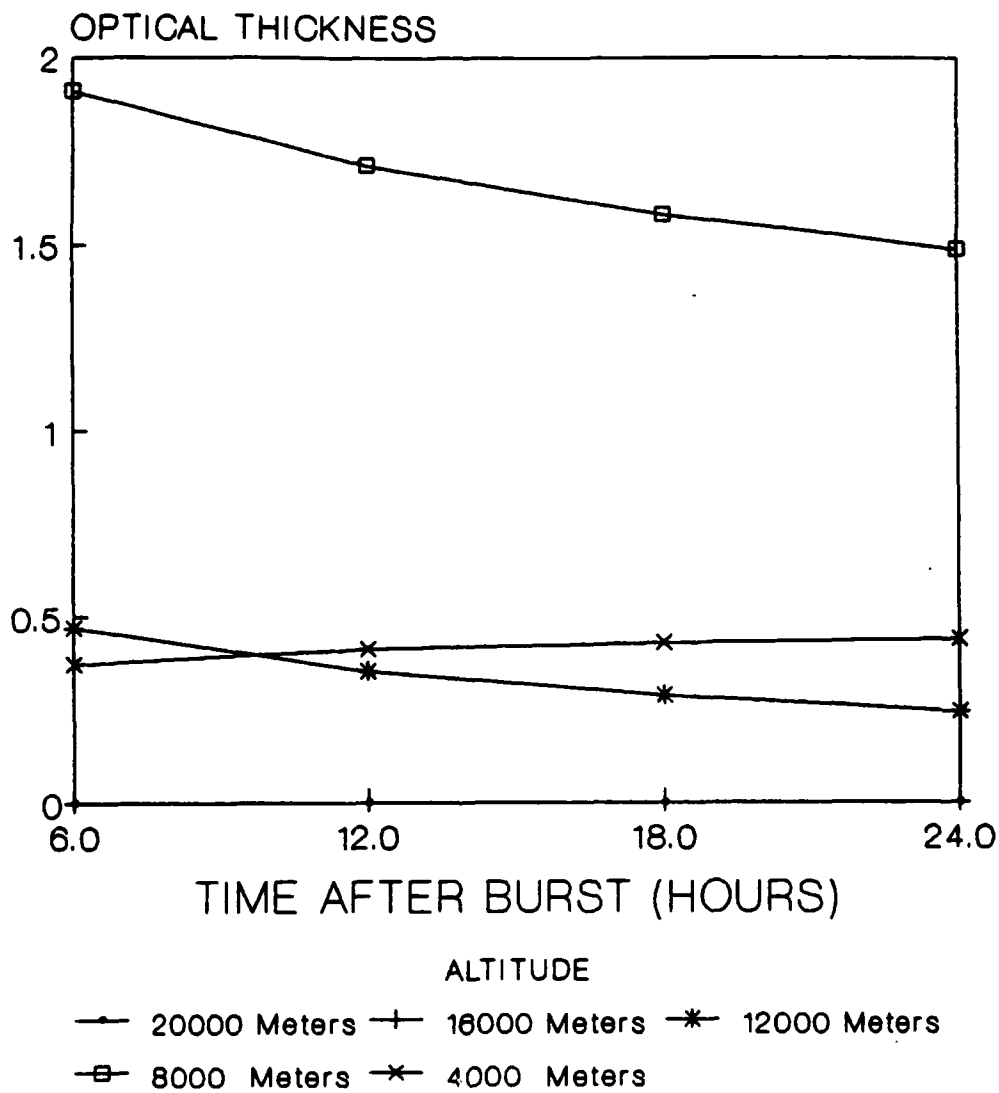


.1 MT-.55 MICRONS-204/4

Figure 7. 100 Kiloton Surface Burst - .55 Micron Signal

OPTICAL THICKNESS

HORIZONTAL PATH THROUGH CLOUD CENTERLINE

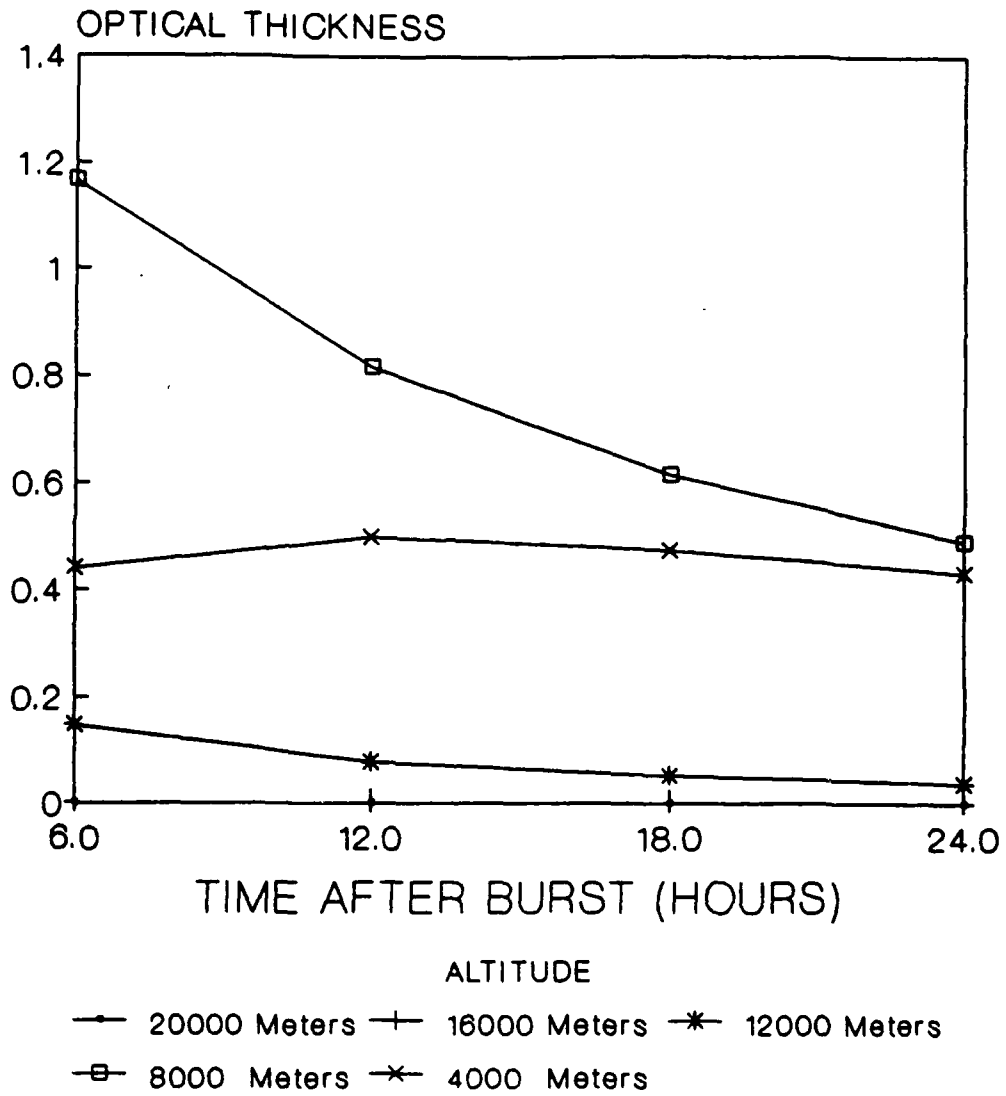


.1MT -2 MICRONS-.204/4

Figure 8. 100 Kiloton Surface Burst - 2 Micron Signal

OPTICAL THICKNESS

HORIZONTAL PATH THROUGH CLOUD CENTERLINE



.1MT-7.9 MICRONS-204/4

Figure 9. 100 Kiloton Surface Burst - 7.9 Micron Signal

V. Discussion and Conclusions

The optical thickness computed using localized dust cloud models is much greater than those found in global fallout models. The reason for this is the areas covered by global cloud models are 10^6 to 10^7 times greater than from smaller, more localized cloud models from smaller burst. When the area covered by the localized dust clouds is adjusted to match global model, optical thickness are well within one percent. See Verification of the Model.

The initial particle group altitude models developed by Hopkins and Pugh are extremely sensitive to the yield of the burst. The optical thickness calculated for yields above 69 megatons computed using OPTHICK, should be approached with caution since Pugh's model is used and places all particle groups at the same initial altitude.

The empirical fit developed by Diermendjian proved to be very useful in approximating the extinction efficiency of the different size dust particles. In order to validate the results achieved by this method, a full Mie calculation needs to be accomplished for comparison.

The optical thickness calculated are the result of interactions with only the dust particles lofted. Any additional attenuation caused by other aerosols already present

in the atmosphere, must be added to this to obtain the full impact on signal attenuation. The reader is directed to LOWTRAN - a computer code developed by the Air Force Geophysics Laboratory - which can be used to model several different atmospheres and climates for signal attenuation calculations.

The results tabulated and graphed in the Results section of this report were done using a no-wind model. This is valid when computing the optical thickness of the cloud since only airborne particles contribute to the optical thickness. This is unlike activity calculation models - which must consider the particles that have fallen to the ground - since these fallen particles contribute to the dose rate. Any wind introduced into the model only moves the cloud to a new location downwind.

VI. Future Considerations

1. This report only considers the direct attenuation of a signal through a dust cloud. It would be very useful to be able to account for any signals that are scattered back into the line-of-sight.
2. The response function of an optical sensor as a function of signal wavelength and intensity through the dust cloud.
3. The monochromatic treatment of light in this report is only valid for such devices that can create such a beam. Future studies should be able to incorporate spectrums of light.
4. Although OPTHICK can handle different distributions of particles, only one is used in this report - the DELFIC nominal distribution. Future studies may address the change in optical thickness with particle size distribution.

Appendix A: OPTHICK Source Code

(Written in QUICK BASIC 4.0)

```
DECLARE SUB SETUP ()
DECLARE FUNCTION PRB (ZX!, ROOT!)
COMMON SHARED INTERVAL!, NUMINT!, YLD, RNDX, INDX, WMIC,
ENTRY(), EX(), WVX
COMMON SHARED NDIST, NF(), STEPS%, HCKFT, FRAC, PI, R(), RMIC(),
RMM()
COMMON SHARED RMMIC(), G, RHOC, PERCENT()
COMMON SHARED ALPHA0!(), ALPHA2!(), ALPHA3!(), BETA!()
COMMON SHARED CF(), NRSQ!(), NTOT, SLOPE(), QEXT(), QABS(),
QSCAT()
DECLARE SUB OPT (LASTGP!(), QEXT!(), SIGX!, SIGY!, SIGZ!,
ALT!(), TACT, ITER)
DECLARE SUB HCCALC (X!, HC!, SIGX!, SIGY!, SIGZ!, T, HCKFT)
DECLARE SUB DISTCALC ()
DECLARE SUB LOFTED ()
DECLARE SUB MCDAVIES (ALT(), TOTTA(), LASTGP(), V(), TACT,
ZLOC(), OT(), SIGX, SIGY, SIGZ)
DECLARE SUB EFFCALC (RMIC!(), WMIC!, LASTGP!(), RNDX!, INDX!,
QEXT!(), QABS!(), QSCAT!(), NDIST)
DECLARE SUB CUMLOGDIST (RMMIC!(), SLOPE!(), RMM!(), ALPHA0!(),
ALPHA2!(), ALPHA3!(), BETA!(), RMIC!(), R!(), PERCENT!(),
FCOUNT)
DECLARE SUB ALPHABETA (A!, B!, A0!, A2!, A3!, BA!)
DECLARE SUB USATMOS (Z!, D!, VIS!)
DECLARE SUB MAINPROGRAM (OT(), ZLOC(), STEPS%, TACT, YLD,
ARUN#)
REDIM X(1000), y(1000), N AS INTEGER, dx AS INTEGER

'*****
*****

CALL MAINPROGRAM(X(), Y(), N, TACT, YLD, ARUN#)

SUB ALPHABETA (A, B, A0, A2, A3, BA)

'THIS IS FOR THE CUMULATIVE LOG-NORMAL DISTRIBUTION

PRINT "A,B"; A, B
BA = LOG(B)
A0 = LOG(A)
A2 = A0 + 2 * BA ^ 2
A3 = A0 + 3 * BA ^ 2
```

```

PRINT 'ALPHABETA'
  PRINT A, A0, A2, A3, B, BA
END SUB

SUB CUMLOGDIST(RMMIC(),SLOPE(),RMM(),ALPHA0(),ALPHA2(),ALP
HA3(),BETA(),
RMC(),R(),PERCENT(),ID)
OPEN 'O', #2, 'DIST' + CHR$(ID + 64) + '.DAT' THIS IS OUTPUT
FROM DISTRUTION
  CLS
  PRINT 'FOR FILE ': ID
  INPUT 'WHAT IS THE MEDIAN RADIUS(MICRONS) AND SLOPE (DEFAULT
= .204,4)'; RMMIC(ID), SLOPE(ID)
  IF RMMIC(ID) = 0 THEN
    RMMIC(ID) = .204
    SLOPE(ID) = 4
  END IF

  RMM(ID) = RMMIC(ID) * 10 ^ -6           'MEDIAN RADIUS IN
  METERS

  PRINT 'RMMIC(ID) ='; ID, RMMIC(ID)
  BEEP
  LOCATE 12, 20
  PRINT 'CALCULATING NEW DISTRIBUTION FILE'

  DIM Z(100), PROB(199)

  CALL ALPHABETA(RMMIC(ID), SLOPE(ID), ALPHA0(ID),
ALPHA2(ID), ALPHA3(ID), BETA(ID))

  PZ = -.005
  FOR I = 1 TO 50
    PZ = PZ + .01
    IF SLOPE(ID) < 1 THEN
      J = 101 - I
    ELSE
      J = I
    END IF
    TP = SQR(LOG(1 / PZ ^ 2))

    DUMMY = PRB(TP, ROOT)

    'ROOT = VALUE OF PROB FUNCTION FOR THE .005TH INCREMENT
    'FIND RADIUS OF THE PARTICLE THAT CORRELATES TO THE MEAN
    OF EACH BIN

```

```

      RMIC(J, ID) = EXP(-ROOT * BETA(ID) + ALPHA2(ID))
'RADIUS IN MICRONS
      RMIC(101 - J, ID) = EXP(ROOT * BETA(ID) + ALPHA2(ID))
'RADIUS IN MICRONS
      R(J, ID) = RMIC(J, ID) * 10 ^ -6          'RADIUS
IN METERS
      R(101 - J, ID) = RMIC(101 - J, ID) * 10 ^ -6      'RADIUS
IN METERS

```

```

      PERCENT(J, ID) = PZ: PERCENT(101 - J, ID) = 1 - PZ
NEXT I
PRINT #2, USING "#.***  *.***"; RMMIC(ID), SLOPE(ID)
FOR L = 1 TO 100
PRINT #2, USING "#.*****^0000  .***"; R(L, ID), PERCENT(L,
ID) 'R IS IN METERS
NEXT L
      CLOSE #2
END SUB

```

SUB DISTCALC

```

PRINT
PRINT "DO YOU WANT TO CREATE A NEW DISTRIBUTION FILE (PARTICLE
RADIUS VS."
PRINT "PERCENTILE IN .005% INCREMENTS) OR USE EXISTING DATA
(ACTDIST.DAT?)"
PRINT
INPUT "ENTER N FOR NEW (OLD IS DEFAULT)"; ANS#

```

FOR ID = 1 TO NDIST

```

IF VAL(ANS#) <> 0 OR ANS# = 'N' THEN
      CALL CUMLOGDIST(RMMIC(), SLOPE(), RMM(), ALPHA0(),
ALPHA2(), ALPHA3(), BETA(), RMIC(), R(), PERCENT(), ID)
ELSE

```

```

INPUT "ENTER NAME OF DISTRIBUTION DATA FILE (DEFAULT =
'C:DIST(A/B).DAT)"; DIST#

```

IF DIST# <> "" THEN

```

      OPEN "I", #2, DIST#          'READS IN DISTRIBUTION CREATED
PRIOR BY CUMLOGDIST
      OPEN "O", #3, "DIST" + CHR$(64 + ID) + ".DAT"
ELSE
      OPEN "I", #2, "DIST" + CHR$(64 + ID) + ".DAT"
      OPEN "O", #3, "SCRN:"

```

```

END IF
INPUT #2, RMMIC(ID), SLOPE(ID)
PRINT #3, RMMIC(ID), SLOPE(ID)

RMM(ID) = RMMIC(ID) * 10 ^ -6           ' CONVERTS MEAN RADIUS
FROM MICRONS TO METERS

FOR I = 1 TO 100
INPUT #2, R(I, ID), PERCENT(I, ID): RMIC(I, ID) = R(I, ID)
* 10 ^ 6 ' READS IN METERS; CONVERTS TO MICRONS
' PRINT #3, R(I, ID), PERCENT(I, ID) ' WRITES TO
'DIST(A,B).DAT FOR FUTURE USE
' PRINT , USING "*****^" "*****"; RMIC(I, ID), PER-
CENT(I, ID)
NEXT I

PRINT "SLOPE"; ID; SLOPE(ID)

CALL ALPHABETA(RMMIC(ID), SLOPE(ID), ALPHA0(ID),
ALPHA2(ID), ALPHA3(ID), BETA(ID))

CLOSE #2: CLOSE #3

END IF

NEXT ID

END SUB

' *****EXTCOEFF*****
' *****

SUB EFFCALC (RMIC(), WMIC, LASTGP(), RNDX, INDX, QEXT(), QABS(),
QSCAT(), NDIST)

' CALCULATES EXTINCTION, ABSORPTION, AND SCATTER EFFICIENCIES

FOR K = 1 TO NDIST

OPEN "O", #2, "EXTCOFS" + CHR$(64 + K) + ".DAT"
PI = 4 * ATN(1)

FOR I = 1 TO LASTGP(K) STEP 1

```

```

ALPH = 2 * PI * RMIC(I, K) / WMIC
TANB = INDX / (RNDX - 1)
B = ATN(TANB)
F = (1 + TANB) * (1 + 3 * TANB)
RHO = 2 * ALPH * (RNDX - 1)

IF RHO <= 5 * (RNDX - 1) AND RHO < 4.08 / (1 + 3 * TANB) THEN
  D = .613 * (RNDX - 1) ^ 2 / RNDX * (1 + F) - (5 * (RNDX -
1) - RHO) * (5 * (RNDX - 1) * F) ^ -1
ELSEIF RHO >= 5 * (RNDX - 1) AND RHO <= 4.08 / (1 + 3 * TANB)
THEN
  D = .123 * (1 + F) * RHO * (RNDX - 1) * RNDX ^ -1
ELSEIF RHO >= 4.08 / (1 + 3 * TANB) AND RHO <= 4.08 / (1 +
TANB) THEN
  D = .5 * (1 + F) * (RNDX - 1) * RNDX ^ -1 / (1 + 3 * TANB)
ELSEIF RHO > 4.08 / (1 + TANB) THEN
  D = 2.04 * (1 + F) * F ^ -1 * (RNDX - 1) * RNDX ^ -1 * RHO
^ -1
END IF

X = RHO * TANB

QEXT(I, K) = (2 - 4 * EXP(-X) * (RHO ^ -1 * COS(B) * SIN(RHO
- B) + RHO ^ -2 * COS(B) ^ 2 * COS(RHO - 2 * B)) + 4 * RHO ^
-2 * COS(B) ^ 2 * COS(2 * B)) * (1 + D)

IF X > 25 THEN
  QABS(I, K) = 1
ELSE
  QABS(I, K) = (1 + EXP(-2 * X) / X + (EXP(-2 * X) - 1) / (2
* X ^ 2)) * (1 + D)
END IF

QSCAT(I, K) = QEXT(I, K) - QABS(I, K)

'PRINT "QEXT,QABS,QSCAT"; QEXT(i, k); QABS(i, k); QSCAT(i, k)
'PRINT , USING "###.###" **.* **.* **.*"; RMIC(I, K);
QEXT(I, K); QABS(I, K); QSCAT(I, K)

PRINT #2, USING "###.###" **.* **.* **.*"; RMIC(I, K);
QEXT(I, K); QABS(I, K); QSCAT(I, K)
  NEXT I
CLOSE #2
NEXT K
PRINT "DONE EXT"
END SUB

```

```

SUB HCCALC (X, HC, SIGX, SIGY, SIGZ, T, HCKFT)

THR = T / 3600                                'TIME IN HOURS

TC = 12 * (HCKFT / 60) - 2.5 * (HCKFT / 60) ^ 2
HC = HCKFT * 1000 / 3.281                      'CONVERT
TO METERS
SIGZ = .18 * HC                                'METERS

PRINT 'HC(METERS) ='; HC
SIGZERO = 1609 * EXP(.7 + .333 * LOG(X) - 3.25 / (4 + (LOG(X)
+ 5.4) ^ 2)) 'METERS

IF THR < 3 THEN
    TASTAR = THR
ELSE
    TASTAR = 3
END IF

SIGX = (SIGZERO ^ 2 * (1 + (8 * TASTAR / TC))) ^ .5 'METERS
SIGY = SIGX 'METERS

END SUB

SUB LOFTED

    PRINT 'LOFTED'

OPEN 'O', #5, 'MASSVSR.PLT'
OPEN 'O', #6, 'NOVSR.PLT'

MASSLOFT = FRAC * 1000 * YLD                    'KTONS = KTON MASS LOFTED PER
KTON OF YIELD

INPUT 'CALCULATE TOTAL NUMBER OF PARTICLES BASED ON YIELD
(Y=DEFAULT/N)'; NTOTYN#
IF NTOTYN# = '' OR NTOTYN# = 'Y' THEN
    IF NF(2) <> 0 THEN
        NTOT = 3 * MASSLOFT * 9.09 * 10 ^ 5 / (4 * PI * RHOC) *
(NF(1) * EXP(-9 / 2 * BETA(1) ^ 2) / RMM(1) ^ 3 + NF(2) *
EXP(-9 / 2 * BETA(2) ^ 2) / RMM(2) ^ 3) 'TOTAL NUMBER OF PARTICLES
    ELSE
        NTOT = 3 * MASSLOFT * 9.09 * 10 ^ 5 / (4 * PI * RHOC) *
(NF(1) * EXP(-9 / 2 * BETA(1) ^ 2) / RMM(1) ^ 3) 'TOTAL NUMBER
OF PARTICLES
    
```

```

      END IF
    ELSE
      INPUT 'ENTER NTOT'; NTOT
    END IF
    PRINT NTOT

    CFTOT = NF(1) * RMM(1) ^ 2 * EXP(2 * BETA(1) ^ 2) + NF(2) *
    RMM(2) ^ 2 * EXP(2 * BETA(2) ^ 2)

    CF(1) = NF(1) * RMM(1) ^ 2 * EXP(2 * BETA(1) ^ 2) / CFTOT
    CF(2) = NF(2) * RMM(2) ^ 2 * EXP(2 * BETA(2) ^ 2) / CFTOT

    NRSQ(1) = NTOT * CF(1) * RMM(1) ^ 2 * EXP(2 * BETA(1) ^ 2)
    TOTAL NUMBER OF PARTICLES * R^2
    NRSQ(2) = NTOT * CF(2) * RMM(2) ^ 2 * EXP(2 * BETA(2) ^ 2)
    TOTAL NUMBER OF PARTICLES * R^2

    PRINT 'DONE MASSLOFT'

    CLOSE #5: CLOSE #6

    END SUB

SUB MAINPROGRAM (OT(), ZLOC(), STEPS%, TACT, YLD, ARUN#)

'*****DEFINE*****CON-
STANTS*****
PI = 4 * ATN(1)
RHOC = 2600 'KG/M^3 'AVERAGE VALUE FOR DENSITY OF
DUST
G = 9.8 'M/S^2 'GRAVITY

'*****ARRAYS*****
*****
DIM N(100), R(100, 2), RMIC(100, 2), RMM(2), RMMIC(2), SLOPE(2)
DIM PERCENT(100, 2), V(100), TOTTA(100, 2), ALT(100, 2),
RACT(100)
DIM NOFR(100, 2), PERACT(100), NF(2), CF(2), ALPHA0(2),
ALPHA2(2), ALPHA3(2)
DIM BETA(2), NRSQ(2)
DIM QEXT(100, 2), QABS(100, 2), QSCAT(100, 2), ENTRY(3), EX(3),
LASTGP(2)

```

```
'*****MAIN
GRAM*****
```

PRO-

CLS

```
'      THIS PROGRAM CALCULATES MASS AND NUMBER DENSITY AT
DISCRETE ALTITUDES
'      AT TIME t. THE PARTICLES HAVE A GAUSSIAN DISTRIBUTION
IN THE X,Y, AND
'      Z DIRECTION FROM THE CENTER OF THE STABILIZED CLOUD.
'      THE DISTRIBUTION IS BASED ON THE USER'S INPUT OF MEAN
RADIUS (MICRONS)
'      AND LOGRITHMIC SLOPE (MICRONS).
```

```
CALL SETUP
CALL DISTCALC
CALL LOFTED
CALL MCDAVIES(ALT(), TOTTA(), LASTGP(), V(), TACT, ZLOC(),
OT(), SIGX, SIGY, SIGZ)
```

CLOSE

END SUB

```
'*****MCDAVIES*****
*****
SUB MCDAVIES (ALT(), TOTTA(), LASTGP(), V(), TACT, ZLOC(),
OT(), SIGX, SIGY, SIGZ)
LASTGP(1) = 100: LASTGP(2) = 100
```

PRINT 'MCDAVIES'

```
CALL EFFCALC(RMIC(), WMIC, LASTGP(), RNDX, INDX, QEXT(),
QABS(), QSCAT(), NDIST)
CALL HCCALC(YLD, Z, SIGX, SIGY, SIGZ, TACT, HCKFT)
'STABILIZED CLOUD HEIGHT
```

ZDEFAULT = Z

```
'*****
*****
'HOPKINS' VERTICLE DISTRIBUTION
```

```
FOR LL = 1 TO NDIST
FOR J = 1 TO LASTGP(LL) STEP 1
```

```

YFAC = LOG(1000 * YLD)
c1 = -EXP(1.574 - .01197 * YFAC + .03636 * YFAC ^ 2 - .0041
* YFAC ^ 3 + .0001965 * YFAC ^ 4)
c2 = EXP(7.889 + .34 * YFAC + .001226 * YFAC ^ 2 - .005227 *
YFAC ^ 3 + .000417 * YFAC ^ 4)
Z = 2 * c1 * RMIC(J, LL) + c2

IF Z > 61000 THEN
  STEP1 = 1
END IF

IF STEP1 = 0 THEN
  ALT(J, LL) = Z
ELSE
  ALT(J, LL) = ZDEFAULT      'STARTS ALL PARTICLES AT STABILIZE
  CLOUD HEIGHT HC
END IF
  TOTTA(J, LL) = 0          'RESET TIME TO ZERO AT STABILIZATION
PRINT J, LL, RMIC(J, LL), ALT(J, LL)
NEXT J
NEXT LL

'*****
*****

OPEN 'O', #1, 'DUMP.DAT'      'OUTPUT ACTIVITY DISTRIBUTION

INTERVAL = INTERVAL * 3600    'CONVERTS HOURS TO SECONDS

FOR I = 1 TO NUMINT

TACT = I * INTERVAL          'ELAPSED TIME (SECS)
CALL HCCALC(YLD, Z, SIGX, SIGY, SIGZ, TACT, HCKFT)
'Stabilized CLOUD HEIGHT

FOR LL = 1 TO NDIST

LASTGP(LL) = 100

PRINT , '*      PARTICLE RADIUS(M)  XTILE  ALT(M)  TIME(HRS)
DELTAZ(M)  VEL(M/S)'
BOTFLAG = 1
PRINT 'LASTGP='; LASTGP(LL)

L = 1

WHILE BOTFLAG AND L <= LASTGP(LL) AND LL <= NDIST

```

```
Z = ALT(L, LL)
DELZ = 100
```

```
  WHILE TOTTA(L, LL) < TACT
    Z = Z - DELZ / 2
    CALL USATMOS(Z, D, VIS)
    RHOA = D
    ETA = VIS
```

```
    Q = (32 / 3) * RHOA * RHOC * G * R(L, LL) ^ 3 / ETA ^ 2
    IF Q <= 100 THEN
```

```
      IF Q < 3.7 * 10 ^ -8 THEN
        Q = 3.7 * 10 ^ -8
```

```
      'QWBASIC UNDERFLOW
```

```
PROTECTOR
  END IF
```

```
  RNUM = (Q / 24) - 2.3363 * 10 ^ -4 * Q ^ 2 + 2.0154 * 10 ^ -6
  * Q ^ 3 - 6.9105 * 10 ^ -9 * Q ^ 4
  ELSE
```

```
  RNUM = 10 ^ (-1.29536 + .986 * .43429 * LOG(Q) - .046677 *
  (.43429 * LOG(Q)) ^ 2 + .0011235 * (.43429 * LOG(Q)) ^ 3)
  END IF
```

```
  V(L) = RNUM * ETA / (RHOA * 2 * R(L, LL))
  TAFLAG = 1
  TA = DELZ / V(L)
```

```
  TOTTA(L, LL) = TA + TOTTA(L, LL)
```

```
  IF TOTTA(L, LL) > TACT THEN
    TOTTA(L, LL) = TOTTA(L, LL) - TA
    TLAST = TACT - TOTTA(L, LL)
    ZLAST = V(L) * TLAST
    TOTTA(L, LL) = TLAST + TOTTA(L, LL)
    Z = Z - ZLAST
  ELSE
    Z = Z - DELZ
  END IF
```

```
  WEND
```

```
ALT(L, LL) = Z
```

```

      IF Z < 0 THEN
        LASTGP(LL) = L - 1
        BOTFLAG = 0
        'LAST GROUP THAT IS STILL
ALOFT
        PRINT 'LAST GROUP = '; LASTGP(LL)

      ELSE
        'PRINT 'DONE MCDAVIES'
        'PRINT #1, USING '***      *.****      **.***      *****.**
        *.****      *.****      *.****; L; R(L,LL); PERCENT(L,LL);
        ALT(L,LL); TOTTA(L,LL) / 3600; DELZ; V(L)
        PRINT USING '***      *.****      **.***      *****.**      **.***
        *.****      *.****; L; R(L, LL); PERCENT(L, LL); ALT(L, LL);
        TOTTA(L, LL) / 3600; DELZ; V(L)
        'PRINT V(L)

      END IF
      L = L + 1

    WEND

  NEXT LL

  CALL OPT(LASTGP(), QEXT(), SIGX!, SIGY!, SIGZ!, ALT(), TACT,
  ITER)

  NEXT I

  CLOSE #1: CLOSE #2

  END SUB

SUB OPT (LASTGP(), QEXT(), SIGX, SIGY, SIGZ, ALT(), TACT, ITER)
  REDIM XLOC(STEPS%), YLOC(STEPS%), ZLOC(STEPS%), OT(STEPS%)
  'COMPUTES LOCATION AND OT ALONG THE LINE OF PATH

  DIRX = EX(1) - ENTRY(1)
  DIRY = EX(2) - ENTRY(2)
  DIRZ = EX(3) - ENTRY(3)

  RHO = SQR(DIRX ^ 2 + DIRY ^ 2 + DIRZ ^ 2)

  DRHO = RHO / STEPS%

```

PRINT DRHO

PRINT RHO; DRHO; DIRX; DIRY; DIRZ
PRINT SIGX; SIGY; SIGZ

FOR I = 1 TO STEPSZ

IF I = 1 THEN

XLOC(1) = ENTRY(1) + DRHO / 2 * DIRX / RHO
YLOC(1) = ENTRY(2) + DRHO / 2 * DIRY / RHO
ZLOC(1) = ENTRY(3) + DRHO / 2 * DIRZ / RHO

ELSE

XLOC(I) = XLOC(1) + (I) * DRHO * DIRX / RHO
YLOC(I) = YLOC(1) + (I) * DRHO * DIRY / RHO
ZLOC(I) = ZLOC(1) + (I) * DRHO * DIRZ / RHO

END IF

SUMFZ = 0

FOR II = 1 TO NDIST
PRINT CF(II), NRSQ(II)
FOR J = 1 TO LASTGP(II) STEP 1

IF ABS(ZLOC(I) - ALT(J, II)) < 3 * SIGZ THEN

SUMFZ = CF(II) * NRSQ(II) * QEXT(J, II) / (SIGZ * (2 *
PI) ^ .5) * EXP(-.5 * ((ZLOC(I) - ALT(J, II)) / SIGZ) ^ 2) +
SUMFZ

END IF

NEXT J

NEXT II

```

IF ABS(XLOC(I) - WVX * TACT) < 3 * SIGX THEN
    SUMFX = EXP(-.5 * ((XLOC(I) - WVX * TACT) / SIGX) ^ 2) /
(SIGX * (2 * PI) ^ .5)
END IF

IF ABS(YLOC(I)) < 3 * SIGY THEN
    SUMFY = EXP(-.5 * (YLOC(I) / SIGY) ^ 2) / (SIGY * (2 *
PI) ^ .5)
END IF

SPATIAL = SUMFX * SUMFY * SUMFZ

OT(I) = .01 * PI * SUMFX * SUMFY * SUMFZ * DRHO
TOTOT = TOTOT + OT(I)
PRINT "TOTOT ="; TOTOT

PRINT , USING " ** ***** ***** ***** *.*****^"; I, XLOC(I),
YLOC(I), ZLOC(I), OT(I)

NEXT I

    OPEN "O", #2, "OT.OUT"
    PRINT #2, USING " ***** ***** *****^"; ZLOC(1), ZLOC(2), ZLOC(3),
ZLOC(4), ZLOC(5)
    PRINT , USING " ***** ***** *****^"; ZLOC(1), ZLOC(2), ZLOC(3), ZLOC(4), ZLOC(5)

PRINT #2, USING " ***.* *.*****^ ***.* *****^ ***.* *****^
*.*****^ ***.* *****^ "; TACT / 3600, OT(1), OT(2), OT(3),
OT(4), OT(5)
PRINT , USING " ***.* *.*****^ ***.* *****^ ***.* *****^
*.*****^ *.*****^ "; TACT / 3600, OT(1), OT(2), OT(3),
OT(4), OT(5)

END SUB

FUNCTION PRB (ZX, ROOT)

C0 = 2.515517: D1 = 1.432788
c1 = .802853: D2 = .189269
c2 = .010328: D3 = .001308

```

```
ROOT = ZX - (C0 + c1 * ZX + c2 * ZX ^ 2) / (1 + D1 * ZX + D2
* ZX ^ 2 + D3 * ZX ^ 3)
```

```
END FUNCTION
```

```
SUB SETUP
```

```
LOCATE 1, 1
```

```
INPUT 'HOW LONG(HRS) AFTER CLOUD STABILIZATION IS THE SIGNAL
TO BE SENT (DEFAULT=.5)'; TD
```

```
IF TD = 0 THEN
```

```
TD = .5
```

```
END IF
```

```
INPUT 'WHAT TIME INCREMENTS DO YOU WANT TO USE (DEFAULT = .5
HRS)'; INTERVAL!
```

```
IF INTERVAL! = 0 THEN
```

```
INTERVAL! = .5
```

```
END IF
```

```
PRINT 'HOW MANY OF THESE TIME INTERVALS WOULD YOU LIKE'
```

```
INPUT '(DEFAULT = TIME DESIRED/TIME INCREMENT)'; NUMINT!
```

```
IF NUMINT! = 0 THEN
```

```
NUMINT! = TD / INTERVAL!
```

```
END IF
```

```
IF ZI = 0 THEN
```

```
ZI = 5000
```

```
END IF
```

```
INPUT 'YIELD IN MEGATONS (DEFAULT = 1MT)'; YLD
```

```
IF YLD = 0 THEN
```

```
YLD = 1
```

```
END IF
```

```
INPUT 'FRACTION OF MASS LOFTED PER TON OF YIELDS (DEFAULT =
.3TONS/TON)'; FRAC
```

```
IF VAL('FRAC') = 0 THEN
```

```
FRAC = .3
```

```
END IF
```

```

INPUT 'ENTER WAVELENGTH(MICRONS) OF SIGNAL(DEFAULT = .55)';
WMIC
IF WMIC = 0 THEN
    WMIC = .55
END IF
RNDX = 0
INDX = 0
INPUT 'ENTER REAL PART OF INDEX OF REFRACTION(DEFAULT=1.53)';
RNDX
INPUT 'ENTER IMAGINARY PART OF INDEX OF REFRACTION(DE-
FAULT=.0066)'; INDX

IF RNDX = 0 THEN
    RNDX = 1.53
END IF
IF INDX = 0 THEN
    INDX = .0066
END IF

INPUT 'PARTICLE NUMBER DISTRIBUTION MADE UP OF (1) OR (2)
DISTRIBUTIONS (DEFAULT = 1)'; NDIST
IF NDIST = 0 OR NDIST = 1 THEN
    NDIST = 1

END IF

INPUT 'WHAT IS THE NUMBER FRACTION OF THE FIRST DISTRIBUTION
(DEFAULT = 1)'; NF(1)

IF NF(1) = 0 OR (NDIST = 1 AND NF(1) < 1) THEN
    NF(1) = 1
    NF(2) = 0
    NDIST = 1
ELSE
    NF(2) = 1 - NF(1)
END IF
PRINT NF(1), NF(2)

INPUT 'ENTER X,Y,Z COORDS OF SIGNAL ORIGIN'; ENTRY(1), ENTRY(2),
ENTRY(3)

INPUT 'ENTER X,Y,Z COORDS OF SIGNAL RECEIPT'; EX(1), EX(2),
EX(3)

```

```

INPUT 'ENTER THE NUMBER OF STEPS ALONG THE SIGNAL PATH TO
COMPUTE(DEFAULT = 100)'; STEPS%
IF STEPS% = 0 THEN
    STEPS% = 100
END IF

INPUT 'ENTER CLOUD STABILIZATION HEIGHT(KFT) (ENTER FOR
DEFAULT)'; HCKFT

IF HCKFT = 0 THEN
    HCKFT = 44 + 6.1 * LOG(YLD) - .205 * (LOG(YLD) + 2.42) *
ABS(LOG(YLD) + 2.42) 'STABILIZED CLOUD CENTER HEIGHT (KFT)
END IF

INPUT 'ENTER THE WIND VELOCITY (M/S) IN THE X-DIRECTION (DEFAULT
= 0)'; WVX

END SUB

```

```

SUB USATMOS (Z, D, VIS)          'MODEL OF US STANDARD ATMOSPHERE

```

```

REM * US STANDARD ATMOSPHERE *
P0 = 1013001
IF Z < 11000 THEN T = 288.15 - .006545 * Z: P = P0 * (288.15
/ T) ^ (-.034164 / .006545)
IF (Z >= 11000) AND (Z < 20000) THEN T = 216.65: P = 226901
* EXP(-.034164 * (Z - 11000) / 216.65)
IF (Z >= 20000) AND (Z < 32000) THEN T = 216.65 + .001 * (Z
- 20000): P = 5528 * (216.65 / T) ^ (.034164 / .001)
IF (Z >= 32000) AND (Z < 470001) THEN T = 228.65 + .0028 *
(Z - 32000): P = 888.8 * (228.65 / T) ^ (.034164 / .0028)
IF (Z >= 470001) AND (Z < 520001) THEN T = 270.65: P = 115.8
* EXP(-.034164 * (Z - 470001) / T)
IF (Z >= 520001) AND (Z < 610001) THEN T = 270.65 - .002 *
(Z - 520001): P = 62.21 * (270.65 / T) ^ (-.034164 / .002)
IF (Z >= 610001) THEN PRINT 'Z OUT OF RANGE'
D = .003484 * P / T
S = SQR(401.86 * T)
VIS = 1.458E-06 * T ^ 1.5 / (T + 110.4)
MI = .10197 * P
END SUB

```

Appendix B: The Lognormal Distribution

The lognormal number distribution of particles per unit radius is given by

$$N(r) = \frac{N_T}{\sqrt{2\pi\beta r}} e^{-\frac{1}{2}\left(\frac{\ln(r)-\alpha_0}{\beta}\right)^2}$$

and the number of particles per unit radius between r and $r + dr$ is

$$N(r)dr = \frac{N_T}{\sqrt{2\pi\beta r}} e^{-\frac{1}{2}\left(\frac{\ln(r)-\alpha_0}{\beta}\right)^2} dr$$

where

N_T is the total number of particles in the distribution

α_0 is the natural log of the mean radius and

β is the natural log of the slope.

The number of particles in one kilogram of mass is then calculated by equation

$$1 \text{ kg} = N_m \frac{4}{3} \pi \rho \int_0^{\infty} r^3 n(r) dr$$

where

N_m are the number of particles per unit mass and

ρ is the density of each particle and

$n(r)$ is a distribution normalized to 1.

Letting

$$z = \frac{\ln(r) - \alpha_0}{\beta}$$

$$dr = \beta r dz$$

$$\text{and } r = e^{z\beta + \alpha_0}$$

Substituting these into the original expression yields

$$1kg = \frac{N_m 4\pi\rho}{3} e^{3\alpha_0} \int_{-\infty}^{\frac{\ln(r) - \alpha_0}{\beta}} \frac{e^{3z\beta} e^{-\frac{1}{2}z^2}}{\sqrt{2\pi}} dz$$

and by completing the square in the exponent we now have

$$1kg = \frac{N_m 4\pi\rho r_m^3}{3} e^{\frac{9}{2}\beta^2} \int_{-\infty}^{\frac{\ln(r) - \alpha_0}{\beta}} \frac{e^{-\frac{1}{2}(z^2 - 6z\beta + 9\beta^2)}}{\sqrt{2\pi}} dz$$

This simplifies to

$$1kg = \frac{N_m 4\pi\rho r_m^3 e^{\frac{9}{2}\beta^2}}{3} \int_{-\infty}^{\frac{\ln(r) - \alpha_0}{\beta}} \frac{e^{-\frac{1}{2}(z - 3\beta)^2}}{\sqrt{2\pi}} dz$$

Now, letting

$$w = z - 3\beta = \frac{\ln(r) - \alpha_0}{\beta} - 3\beta = \frac{\ln(r) - \alpha_3}{\beta}$$

$$dw = dz \text{ and } \alpha_3 = \alpha_0 + 3\beta^2$$

(This last parameter is a property of the third moment of the lognormal distribution.)

Substituting these parameters into the previous expression and evaluating the integral yields

$$N_m = \frac{3}{4\pi\rho\langle r^3 \rangle}$$

where $\langle r^3 \rangle$ is defined as $\Gamma_m e^{\frac{3}{2}\beta^2}$.

Multiplying N_m by the total mass of the dust lofted in the cloud, M_T , yields the total number of particles in the cloud.

Similarly the second moment property of the lognormal distribution is defined as

$$\langle r^2 \rangle = \Gamma_m e^{\frac{5}{2}\beta^2}.$$

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