

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12

DTIC FILE COPY

AFGL-TR-86-0266

Review of Inversion Techniques for
Spaceborne Lidar Systems

Derek W. Gallon
John R. Hummel

OptiMetrics, Inc
121 Middlesex Turnpike
Burlington, MA 01803

DTIC
ELECTE
SEP 03 1987
S D
D

AD-A184 164

December 1986

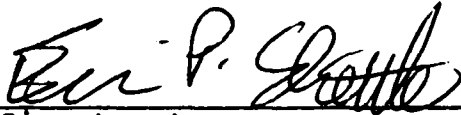
Scientific Report No. 2

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

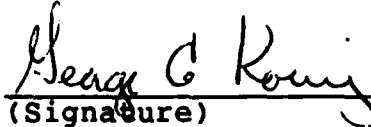
AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731

87 9 2 00

"This technical report has been reviewed and is approved for publication"



(Signature)
ERIC P. SHETTLE
Contract Manager



(Signature)
GEORGE G. KOENIG, Lt Col, USAF
Acting Branch Chief

FOR THE COMMANDER



(Signature)
R. EARL GOOD
Division Director

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified		1b RESTRICTIVE MARKINGS	
2a SECURITY CLASSIFICATION AUTHORITY		3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			
4 PERFORMING ORGANIZATION REPORT NUMBER(S) OMI-181		5. MONITORING ORGANIZATION REPORT NUMBER(S) AFGL-TR-86-0266	
6a NAME OF PERFORMING ORGANIZATION OptiMetrics, Inc.	6b OFFICE SYMBOL (if applicable)	7a NAME OF MONITORING ORGANIZATION Air Force Geophysics Laboratory	
6c ADDRESS (City, State, and ZIP Code) 121 Middlesex Turnpike Burlington, MA 01803		7b ADDRESS (City, State, and ZIP Code) Hanscom AFB, MA 01731	
8a NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Geophysics Lab	8b OFFICE SYMBOL (if applicable) OPA	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F19628-85-C-0178	
8c ADDRESS (City, State, and ZIP Code) Hanscom AFB, MA 01731		10 SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO 62101F	PROJECT NO 7670
11 TITLE (Include Security Classification) Review of Inversion Techniques for Spaceborne Lidar Systems			
12 PERSONAL AUTHOR(S) Derek W. Gallon and John R. Hummel			
13a TYPE OF REPORT Scientific No. 2	13b TIME COVERED M 4/86 TO 9/86	14 DATE OF REPORT (Year, Month, Day) 1986 December	15 PAGE COUNT 88
16 SUPPLEMENTARY NOTES			
17 COSMIC CODES		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Lidar Lasers Aerosol optical properties	
FIELD	GROUP SUB-GROUP		
19 ABSTRACT (Continue on reverse if necessary and identify by block number) An examination of inversion techniques applicable for a spaceborne lidar system has been made. The purpose has been to recommend a technique that could be used with the lidar system under development by AFGL. In a Rayleigh atmosphere with no or minimal gaseous absorption, a power law relationship between backscattering and extinction exists in which k=1. In an atmosphere with aerosols and clouds, the assumption of a power law relationship is tenuous at best. An examination of the literature leads us to conclude that the power law relationship has no physical basis to support its extensive use. For any application probing different regions of the atmosphere and different types of aerosols, one cannot assume a single set of power law parameters for the entire atmosphere. -Over-			
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS		21 ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL Eric Shettle		22b TELEPHONE (Include Area Code) 617-377-3665	22c OFFICE SYMBOL AFGL/OPA

Contents

1.	INTRODUCTION	1
2.	FORMULATION OF THE LIDAR INVERSION PROBLEM	3
2.1	The Lidar Equation	3
2.2	Homogeneous Atmosphere	4
2.3	The Ratio Method	6
2.4	Power Law Relationship Between Scattering & Extinction Coefficients	7
2.4.1	The "Klett Method"	9
2.4.2	Mid-Field Solution	10
2.4.3	The Validity of the Power Law Relationship	10
2.5	Linear Wavelength Dependence of Aerosol Scattering	18
2.6	Applicability of the Available Inversion Techniques for Spaceborne Applications	22
3.	SIMULATIONS OF INVERSIONS FROM A SPACEBORNE LIDAR SYSTEM	25
3.1	Simulated Atmosphere	25
3.1.1	Case 1 - Aerosol-free Atmosphere at 337 nm	34
3.1.2	Case 2 - Aerosol-free Atmosphere at at 514.5 nm	34
3.1.3	Case 2 Plus Background Stratospheric Aerosols	39
3.1.4	Case 2 Plus Clear Tropospheric Aerosols	44
3.1.5	Case 2 Plus Combined Stratospheric and Tropospheric Aerosols	44
3.1.6	Case 2 Plus Aged Volcanic Aerosols	53
3.1.7	Case 2 Plus Fresh Volcanic Aerosols	53
3.1.8	Case 2 Plus Combined Background Stratospheric and Fresh Volcanic Aerosols	59
3.2	Evaluating the Boundary Conditions in a "Real World" Situation	67
3.3	Summary of Results Utilizing a Power Law Inversion Approach	68

4.	AN ALTERNATE INVERSION APPROACH FOR A SPACE-BORNE LIDAR SYSTEM	70
5.	SUMMARY OF INVERSION TECHNIQUES AND RECOMMENDATIONS FOR FUTURE WORK	75
5.1	Summary of Results	75
5.2	Recommendations for Future Research	76
	REFERENCES	77

Illustrations

1. Backscatter and Extinction Coefficients for Different AFGL Aerosol Models At (a.) 0.53 microns and (b.) 10.59 microns 15
2. Backscatter and Extinction Coefficients At 0.55 microns for Representative Background Stratospheric Aerosols, Aged Volcanic Aerosols and Fresh Volcanic Aerosols (Shettle, private communication) 17
3. Backscatter and Extinction Coefficients As A Function of Wavelength for (a.) Background Stratospheric Aerosols, (b.) Aged Volcanic Aerosols and (c.) Fresh Volcanic Aerosols 21
4. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer, Aerosol-free Atmosphere at 337 nm 27
5. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer, Aerosol-free Atmosphere at 514.5 nm 28
6. Backscatter Coefficients As A Function of Extinction Coefficients at 337 nm For An Aerosol-free Atmosphere 29
7. Extinction, Scattering and Absorption Coefficients As A Function of Altitude at 337 nm 30
8. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For An Aerosol-free Atmosphere 32
9. Comparison of Simulated and Inverted Data at 337 nm for an Aerosol-free Atmosphere for the (a.) Near-field and (b.) Far-field Solutions 34
10. Inverted Results at 337 nm with Variations in the Boundary Conditions Considered for (a.) Near-field and (b.) Far-field Solutions 36
11. Comparison of Simulated and Inverted Data at 514.5 nm for an Aerosol-free Atmosphere for the (a.) Near-field and (b.) Far-field Solutions 37
12. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for (a.) Near-field and (b.) Far-field Solutions 38

13. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Background Stratospheric Aerosols	40
14. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Background Stratospheric Aerosols	41
15. Comparison of Simulated and Inverted Data at 514.5 nm for Case 3 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	42
16. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 3 for the (a.) Near-field and (b.) Far-field Solutions	43
17. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With "Clear" Tropospheric Aerosols	45
18. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With "Clear" Tropospheric Aerosols	46
19. Comparison of Simulated and Inverted Data at 514.5 nm for Case 4 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	47
20. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 4 for the (a.) Near-field and (b.) Far-field Solutions	48
21. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Background Stratospheric and "Clear" Tropospheric Aerosols	49
22. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm for a Midlatitude Summer Atmosphere With Background Stratospheric Aerosols and "Clear" Tropospheric Aerosols	50
23. Comparison of Simulated and Inverted Data at 514.5 nm for Case 5 for Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	51
24. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 5 for the (a.) Near-field and (b.) Far-field Solutions	52

25. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Aged Volcanic Aerosols	54
26. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm for a Midlatitude Summer Atmosphere With Aged Volcanic Aerosols	55
27. Comparison of Simulated and Inverted Data at 514.5 nm for Case 6 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	56
28. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 6 for the (a.) Near-field and (b.) Far-field Solutions	57
29. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Fresh Volcanic Aerosols	58
30. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm for a Midlatitude Summer Atmosphere With Fresh Volcanic Aerosols	60
31. Comparison of Simulated and Inverted Data at 514.5 nm for Case 7 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	61
32. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 7 for the (a.) Near-field and (b.) Far-field Solutions	62
33. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With 50 % Background Stratospheric and 50 % Fresh Volcanic Aerosols	63
34. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm for a Midlatitude Summer Atmosphere With Background and Fresh Volcanic Aerosols	64
35. Comparison of Simulated and Inverted Data at 514.5 nm for Case 8 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions	65
36. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 8 for the (a.) Near-field and (b.) Far-field Solutions	66
37. Inverted Results at 514.5 nm with the Alternate Inversion Techniques for a Simulated Atmosphere with Aged Aerosols	72

38. Inverted Results at 514.5 nm with Variations in
(a.) the Single Scattering Albedo and (b.) the
Fraction of Backscattered Radiation

73

Tables

1. A Partial Examination of the History of the Power Law Assumption Relating Backscatter and Extinction 12
2. Values of the Exponent k Required to Fit the AFGL Boundary Layer Aerosol Models Shown in Figure 1 (a.) With A Power Law Over the Given Relative Humidity Ranges 16
3. Summary of Results of Evans¹⁸ Relating to Power Law Relationships Between Backscatter and Extinction 19
4. Summary of Examination of Inversion Techniques for Use With A Space-borne Lidar System 23
5. Details of the AFGL Lidar System and the Test Flight From the White Sands Missile Range, NM 26
6. Test Cases Used in the Lidar Simulation 33

1. INTRODUCTION

Laser radars, or lidars, are powerful tools for probing the atmosphere. They have been used, for example, in studies to probe for the presence of aerosols in the atmosphere, to obtain the profiles of absorbing gases such as water vapor and as a wind measuring tool. Theoretical studies have also been done to investigate the possibility of using lidars to invert the temperature structure of the atmosphere. In the past, the lidars have been typically used from ground-based platforms looking upwards or horizontally. A few studies have also utilized lidars mounted in aircraft or on balloons. Some of these latter studies have focused on preparing lidars for eventual use on space shuttles or satellites.

The Air Force Geophysics Laboratory (AFGL) is developing a lidar system to be flown on the Defense Meteorological Satellite Platforms (DMSP) series of meteorological satellites. The lidar system is being designed to study the optical properties of the atmosphere as well as to measure wind and composition.

The reflected laser energy can be used to invert information about the optical properties of the atmosphere. The techniques used to invert this information are the subject of this report. Chapter 2 examines the mathematical formulation of the inversion problem and presents the inversion techniques commonly used by researchers. Chapter 3 presents and compares results from a simulated spaceborne lidar

system utilizing one of the commonly used inversion techniques. Chapter 4 presents a proposal for an inversion technique that addresses the needs and goals of a spaceborne lidar system. Finally, chapter 5 summarizes our results and conclusions.

2. FORMULATION OF THE LIDAR INVERSION PROBLEM

2.1 The Lidar Equation

The received signal for a single wavelength lidar system is described by the equation

$$P(r) = P_0 \frac{rc}{2r^2} A \beta(r) \exp \left[-2 \int_0^r \sigma(r') dr' \right] \quad (1)$$

where $P(r)$ is the instantaneous received power from the range r , P_0 is the transmitted power of the laser over the pulse length τ , c is the speed of light, A is the effective system receiver area, $\beta(r)$ and $\sigma(r)$ are the backscatter and extinction coefficients, respectively. The equation (1) is commonly known as the lidar equation. In the above, the backscatter and extinction coefficients include contributions from all sources, molecular and particulate. The equation also assumes a single scattering atmosphere. Although not done at this time, (1) can be broken down to include the separate contributions. A more manageable form of the lidar equation can be established by defining a quantity, $S(r)$, that is the logarithmic range-adjusted power

$$S(r) = \ln[r^2 P(r)] \quad (2)$$

Utilizing this quantity eliminates system dependent parameters from the lidar equation. The new form of the lidar equation then becomes

$$S - S_0 = \ln[\beta/\beta_0] - 2 \int_{r_0}^r \sigma dr' \quad (3)$$

where $S_0 = S(r_0)$, $\beta_0 = \beta(r_0)$ and r_0 is a constant reference range. The differential equation corresponding to equation (3) is

$$dS/dr = 1/\beta (d\beta/dr) - 2\sigma \quad (4)$$

One of the goals of using lidars to probe the atmosphere is to invert information about the optical parameters, σ and β . However, a crucial problem is faced when inverting the lidar equation in that it contains two unknown variables, the backscatter and extinction coefficients, and only one equation. In order to eliminate the problem of one equation and two unknowns, researchers have made assumptions about the relationship between σ and β . We shall now examine some of the assumptions made concerning σ and β to put the lidar equation into a form that can be inverted. The implications of the assumptions will be discussed along with the advantages and disadvantages of each approach.

2.2 Homogeneous Atmosphere

If one assumes that the atmosphere is homogeneous, then $d\beta/dr = 0$ and equation (4) reduces to

$$\sigma_{\text{hom}} = -1/2 \, dS/dr \quad (5)$$

The assumption of $d\beta/dr = 0$ gives rise to what is called the slope method of inversion. The value of the homogeneous extinction coefficient is evaluated as the slope of the least squares fit of the $S(r)$ data. An obvious requirement for the use of the slope method is that dS/dr be negative otherwise negative values of the extinction coefficient will be obtained.

The slope method has been used by Murray¹ with an infrared lidar system. In their study they used a CO_2 lidar that operated at four wavelengths near 10.3 microns. The system operated over horizontal paths and was conceived as a way to measure visibility for aircraft landing operations. Their study indicated that a single-ended measurement approach yielded results that agreed with other measurements for ranges up to 10 km. For additional details on the slope method, the interested reader is referred to the papers by Collis² and Viezee³.

1. Murray, E. R., M. F. Williams and J. E. van der Laan (1978) Single-ended Measurement of Infrared Extinction Using Lidar, Applied Optics, 17:296.
2. Collis, R. T. H. (1966) Lidar: A New Atmospheric Probe, Q. J. R. Meteorol. Soc. 92:220.
3. Viezee, W., E. E. Uthe and R. T. H. Collis (1969) Lidar Observations of Airfield Approach Conditions: An Exploratory Study, J. Appl. Meteorol. 8:274.

2.3 The Ratio Method

The atmosphere is unlikely to be homogeneous over the entire path being probed by a lidar, especially a space-borne platform. However, the atmosphere may be nearly homogeneous over small intervals of the path. In this case, one can apply a form of the slope method over the small, nearly homogeneous layers and then build up an approximation of the profile of $\sigma(r)$. This method, known as the ratio or slice method of inversion assumes homogeneity within each layer, yet relaxes the condition that the extinction coefficient is constant. The extinction coefficient is then given as^{4,5,6}

$$\sigma(r_i) = \frac{1}{2\Delta r_i} \ln[r_i^2 P(r_i)/r_{i+1}^2 P(r_{i+1})] \quad (6)$$

where the subscripts i and $i+1$ refer to the small, nearly homogeneous layers and Δr_i is the distance between the layers.

The assumption of a homogeneous or near homogeneous atmosphere suits this method primarily to horizontal viewing paths, such as would be used for aircraft visibility operations. The technique could also be used for low elevation

4. Kohl, R. H. (1978) Discussion of the Interpretation Problem Encountered in Single-Wavelength Lidar Transmissometers, J. Appl. Meteor., 17:1034.

5. Brown, Jr., R. T. (1979) Comments on "Discussion of the Interpretation Problem Encountered in Single-Wavelength Lidar Transmissometers, J. Appl. Meteor., 18:711.

6. Kohl, R. H. (1979) Reply, J. Appl. Meteor., 18:712.

slant paths if it was known beforehand that the medium being studied did not have sharp boundaries below any critical altitude levels. However, before applying the ratio or slope techniques, one must be reasonably sure that homogeneity exists⁶. Unfortunately, for many interesting situations such as dense cloud, fog, smoke and dust, these methods cannot be used. Even under stable conditions in fogs, local heterogeneities occur, thus invalidating the inversion process.

Looking down from space, the atmospheric density is exponentially increasing. The slope method will then be, by definition, inappropriate. The ratio method, however, could be utilized if the data were devoid of large fluctuations. Unfortunately, the large fluctuations can result from scientifically interesting phenomena such as aerosol layers or clouds. (The presence of these "scientifically interesting phenomena" can further complicate the inversion process by introducing multiple scattering effects for which there is not current accounting.)

2.4 Power Law Relationship Between Scattering & Extinction Coefficients

It has been suggested that under certain conditions the backscatter and extinction coefficients can be related by a power law expression of the form

$$\beta = c \sigma^k \quad (7)$$

where c is a constant and k depends upon the wavelength of the lidar and the properties of the obscuring medium. Assuming that the power law relationship is valid, the lidar equation can be given as

$$dS/dr = (k/\sigma)d\sigma/dr - 2\sigma \quad (8)$$

This is a form of the Bernoulli or homogeneous Ricatti equation which has the general solution⁷

$$\begin{aligned} \sigma^{-1} = & \exp \left[- \int_{r_0}^r \frac{1}{k} \frac{dS}{dr'} dr' \right] \\ & \times \left[c - 2/k \int_{r_0}^r \exp \left(- \int_{r_0}^{r'} \frac{1}{k} \frac{dS}{dr''} dr'' \right) dr' \right] \end{aligned} \quad (9)$$

Assuming k to be constant, the solution may be simplified to the following

$$\sigma = \frac{\exp [(S - S_0)/k]}{\left[\sigma_0^{-1} - 2/k \int_{r_0}^r \exp [(S - S_0)/k] dr' \right]} \quad (10)$$

This is sometimes known as the near-field solution. This solution is not a new one. It has been known for a number of years but, for horizontal or upward looking paths, the solution can be plagued with instability problems that result in questionable and/or unrealistic results. This

7. Klett, J. D. (1981) Stable Analytical Inversion Solution for Processing Lidar Returns, Applied Optics 20:211.

happens despite the fact that both the numerator and the denominator approach zero at nearly the same rate. The denominator tends to zero as the difference of two large numbers, creating a highly unstable situation. (A more detailed discussion of the instabilities inherent in (10) can be found in Klett⁷.)

2.4.1 The "Klett Method"

Klett⁷ has proposed an alternate solution to (10) in which the integration constant in (9) is evaluated in terms of a range r_m far from the lidar. Under this assumption, the solution is generated for ranges less than r_m rather than ranges greater than r_0 as in the case of (10). Klett's approach, that utilizes what is known as the far-field solution, is given as

$$\sigma = \frac{\exp [(S - S_m)/k]}{\left[\sigma_m^{-1} + 2/k \int_r^{r_m} \exp [(S - S_m)/k] dr' \right]} \quad (11)$$

This solution form of the Bernoulli equation is what is often known as "the Klett method." In a further modification to his solution, Klett⁸ allows for a variable backscatter-extinction ratio and the inclusion of Rayleigh scattering. Although similar in form to the near-field solution, it has

8. Klett, J. D. (1985) Lidar Inversion with Variable Backscatter/Extinction Ratios, Applied Optics 24:1638.

been found by many researchers^{9,10} to be more stable than the near-field solution. However, the majority of studies that have utilized the "Klett method" have employed horizontal or upward looking orientations.

2.4.2 Mid-Field Solution

Ferguson and Stephens¹¹ have proposed a further alternative to the near-field solution that utilizes the stability of the Klett algorithm to calculate a boundary value at some middle range. In their original proposal, an iterative approach was employed to calculate an accurate far-field boundary condition. Mulders¹² later pointed out that the iterative approach could be replaced with an analytic solution.

2.4.3 The Validity of the Power Law Relationship

The power law relationship allows the researcher to work with an equation with a known solution. The use of the "Klett method" offers mathematical stability. However, use of the power law presupposes knowledge of the attenuating medium being studied. In addition to "throwing the baby out

9. Hughes, H. G., J. A. Ferguson and D. H. Stephens (1985) Sensitivity of a Lidar Inversion Algorithm to Parameters Relating Atmospheric Backscatter and Extinction, Applied Optics, 24:1609.
10. Bissonnette, L. R. (1986) Sensitivity Analysis of Lidar Inversion Algorithms, Applied Optics, 25:2122.
11. Ferguson, J. A. and D. H. Stephens (1983) Algorithm For Inverting Lidar Returns, Applied Optics, 22:3673.
12. Mulders, J. M. (1984) Algorithm for Inverting Lidar Returns: Comment, Applied Optics, 23:2855.

with the bath water", the power law relationship is not valid for all types of media that might be encountered by a spaceborne lidar system.

In all fairness to Klett, he stated in his original paper (see page 212 of Klett⁷) that the use of the power law relationship is not appropriate for all aerosol types or wavelengths. Considering that so many researchers have been utilizing the power law relationship, it seems reasonable to examine the history of the power law relationship between backscattering and extinction. The results of that examination are summarized in Table 1.

Curcio and Knestrick¹³ are one of the earliest sources for the power law relationship between backscattered radiation and attenuation. In their paper, they correlated backscattering and atmospheric transmission from a series of horizontal measurements through fog, rain, drizzle, snow and clear air and found that an empirical relationship of the form $\beta = c \sigma^{0.66}$ fit their data. Their data were taken for white light conditions rather than for monochromatic radiation, such as one would have with a laser. The authors also note that their relationship will not hold in "industrially contaminated air."

There is no a priori reason to assume that the backscatter and extinction coefficients would be related by a

13. Curcio, J. A. and G. L. Knestrick (1958) Correlation of Atmospheric Transmission and Backscattering, J. Opt. Sci. Am., 48:686.

Table 1. An Examination of the History of the Power Law Assumption Relating Backscatter and Extinction

AUTHOR(s)	FINDINGS
Curcio and Knestrick ¹³	<p>From Measurements of Visibility in Clean Air A Relationship of the Form</p> <p style="padding-left: 40px;">Range = Constant x Backscatter 1.5</p> <p>Was Found to Be Valid Within About 20 %</p> <p>From a Theoretical Study Using Four Types of Size Distributions:</p> <ol style="list-style-type: none"> 1. A Relationship, but not An Unique One, Exists Between Backscattering & Extinction 2. The Relationship Holds Better For White Light Rather Than Monochromatic Radiation
Twomey and Howell ¹⁴	<p>From A Theoretical Examination Concludes That No General Relationship Exists Between Backscatter and Extinction - The Variety of Aerosol Formation and Decay Processes Leads to Different Relationships</p>
Penn ¹⁵	<p>From A Theoretical Examination of Water Clouds Conclude That An Approximate Relationship Can Be Found Between Backscatter and Extinction for Visible and Near-infrared Radiation</p>
Pinnick et. al. ¹⁶	<p>Measurements Indicated Rapid Changes Can Occur in Backscatter and Extinction Relationships</p>
Mulders ¹²	

14. Twomey, S. and H. B. Howell (1965) The Relative Merit of White and Monochromatic Light for the Determination of Visibility by Backscattering Measurements, Applied Optics, 4:501.

unique power law relationship. Fenn¹⁵ has pointed out that only with a combination of changes in number densities and size distributions can one get a power law relationship between backscattering and extinction. If the aerosol size distributions, complex indices of refraction and particle shapes were all constant then one could assume a power law relationship. However, aerosols and clouds are highly variable phenomena with strong shape, altitude, humidity, composition and meteorological (e.g. wind) dependencies. Even if power law relationships did exist for the aerosols and clouds, one would not know which set of values, k and c , to use because clouds and aerosols can be found at the same altitudes, often at the same times. Also, Mulders¹² has shown that power law relationships, if they can be obtained, can be fitted to data but that the values of the relevant parameters can change as a function of time. Mulders concludes from a series of horizontal measurements over the ocean that the power law parameters are not constant for more than a few hours.

Pinnick et. al.¹⁶ have presented results from calculations of backscatter and extinction through stratus and cumulus clouds. Their zero order solution (their term) calculations were performed for 156 measured cloud droplet

15. Fenn, R. W. (1966) Correlation Between Atmospheric Backscattering and Meteorological Range, Applied Optics, 5:293.

16. Pinnick, R. G., S. G. Jennings, P. Chylek, C. Ham and W. T. Grandy, Jr. (1983) Backscatter and Extinction in Water Clouds, J. Geophys. Res., 88:6787.

distributions for visible, near IR and IR wavelengths. They found that a linear relationship exists between backscatter and extinction at $0.6328 \mu\text{m}$ but that none exists at $10.6 \mu\text{m}$.

Shettle¹⁷ has presented results of backscatter and extinction coefficient comparisons for the tropospheric aerosol models in LOWTRAN 6 as a function of relative humidity. His calculated results for the wavelengths 0.53 and $10.59 \mu\text{m}$ are reproduced as Figures 1 (a.) and (b.), respectively. Each point on the curves represents a different relative humidity. Table 2 gives the corresponding exponents required to fit the data in Figure 1 (a.) with a power law over the given relative humidity ranges. (The attenuation coefficients increase with relative humidity.) His results demonstrate that a power law relationship is not appropriate for tropospheric aerosols except over very limited relative humidity ranges and for given wavelengths. Figure 2 shows similar results for the AFGL stratospheric aerosol models. The three points refer to representative background stratospheric conditions, aged volcanic aerosols and fresh volcanic aerosols [Shettle, private communication, 1986]. Again, a unique power law relationship does not exist for stratospheric aerosols. In a realistic situation, the stratosphere could contain all three types of aerosols with three different characteristic indices of refraction and size distributions.

17. Shettle, E. P. (1985) Backscattering by Atmospheric Aerosols, Presented at the IAMPA/IAPSO Joint Assembly, Honolulu, Hawaii, 5-16 August 1985.

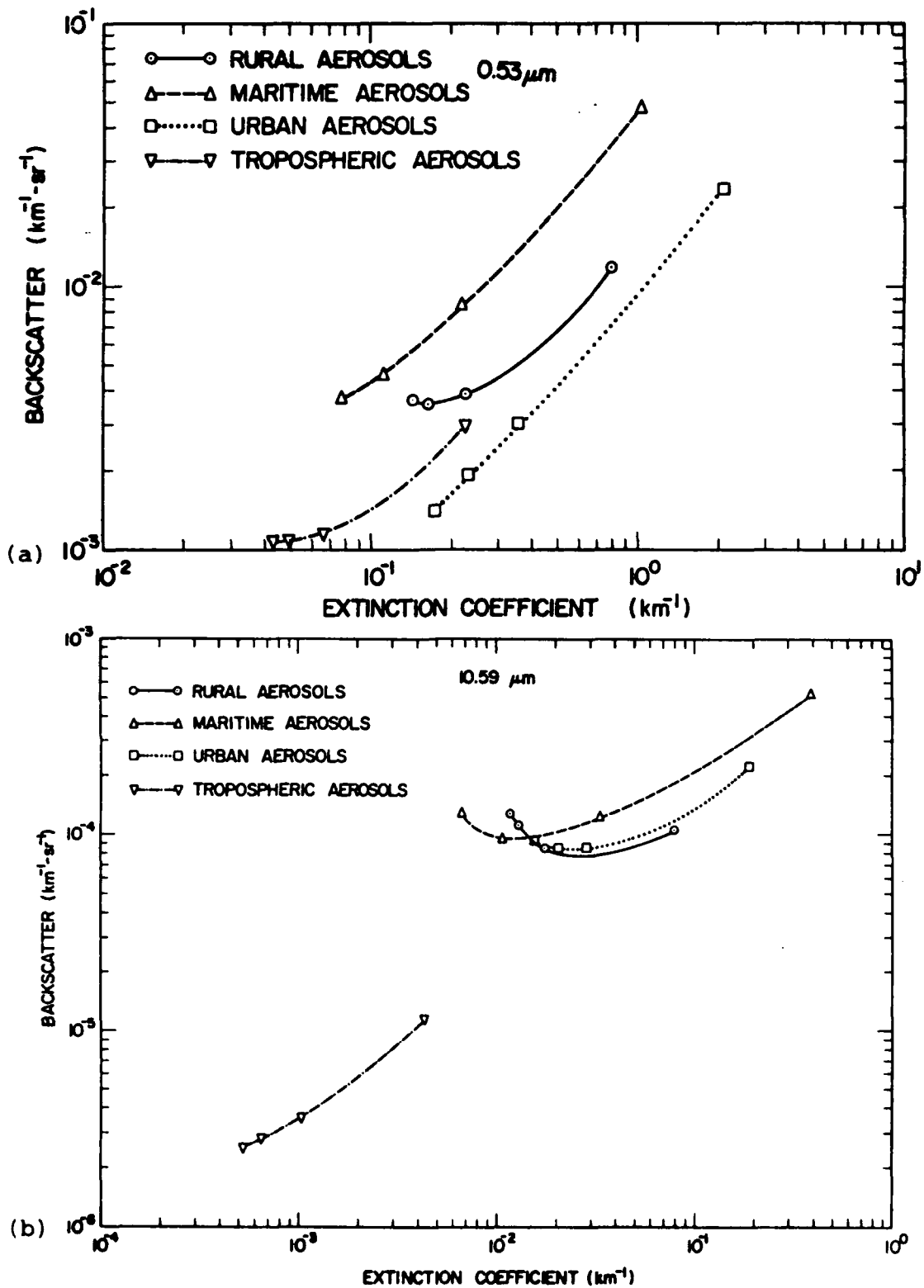


Figure 1. Backscatter and Extinction Coefficients for Different APGL Aerosol Models At (a.) 0.53 microns and (b.) 10.59 microns

Table 2. Values of the Exponent k Required to Fit the APGL Boundary Layer Aerosol Models Shown in Figure 1 (a.) With A Power Law Over the Given Relative Humidity Ranges

Aerosol Type	Relative Humidity Range (%)		
	0 - 70	70 - 80	80 - 99
Rural	-0.4	0.09	0.9
Maritime	0.7	0.9	1.2
Urban	1.2	1.2	1.2
Tropospheric	0.05	0.1	0.7

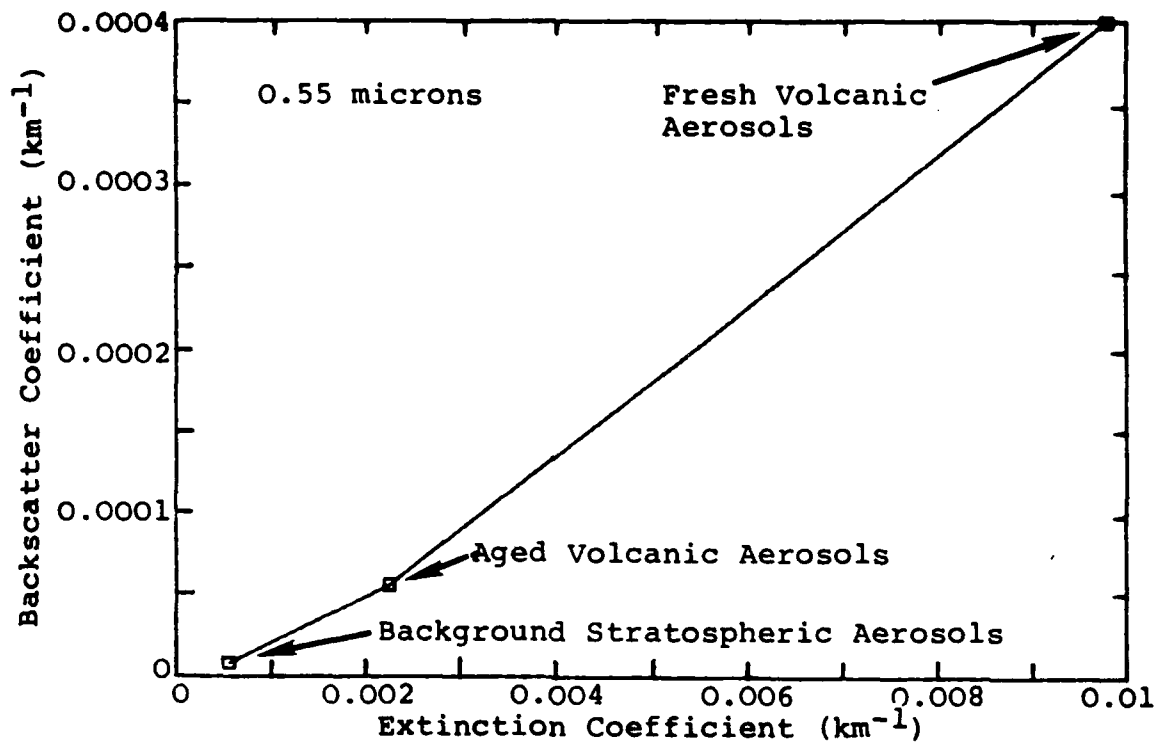


Figure 2. Backscatter and Extinction Coefficients At 0.55 microns for Representative Background Stratospheric Aerosols, Aged Volcanic Aerosols and Fresh Volcanic Aerosols (Shettle, private communication)

Evans¹⁸ has confirmed the results of Shettle¹⁷ and extended the analysis to other aerosol types. Evans performed calculations of the backscatter/extinction ratio using Mie theory for a large range of values of the real and imaginary components of the index of refraction and the modal size parameter. His results are summarized in Table 3 and can be used by researchers to determine for what wavelengths and size distributions one could utilize a power law relationship.

2.5 Linear Wavelength Dependence of Aerosol Scattering

The use of more than one laser wavelength increases the amount of information about the medium being studied. Utilizing frequency doubling and tripling techniques, one can, for instance, use one laser line to provide information about the molecular components of the atmosphere, thereby helping to define the background atmospheric signal, and use a second line to study aerosol contributions.

DeLuisi et.al.¹⁹ have proposed using a dual or triple wavelength lidar system in which the aerosol scattering is

18. Evans, B. T. N. (1986) Sensitivity of the Lidar Ratio to Changes in Size Distribution and Index of Refraction, Thirteenth International Laser Radar Conference, NASA Conference Publication 2431, National Aeronautics and Space Administration, Code NIT-4, Washington, D. C.

19. DeLuisi, J. J., Schuster, B. G. and Sato (1975) Separation of Dust and Molecular Scattering Contributions to the Lidar Observation: A Method, Applied Optics 14:1917.

Table 3. Summary of Results of Evans¹⁸ Relating to Power Law Relationships Between Backscatter and Extinction Coefficients

<p>The Ratio of Backscatter to Extinction Coefficients Is <u>In</u>sensitive to Changes in the Size Distribution:</p>	<p>The Ratio of Backscatter to Extinction Coefficients Is <u>S</u>ensitive to Changes in the Size Distribution:</p>
<p>For Small Non-absorbing Particles</p>	<p>For Water Droplets with Modal Size Parameters ≤ 2 and Wavelengths in the Range 0.2 - 12 microns</p>
<p>For Water Droplets with a Modal Particle Size Greater than 1 micron and Visible & Near-infrared Wavelengths</p>	<p>For Rural or Maritime Type Aerosols at Any Wavelength in the Visible & Infrared</p>
<p>For Water Droplets with a Modal Particle Size Greater than 10 microns and Wavelengths in the Range 6 - 12 microns</p>	<p>For Water Droplets with Particle Sizes on the Order of Several Microns & Far-infrared Wavelengths</p>
<p>Real Part of Index of Refraction = 1.5, Imaginary Part $\leq 10^{-4}$ and the Modal Size Parameter, $X_m \geq 6$</p>	<p>Hygroscopic Aerosols and Relative Humidity Above 70 %</p>
<p>$2kX_m \geq 1$</p>	

$$X_m = (2 \tau R_m / \lambda)$$

k = Imaginary Part of Index of Refraction

linearly related. With their formulation, the scattering coefficient for wavelength i is given as

$$\beta(\tau)_i = [1 + c (\lambda_1 - \lambda_i)/(\lambda_1 - \lambda_3)] \beta(\tau)_1 \quad (12)$$

$i = 1, 2, 3$

where λ is the wavelength. Utilizing this assumption DeLuisi et.al. were able to develop an inversion technique with equal numbers of equations and unknowns that would allow one to obtain a separate inversion of molecular and aerosol optical properties.

The key to the DeLuisi et. al. approach is the assumption that a linear relationship exists relating the aerosol extinction properties at different wavelengths. Figure 3 displays the wavelength dependence of the aerosol extinction and scattering coefficients for the background stratospheric, aged volcanic and fresh volcanic aerosol models used in the AFGL model atmospheres (Shettle, private communication). (For the background stratospheric conditions the extinction and backscatter coefficients overlap.) The figures show that the wavelength dependences are not necessarily linear and that they differ from one aerosol type to another. This being the case, one would have to guess the type of aerosol being probed in order to incorporate the appropriate wavelength dependence.

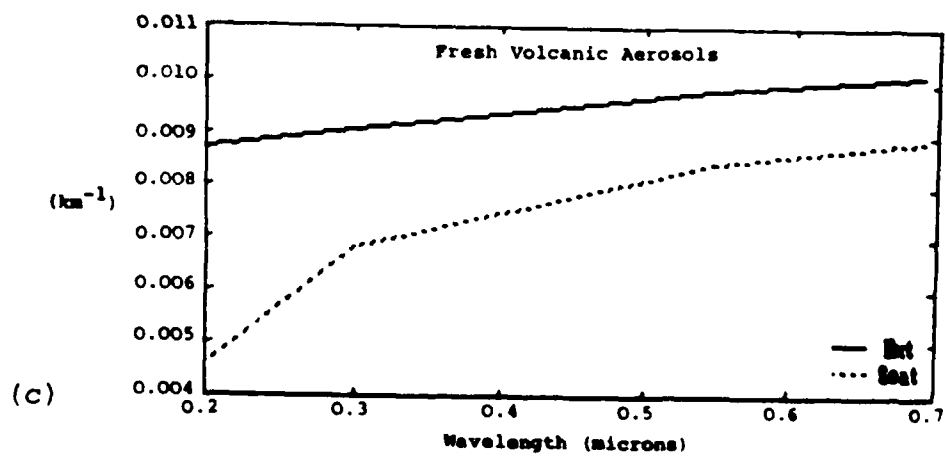
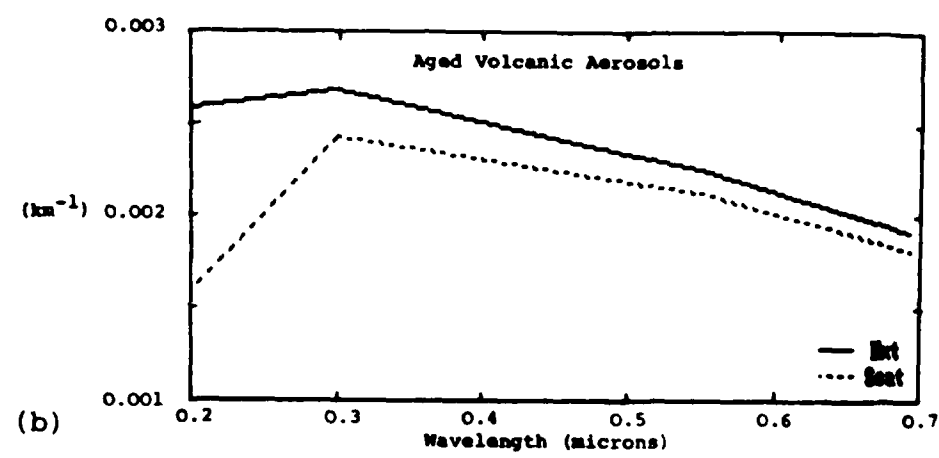
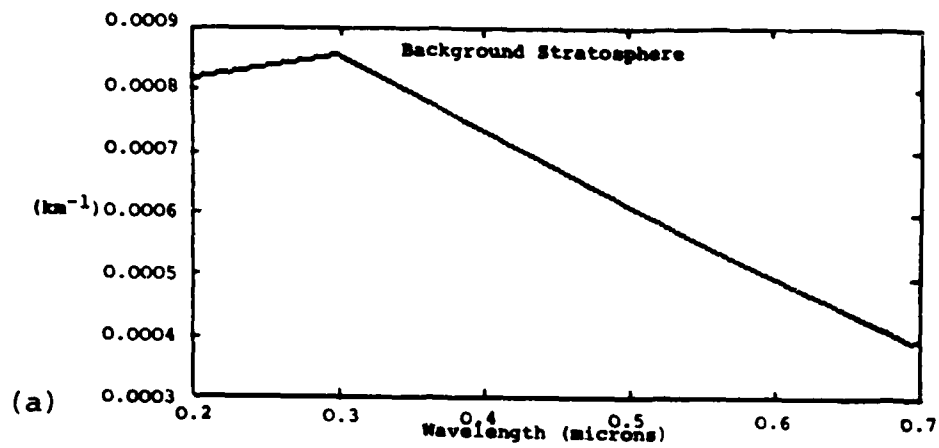


Figure 3. Backscatter and Extinction Coefficients As A Function of Wavelength for (a.) Background Stratospheric Aerosols, (b.) Aged Volcanic Aerosols and (c.) Fresh Volcanic Aerosols

2.6 Applicability of the Available Inversion Techniques for Spaceborne Applications

Table 4 summarizes the results from the examination of the various inversion techniques from the perspective of a spaceborne lidar system. The table lists the fundamental assumptions of each of the techniques, advantages and disadvantages.

The slope and ratio methods offer simplicity but are not appropriate for a spaceborne system. The slope method cannot be used because the viewing path is inhomogeneous (i.e. exponentially increasing). The ratio method also cannot be used because the degree of inhomogeneity gives rise to negative attenuation coefficients.

The inversion technique that is commonly used by researchers is based on the power law assumption with the "Klett technique" for the solution. The assumption of a power law relationship yields an equation with a known solution. The "Klett" approach is used rather than the near-field solution because of its supposed improvements in stability. The use of the word "supposed" is deliberate. The studies to-date with the "Klett" technique have not demonstrated that the far-field solution is inherently more stable than the near-field solution. The studies to-date have primarily involved horizontal or upward looking path configurations and it may be that the choice of path configuration determines the stability characteristics of a given form of a Bernoulli equation solution. Kastner and

Table 4. Summary of Inversion Techniques for Use With a Spaceborne Lidar System

INVERSION TECHNIQUE	FUNDAMENTAL ASSUMPTION(S)	ADVANTAGES	DISADVANTAGES
Slope Method	Homogeneous Atmosphere Over Entire Path	Simple Solution	Not Applicable (Atmosphere is Inhomogeneous)
Ratio Method	Homogeneous Atmosphere Over Portions of Path	Allows Limited Inhomogeneity	Not Applicable (Gives Negative Values of Extinction)
Power Law	Backscatter-Extinction Related By A Power Law $\beta = c \sigma^k$	Analytic Solution Can Be Used to Estimate Optical Properties	No Physical Basis No One Power Law for Entire Atmosphere Can Change Quickly
"Far-field" Solution		More Stable for Horizontal and Ground Up Paths	Difficult to Accurately Calculate Boundary Conditions
"Near-field" Solution		Improved Stability for Downward Paths Easier to Estimate Boundary Conditions	More Sensitive to Variations in k
DeLuigi et. al.	Aerosol Properties Linearly Related by Wavelength	Gives A Complete Set of Equations	Aerosols Not Linearly Related By Wavelength Need to Know the Relationship In Advance

Quenzel²⁰ have examined the usefulness of the near- and far-field algorithms in the context of a downward-looking, spaceborne lidar system. Their results indicate that in an atmosphere with low turbidity the near-field solution yields better results than a far-field solution. In an atmosphere with high turbidity, they found that the far-field solution gave better results.

The next chapter presents results from a simulated downward looking spaceborne system that utilizes a power law approach for inversion. Results from both near- and far-field solutions will be presented in order to gauge the superiority, if any, of one solution approach over another.

20. Kastner, M. and H. Quenzel (1986) The Usefulness of Klett's Inversion Algorithms to Simulated Satellite Lidar Returns, Thirteenth International Laser Radar Conference, NASA Conference Publication 2431, National Aeronautics and Space Administration, Code NIT-4, Washington, D. C.

3. SIMULATION OF INVERSIONS FROM A SPACEBORNE LIDAR SYSTEM

The simulation is intended to be representative of data taken from the lidar system under development by AFGL. A version of the system has been flown on a high altitude balloon from the White Sands Missile Range, New Mexico. The features of the lidar system and the test flight are summarized in Table 5 (Bedo, private communication, 1986).

3.1 Simulated Atmosphere

Lidar signals from a midlatitude summer atmosphere under a variety of conditions are being simulated. A midlatitude summer atmosphere was chosen as being most representative of the conditions at the time of the launch. Tabulated optical parameters at 337 and 514.5 nm were taken from the work of McClatchey et. al.²¹ for this study. These wavelengths were assumed to be close enough to the actual lidar lines for the purpose of this study.

The scattering and extinction coefficients for an aerosol-free atmosphere at 337 and 514.5 nm are shown in Figures 4 and 5, respectively. The 337 nm extinction coefficients include molecular absorption from ozone as well as Rayleigh scattering. As shown in Figure 6, the data do not exhibit a linear relationship that corresponds to a power law of $k=1$. Figure 7 shows the individual components

21. McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Volz and J. S. Garing (1972) Optical Properties of the Atmosphere, Air Force Cambridge Research Laboratories, Hanscom Field, Bedford, Massachusetts, AFCRL-72-0497, AD753075.

Table 5. Details of the AFGL Lidar System and the Test Flight From the White Sands Missile Range, NM

Wavelengths	355 and 532 nm
Field of View	2 1/2 milliradians. Lidar looks up, down and 2 degrees above horizon
Altitude Resolution	150 meters
Pulse Rate	10 pulses per second. (Data averaged over 10 pulses to smooth out expected 10 % deviation between pulses.)
Date of Flight	24 Aug 1984
Balloon Float Altitude	33 Km
Weather Support Data	Radiosonde data taken from Roswell, NM at 2130 LST. No moonlight reported.

Aerosol Free Atmosphere – 337nm

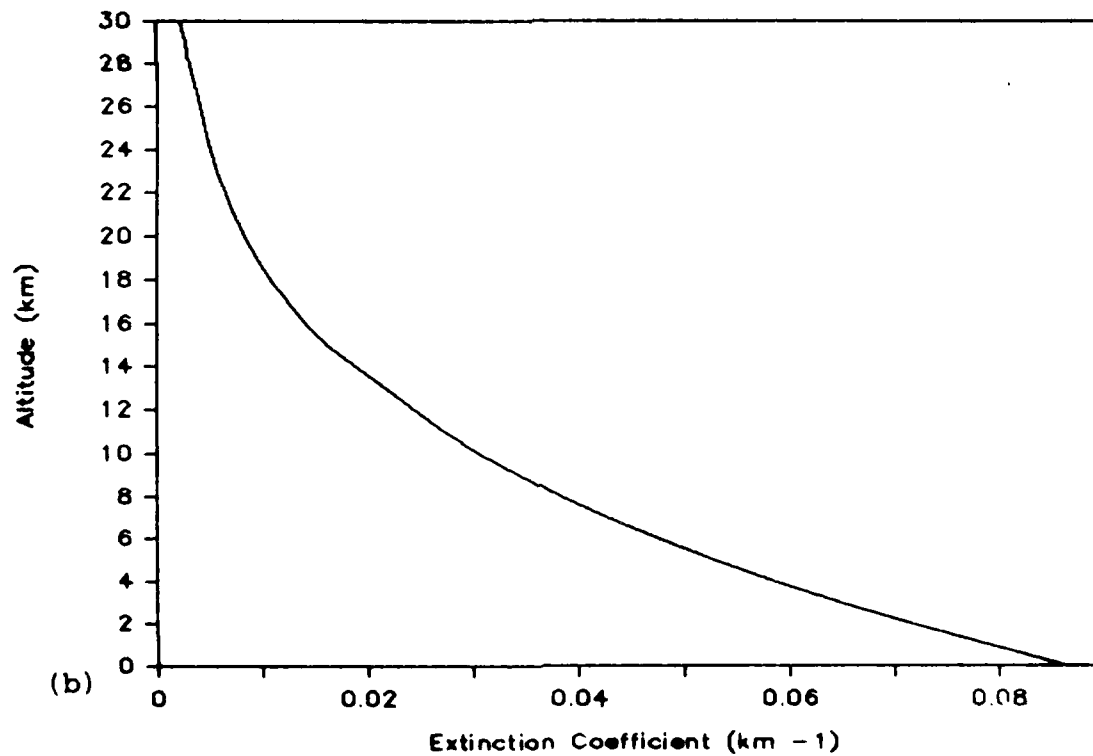
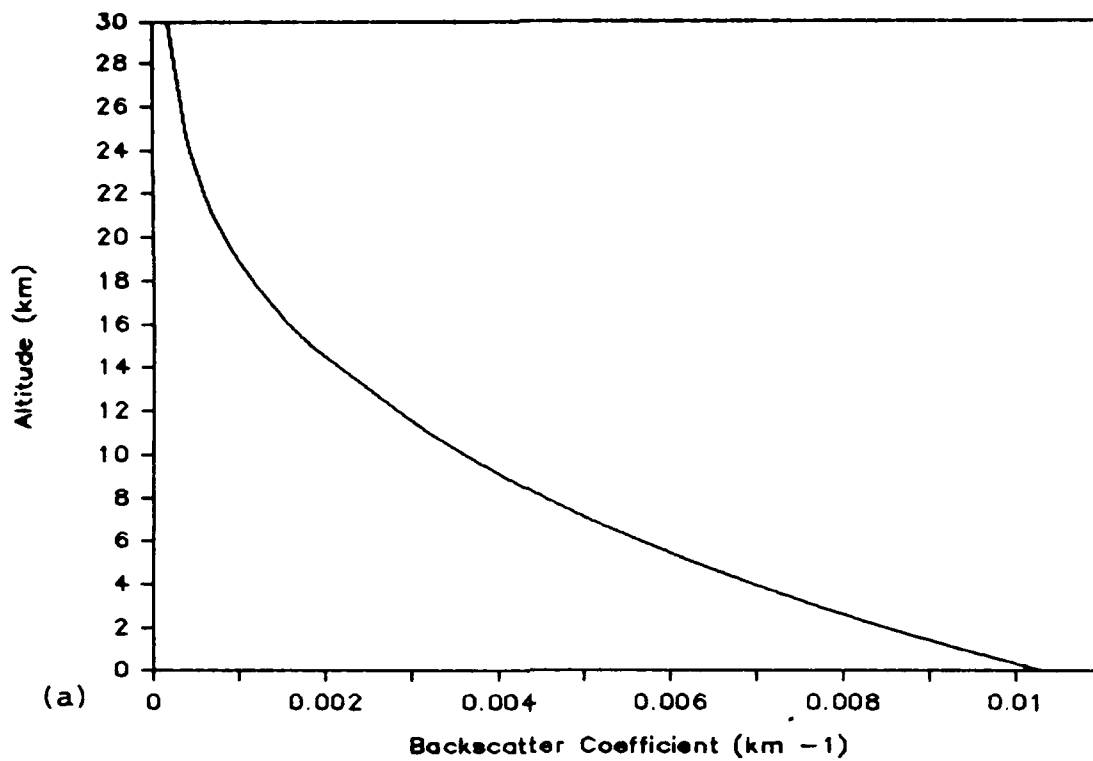


Figure 4. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer, Aerosol-free Atmosphere at 337 nm

Aerosol Free Atmosphere - 514.5nm

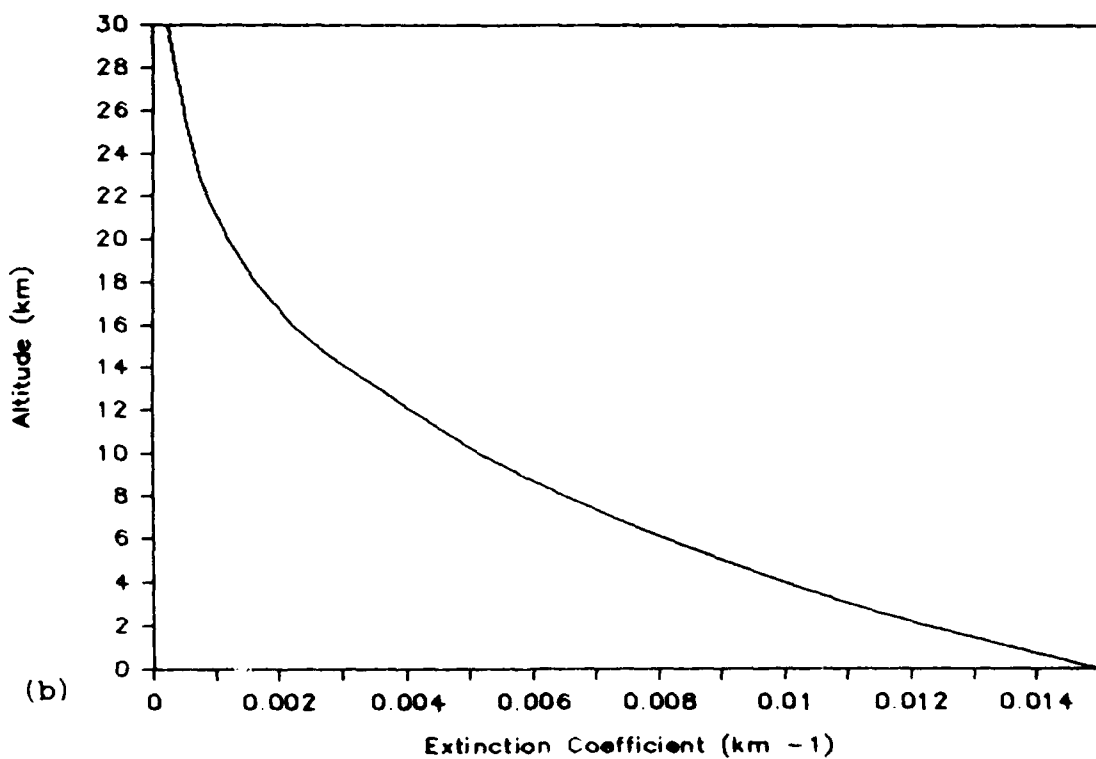
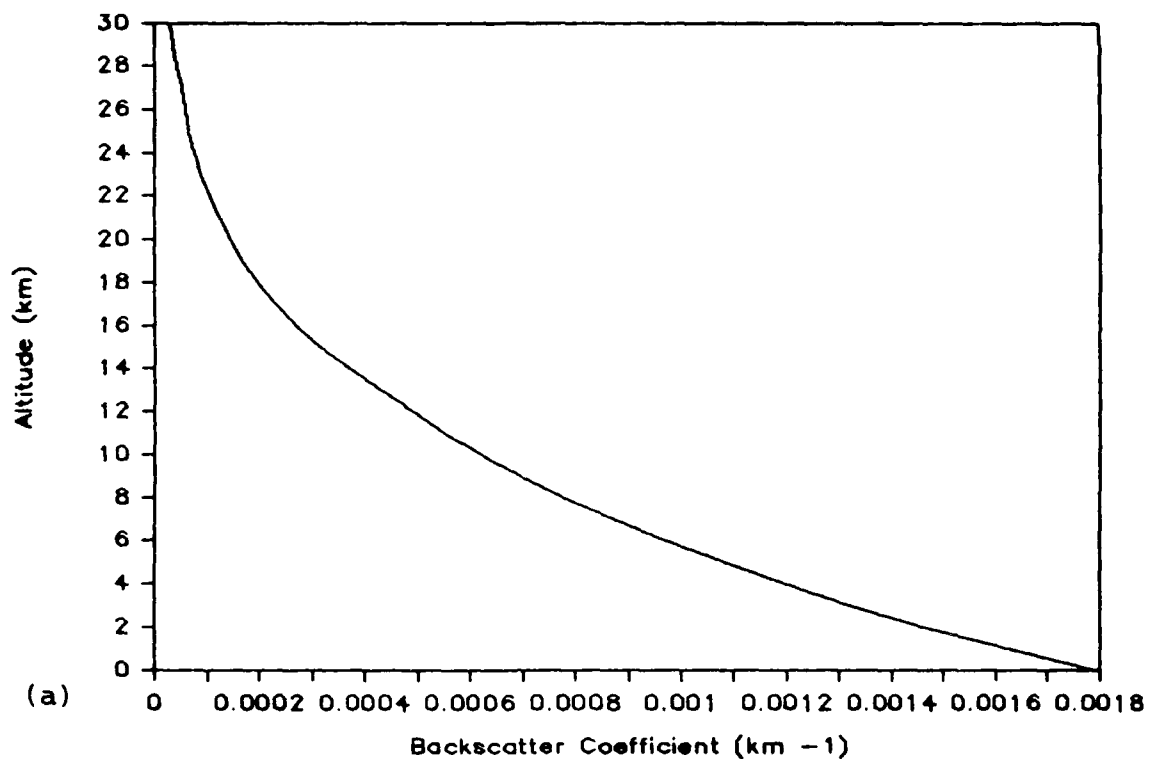


Figure 5. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer, Aerosol-free Atmosphere at 514.5 nm

Aerosol-Free Atmosphere - 337nm

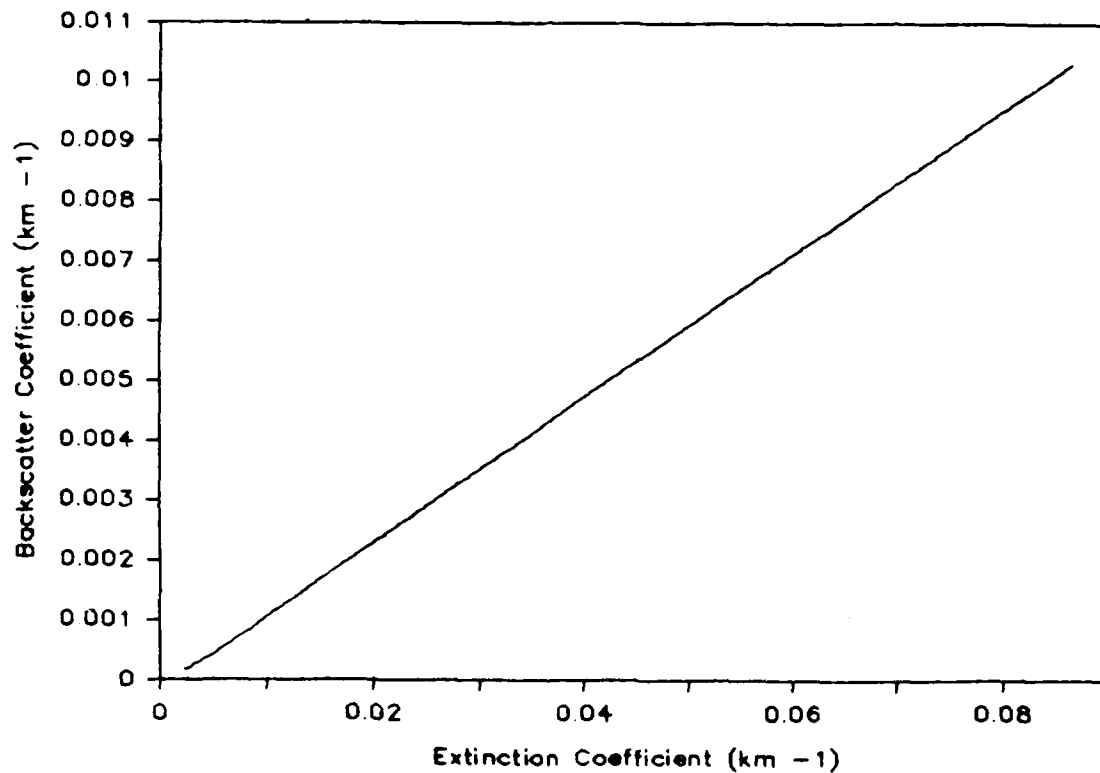


Figure 6. Backscatter Coefficient As A Function of Extinction Coefficients at 337 nm For An Aerosol-free Atmosphere

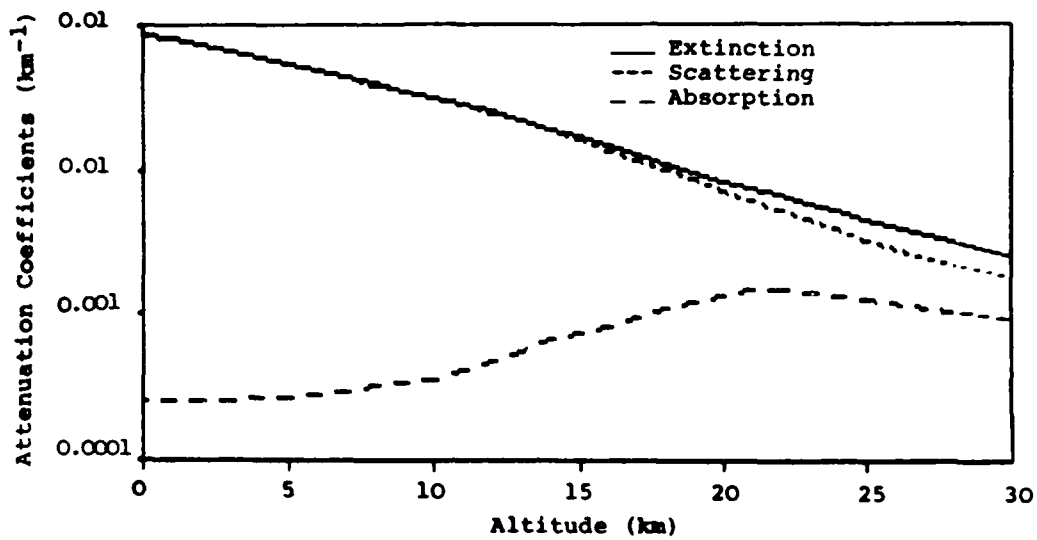


Figure 7. Extinction, Scattering and Absorption Coefficients As A Function of Altitude at 337 nm

as a function of altitude. The 514.5 nm values consist of Rayleigh scattering only and correspond to a power law relationship in which $k=1$, as shown in Figure 8. At both wavelengths, the scattering coefficients are those at a backscattering angle of 180 degrees.

The results to be presented are referenced to a spaceborne platform. Therefore, the near-field solution refers to a solution that begins at high altitudes and proceeds toward the surface. The far-field solution begins at or near the surface and proceeds towards the spacecraft.

The simulations will be performed for the eight cases listed in Table 6. It is assumed that the short wavelength laser line would be used primarily to define the molecular components of the atmosphere and that the visible line would be used for aerosol studies. Under this assumption, one would invert the shorter wavelength data first to determine the gaseous components and then invert the visible data to extract any aerosol information.

In the results that follow it is assumed that the near- and far-field boundary conditions are known accurately. Results will also be presented in which the boundary conditions are perturbed by +/- 10 and 40 % to determine the effects of inaccuracies in the boundary conditions on the inversion algorithms.

Aerosol-Free Atmosphere – 514.5nm

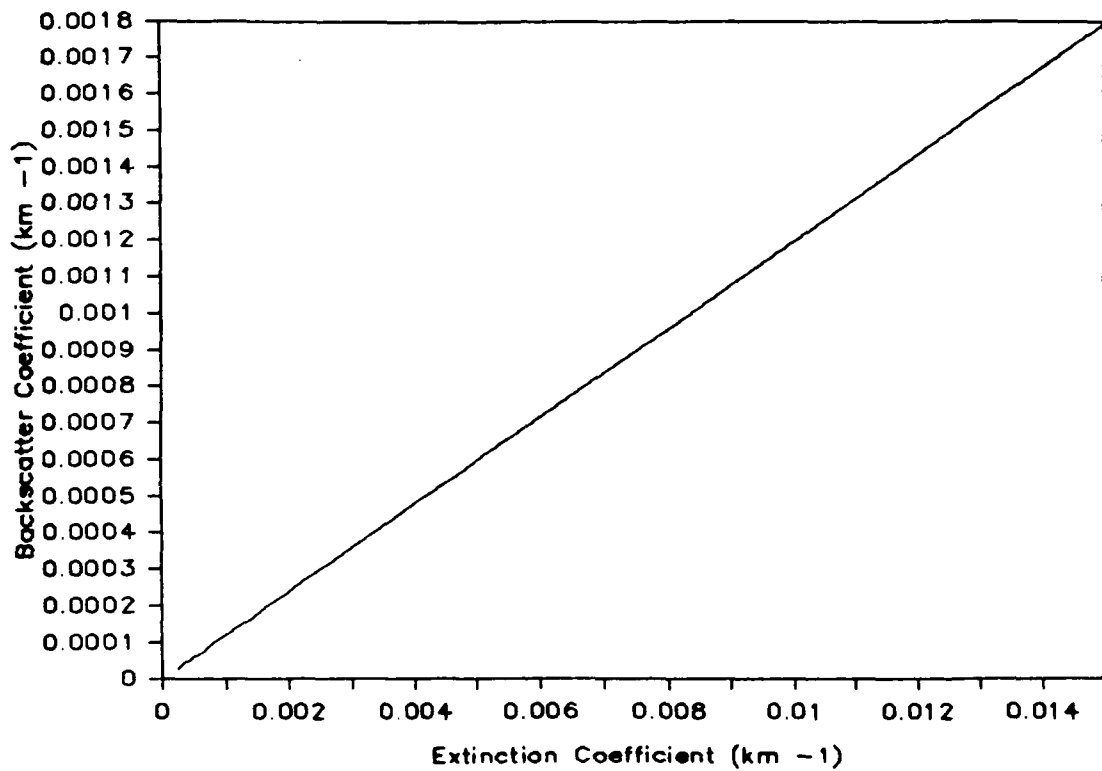


Figure 8. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For An Aerosol-free Atmosphere

Table 6. Test Cases Used in the Lidar Simulation.

CASE	CONDITIONS
1	Aerosol-Free Atmosphere at 337 nm
2	Aerosol-Free Atmosphere at 514.5 nm
3	Case 2 Plus Background Stratospheric Aerosols
4	Case 2 Plus Clear Tropospheric Conditions
5	Case 2 Plus Combined Stratospheric & Tropospheric Aerosols (Cases 3 & 4)
6	Case 2 Plus Aged Volcanic Aerosols
7	Case 2 Plus Fresh Volcanic Aerosols
8	Case 2 Plus Combined Background Stratospheric & Fresh Volcanic Aerosols

3.1.1 Case 1 - Aerosol-free Atmosphere at 337 nm

Figures 9 (a.) and (b.) show the results for an aerosol-free simulated atmosphere at 337 nm from the near- and far-field inversions, respectively. The results are given for k values of 0.8, 1.0 and 1.2. The differences between the inverted atmospheric data and the simulated atmosphere with $k=1.0$ are small for both the near- and far-field solutions with the differences being due to the presence of ozone absorption (see Figure 7).

Figure 10 shows the results of the inversions with changes in the boundary conditions considered. The near-field solution results, Figure 10 (a.), show a somewhat greater sensitivity to changes in the boundary conditions than do the far-field solution results, Figure 10 (b).

3.1.2 Case 2 - Aerosol-free Atmosphere at 514.5 nm

Figures 11 (a.) and (b.) show the results for a simulated atmosphere at 514.5 nm from the near- and far-field inversions, respectively. For both solution forms, a value of $k=1$ yielded the best solutions, as they should, seeing that the simulated data were based on a power law relationship between the extinction and backscattering. The differences shown in the curves are due to the linear fitting of the simulated data. Figures 12 (a.) and (b.) show the results with perturbations in the boundary conditions considered.

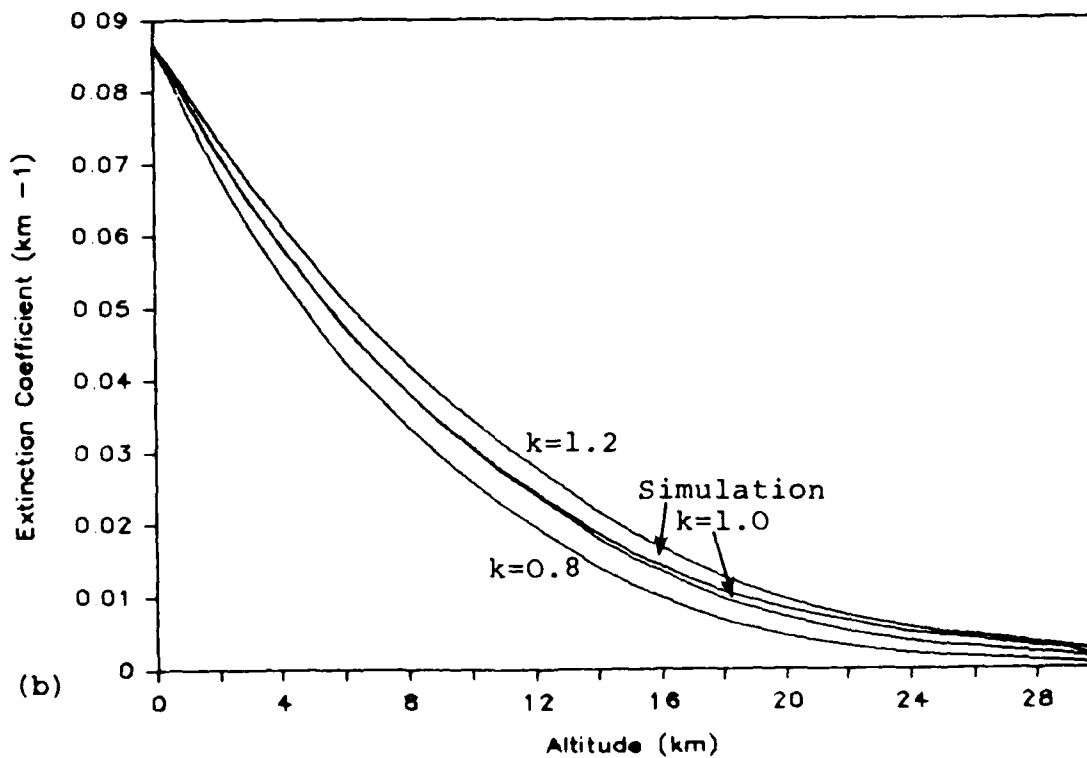
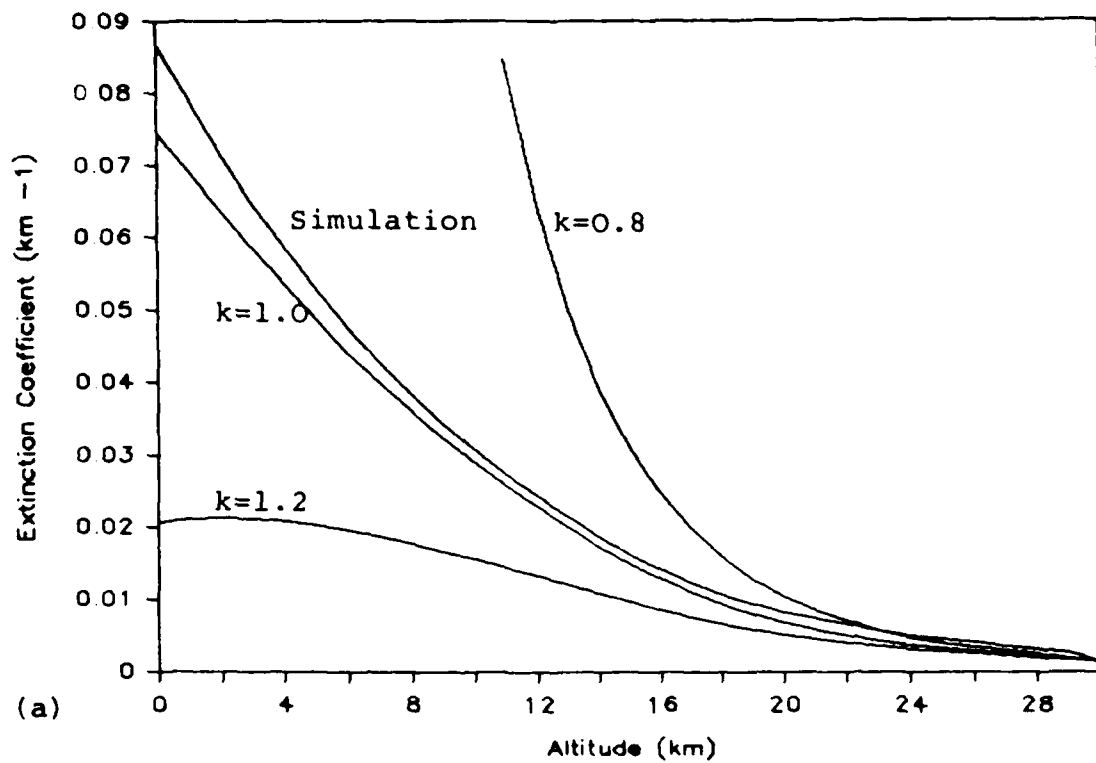


Figure 9. Comparison of Simulated and Inverted Data at 337 nm for an Aerosol-free Atmosphere for the (a.) Near-field and (b.) Far-field Solutions

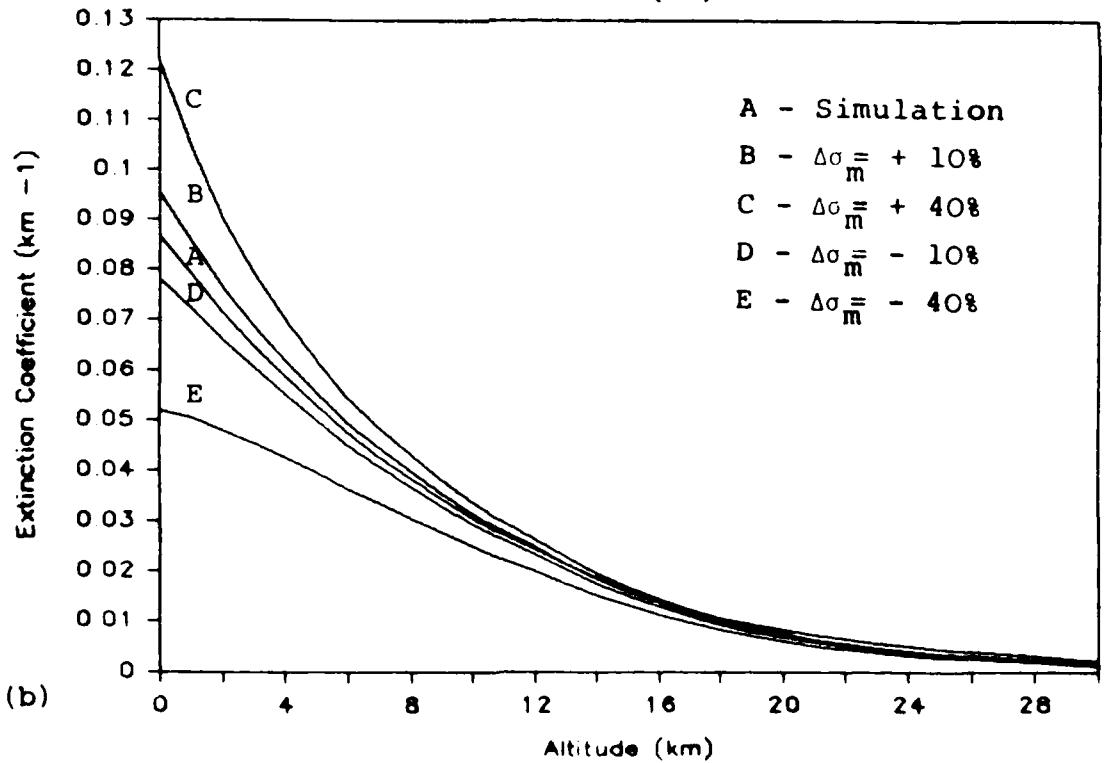
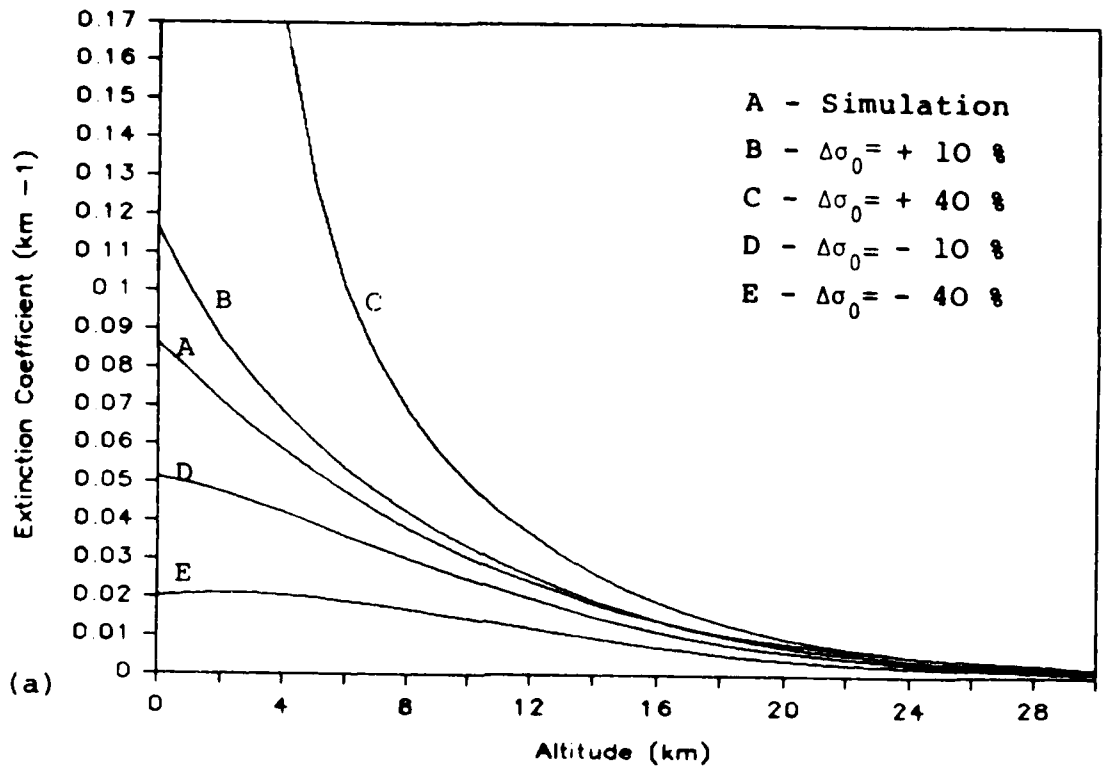


Figure 10. Inverted Results at 337 nm with Variations in the Boundary Conditions Considered for (a.) Near-field and (b.) Far-field Solutions

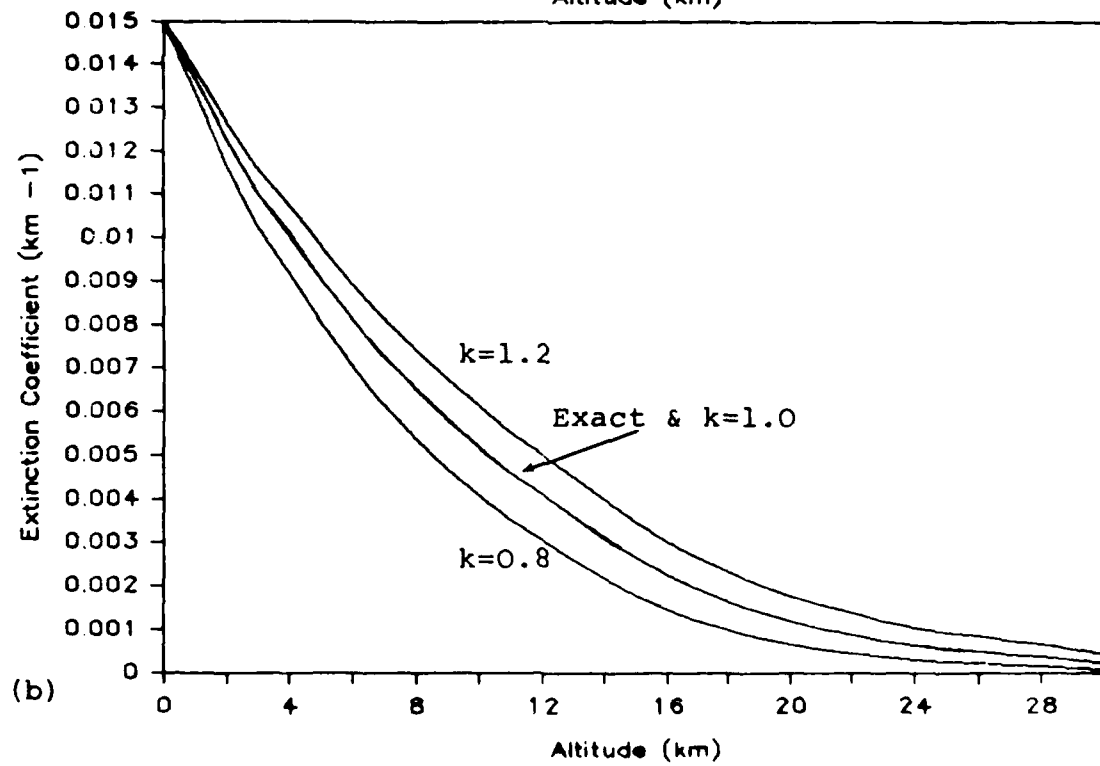
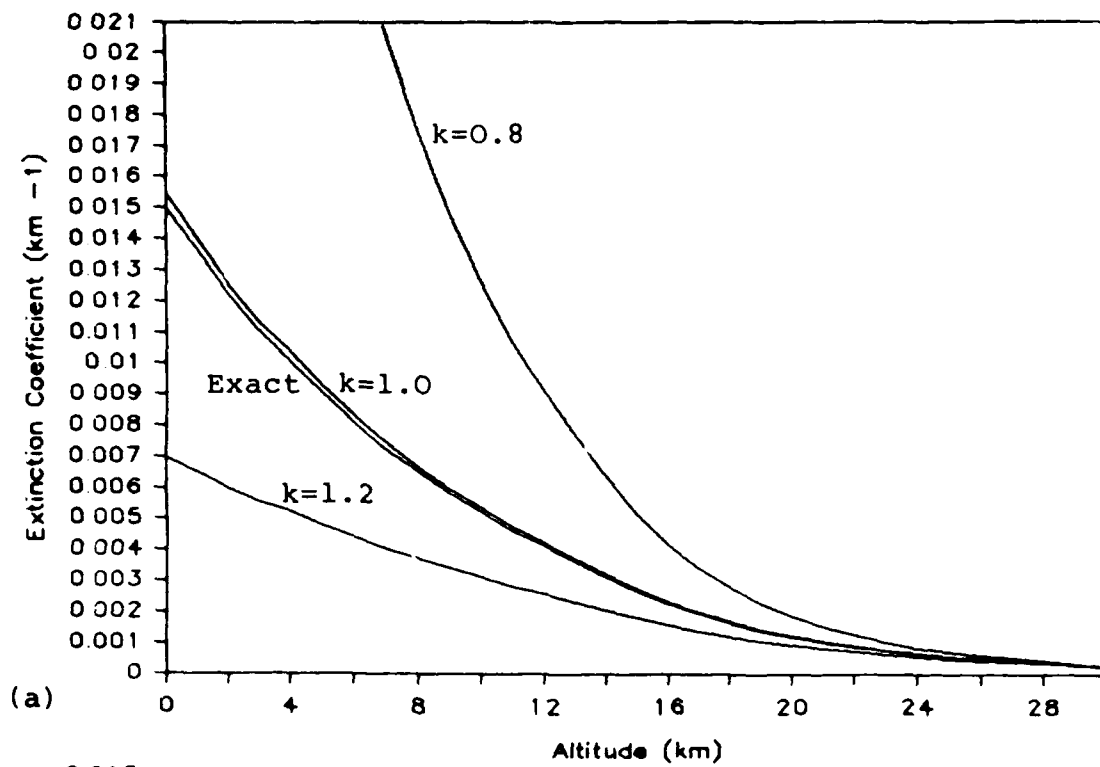


Figure 11. Comparison of Simulated and Inverted Data at 514.5 nm for an Aerosol-free Atmosphere for the (a.) Near-field and (b.) Far-field Solutions

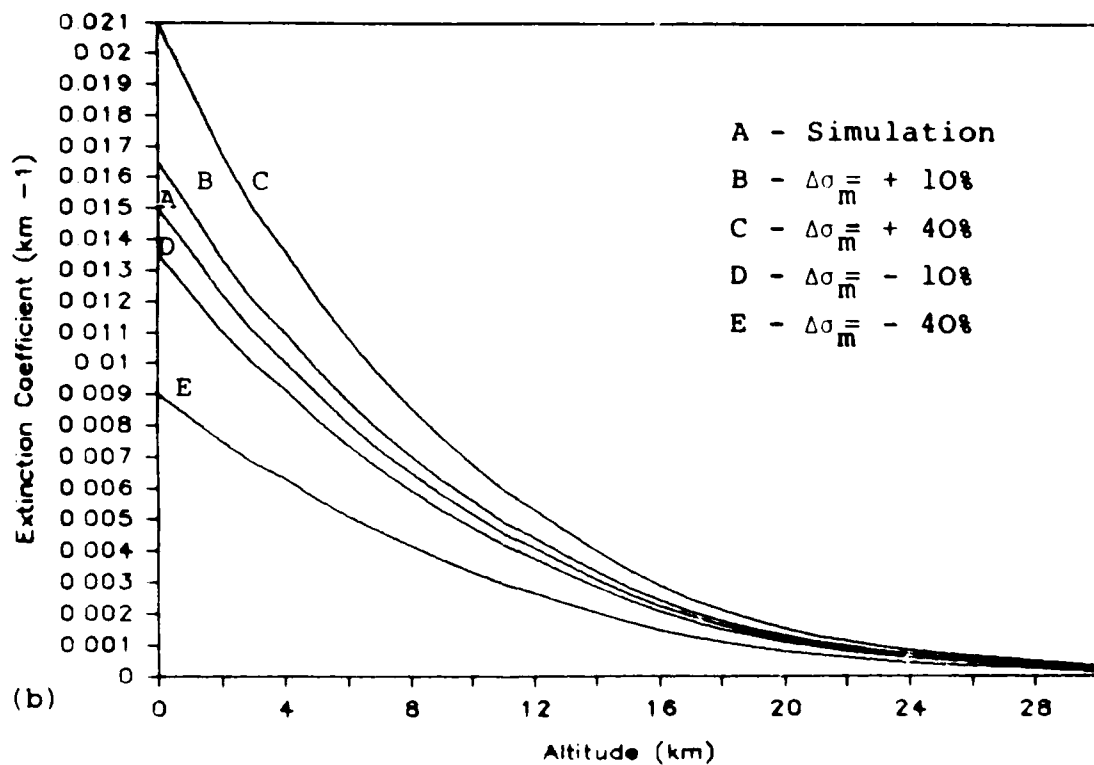
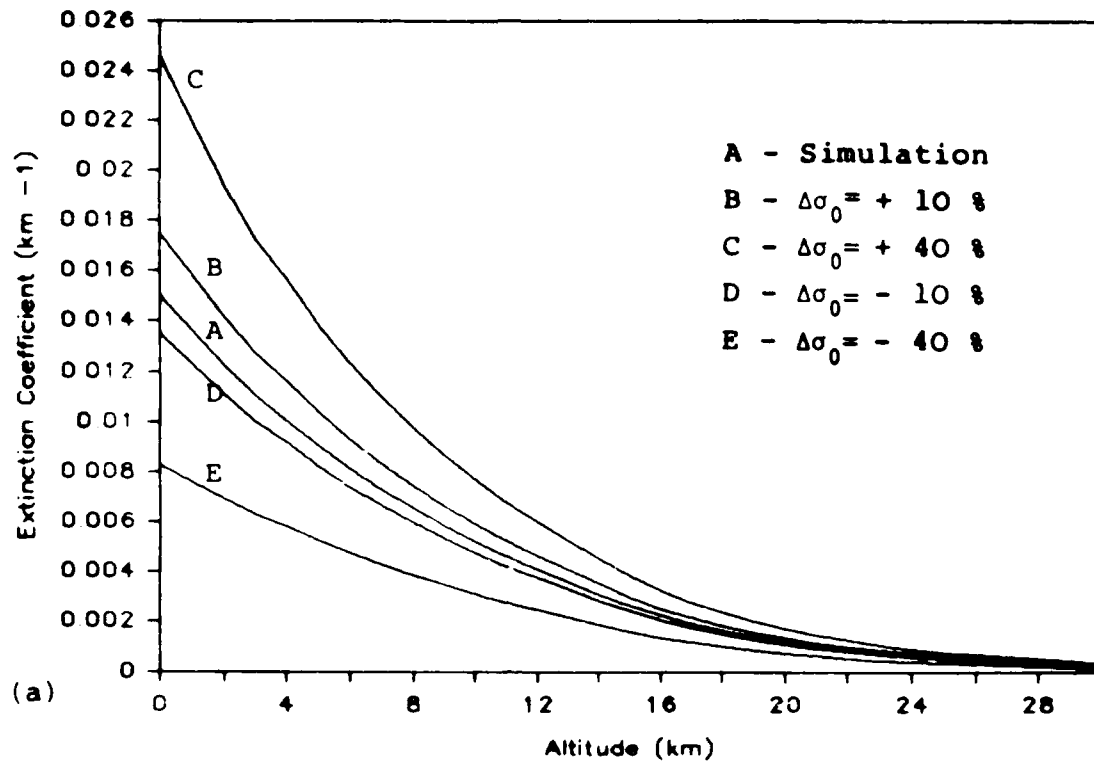


Figure 12. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for (a.) Near-field and (b.) Far-field Solutions

The preceding two sets of results demonstrate that a power law approximation will reproduce an atmosphere consisting of Rayleigh scatterers with little or no molecular absorption. The results to follow will examine the ability of a power law approach to accurately reproduce an atmosphere containing Rayleigh as well as non-Rayleigh components. It is presumed that the non-Rayleigh components are aerosols or clouds. The results will utilize the 514.5 nm laser line.

3.1.3 Case 2 Plus Background Stratospheric Aerosols

This case considers an atmosphere with background stratospheric aerosols added to a background Rayleigh atmosphere. The aerosols are added between 10 and 25 km. Figures 13 (a.) and (b.) show, respectively, the backscatter and extinction coefficients for the case. The background aerosol-free values are dashed in for reference. Figure 14 gives the backscatter coefficients plotted against the extinction coefficients.

The near- and far-field inversions are shown in Figures 15 (a.) and (b.), respectively. In both the near- and far-field solutions, a profile based $k=1$ reproduces the simulated data above and below the aerosol layer. Figures 16 (a.) and (b.) show the sensitivity of each solution to changes in boundary conditions with a value of $k=1$.

Rayleigh + Background Stratospheric

Wavelength - 514.5nm

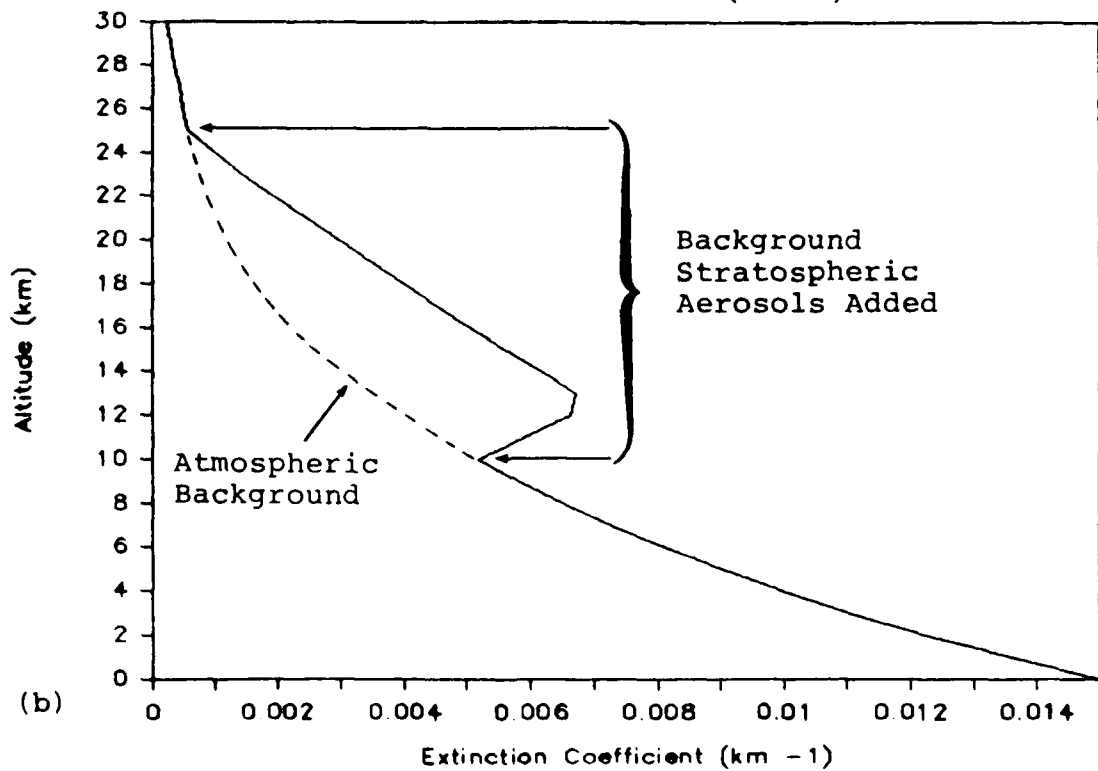
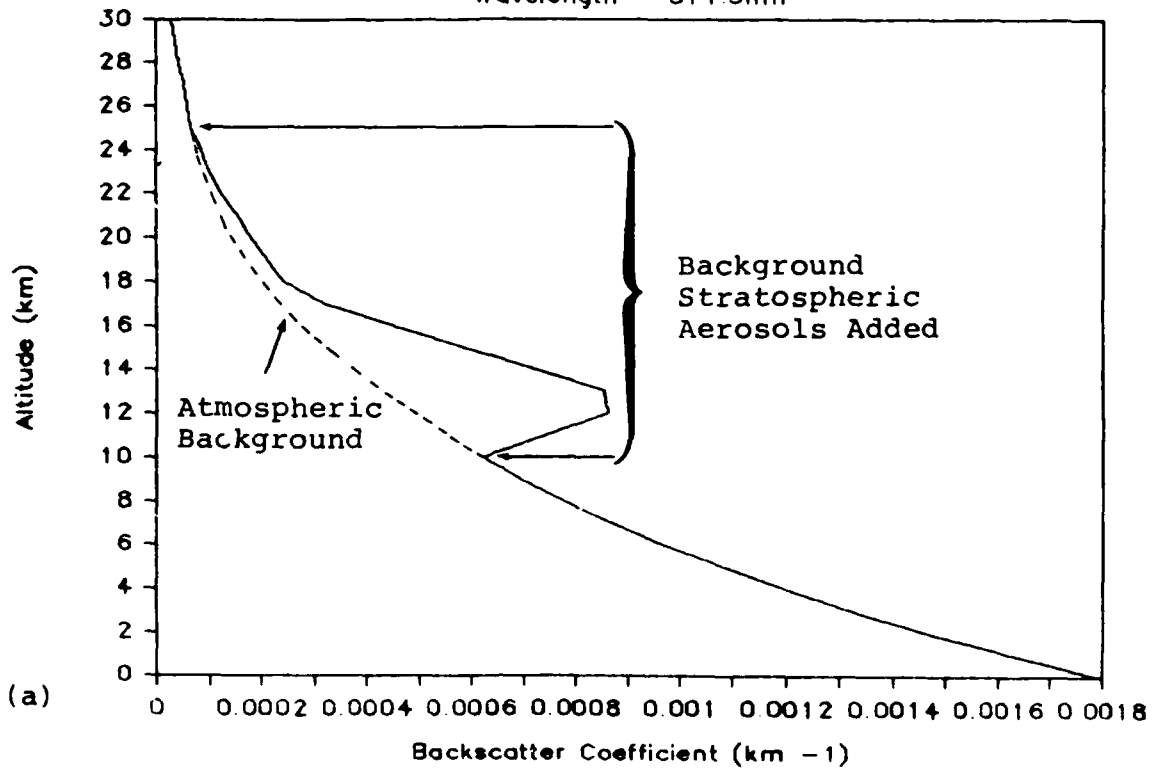


Figure 13. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Background Stratospheric Aerosols

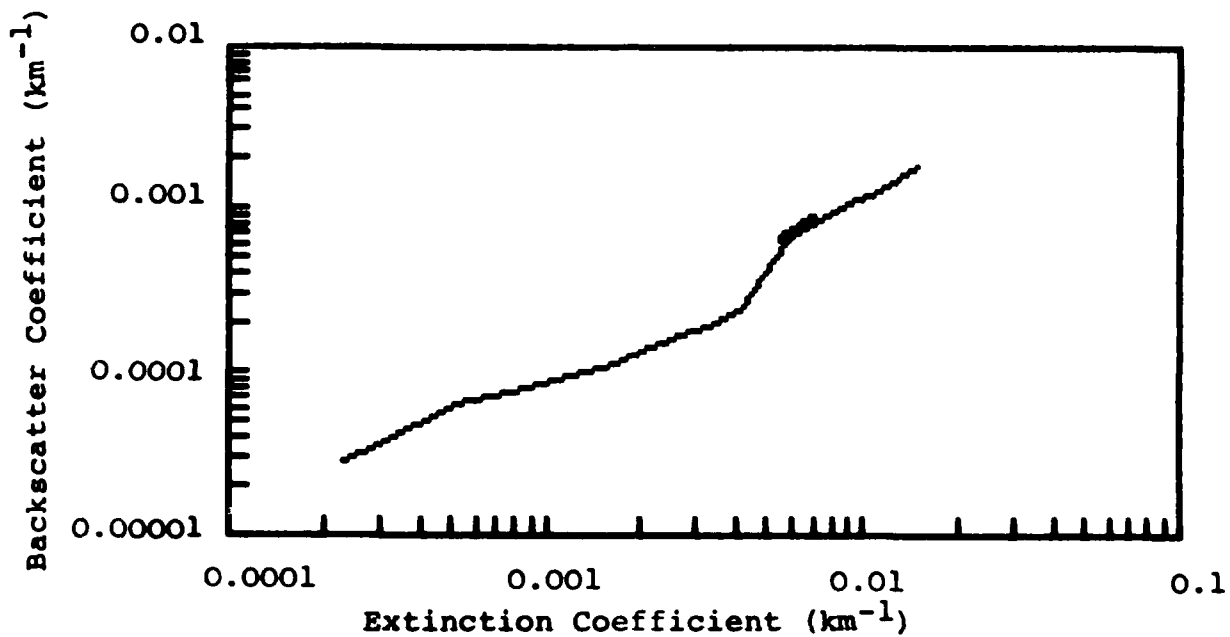


Figure 14. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Background Stratospheric Aerosols

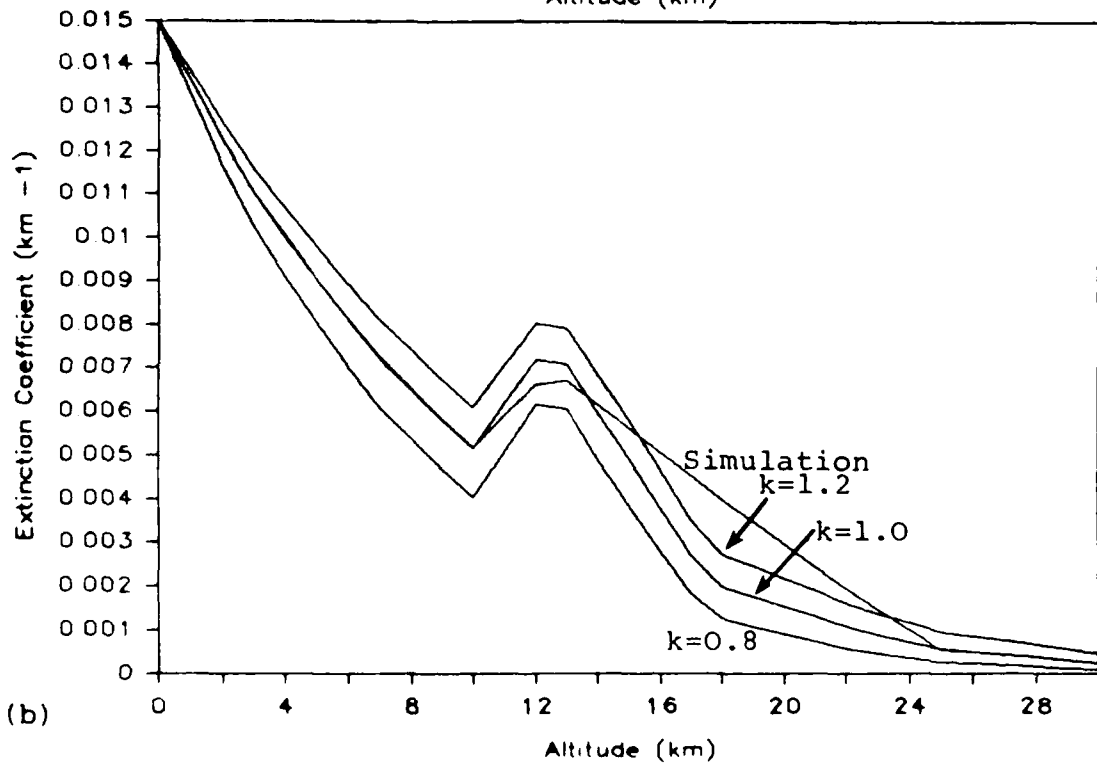
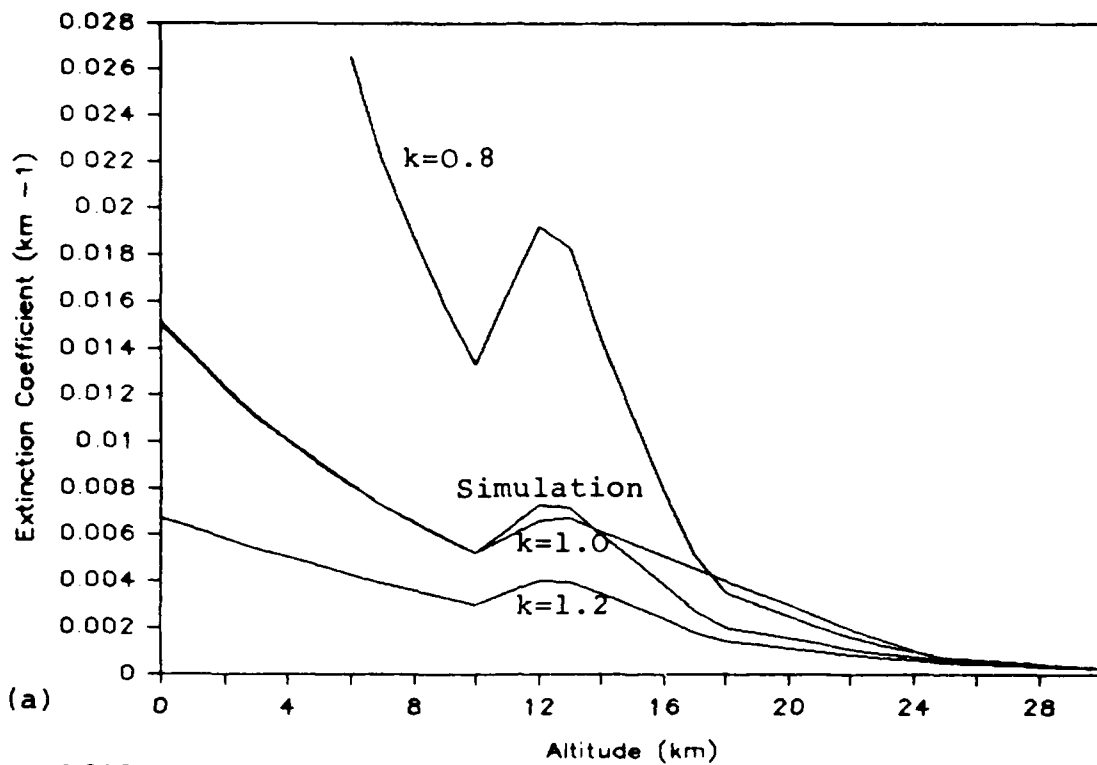


Figure 15. Comparison of Simulated and Inverted Data at 514.5 nm for Case 3 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

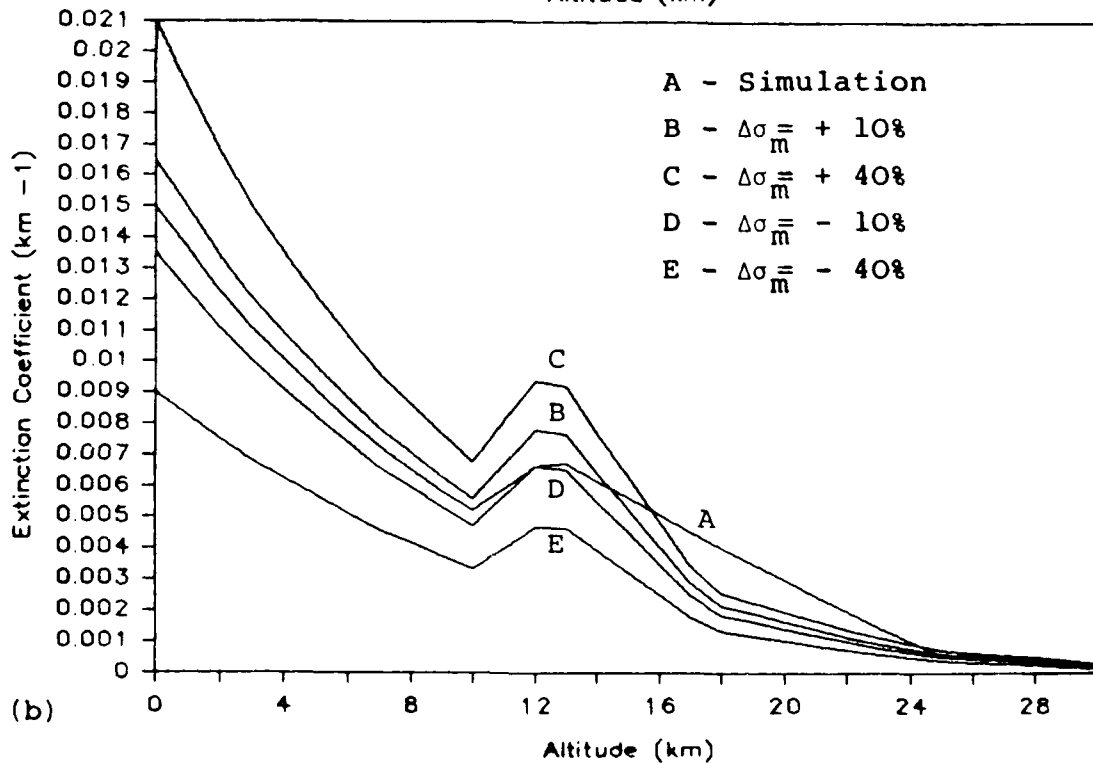
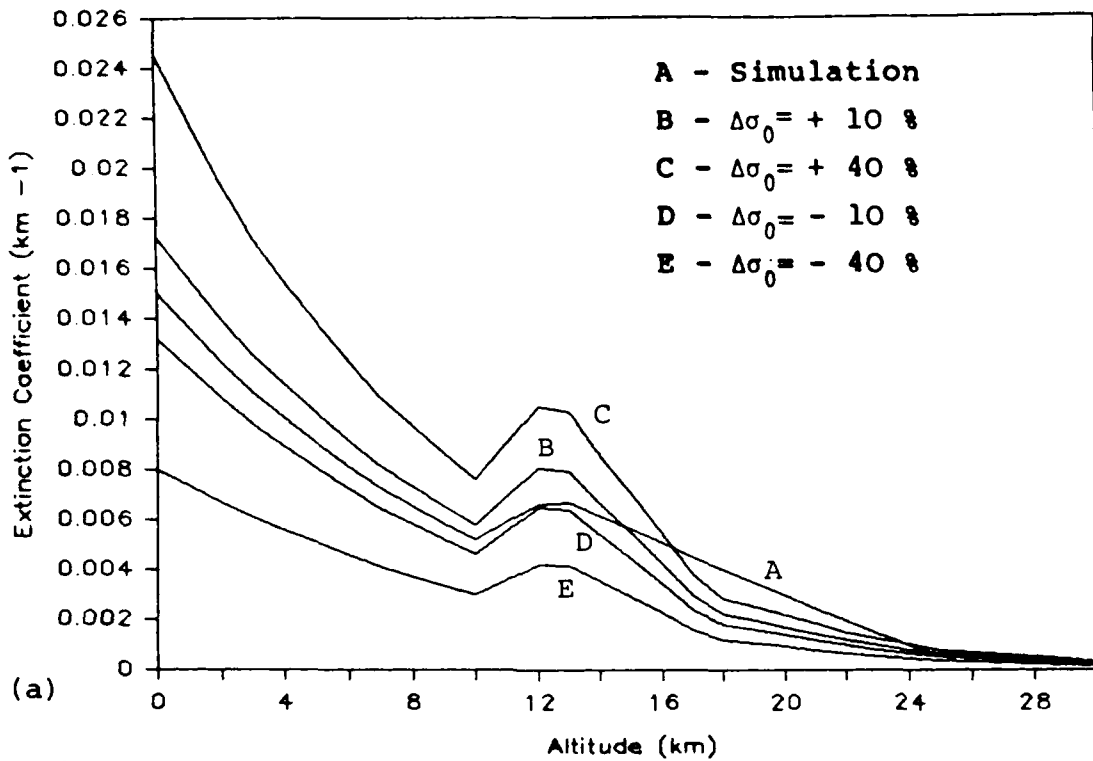


Figure 16. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 3 for the (a.) Near-field and (b.) Far-field Solutions

3.1.4 Case 2 Plus Clear Tropospheric Aerosols

In this example, a layer of tropospheric aerosols is added between the surface and 10 km. The optical conditions correspond to a "clear" atmosphere. Figures 17 (a.) and (b.) show the backscatter and extinction coefficients as a function of altitude. Figure 18 shows the plot of the backscatter versus the extinction coefficients.

The results from the inversion with various values of k are shown in Figures 19 (a.) and (b.). Both approaches give good results with a $k=1$ power law for altitudes above 10 km. The near-field solution looks like a value of k between 0.8 and 1.0 will give a reasonable fit. The far-field solution has reasonable fit with $k=0.8$. Figures 20 (a.) and (b.) show the results with variations in the boundary condition considered. The results assumed $k=1$.

3.1.5 Case 2 Plus Combined Stratospheric and Tropospheric Aerosols

This case corresponds to the combination of the background stratospheric aerosols with the clear tropospheric aerosols from the preceding case. Figures 21 (a.) and (b.) show the backscatter and extinction coefficients, respectively, as a function of altitude. Figure 22 displays the backscatter coefficients plotted against the extinction coefficients.

Figures 23 (a.) and (b.) show the results of the inversion with k varied and Figures 24 (a.) and (b.) show the results of the variation of the boundary conditions.

Rayleigh + Tropospheric Aerosols

Wavelength - 514.5nm

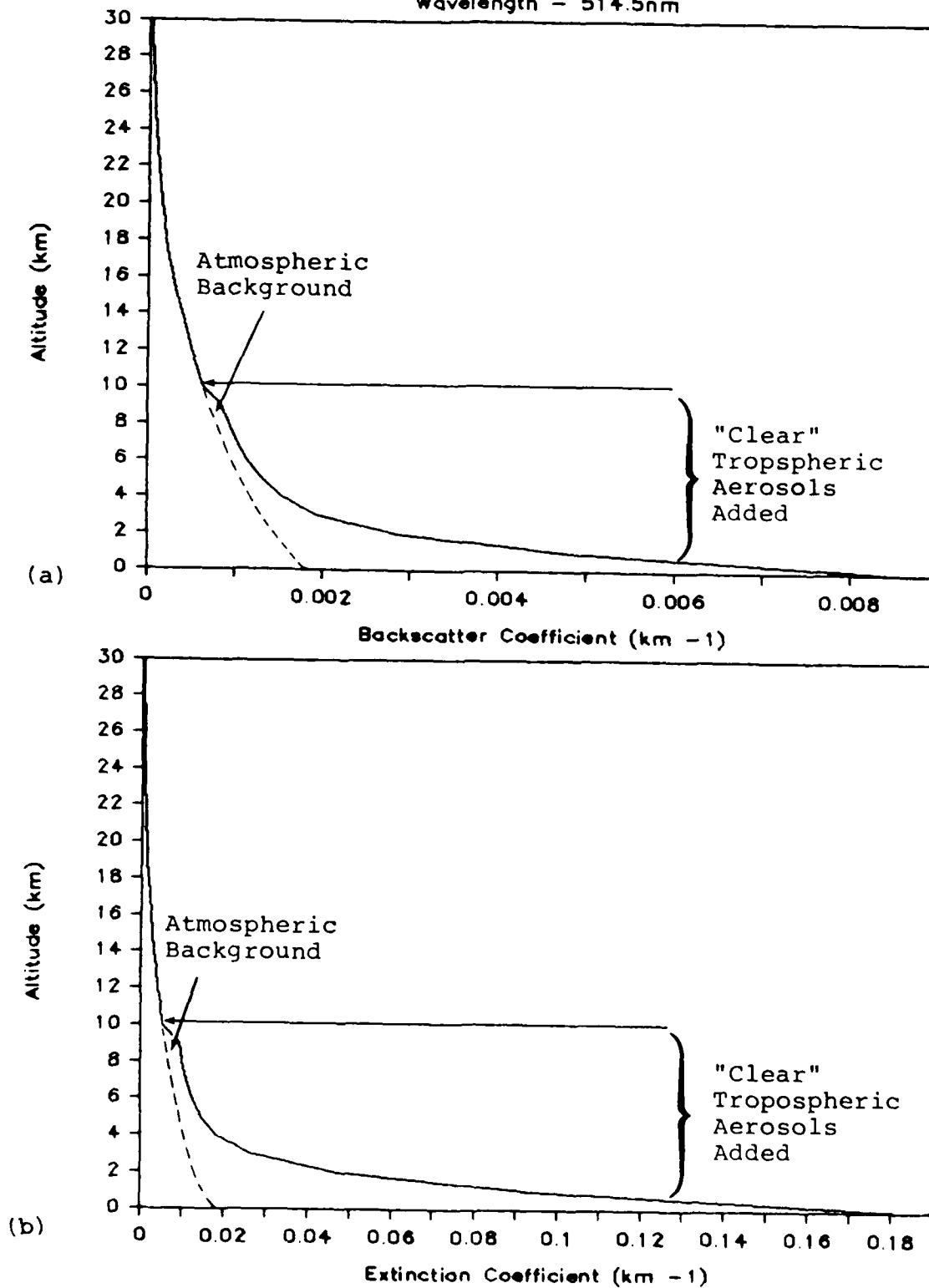


Figure 17. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With "Clear" Tropospheric Aerosols

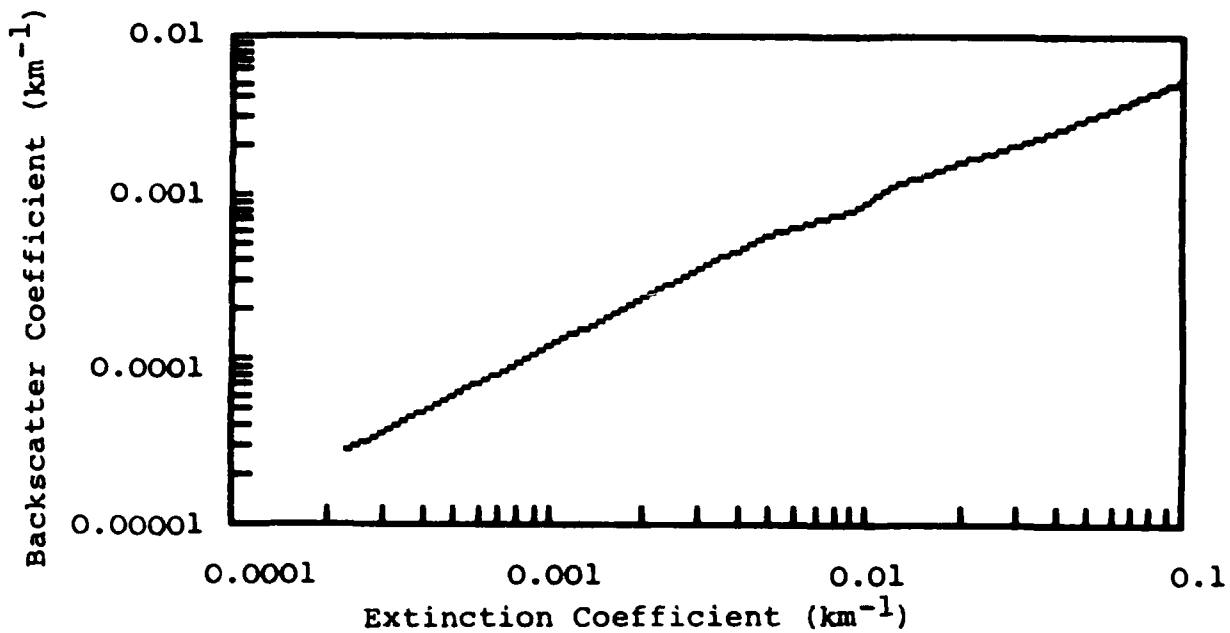


Figure 18. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With "Clear" Tropospheric Aerosols

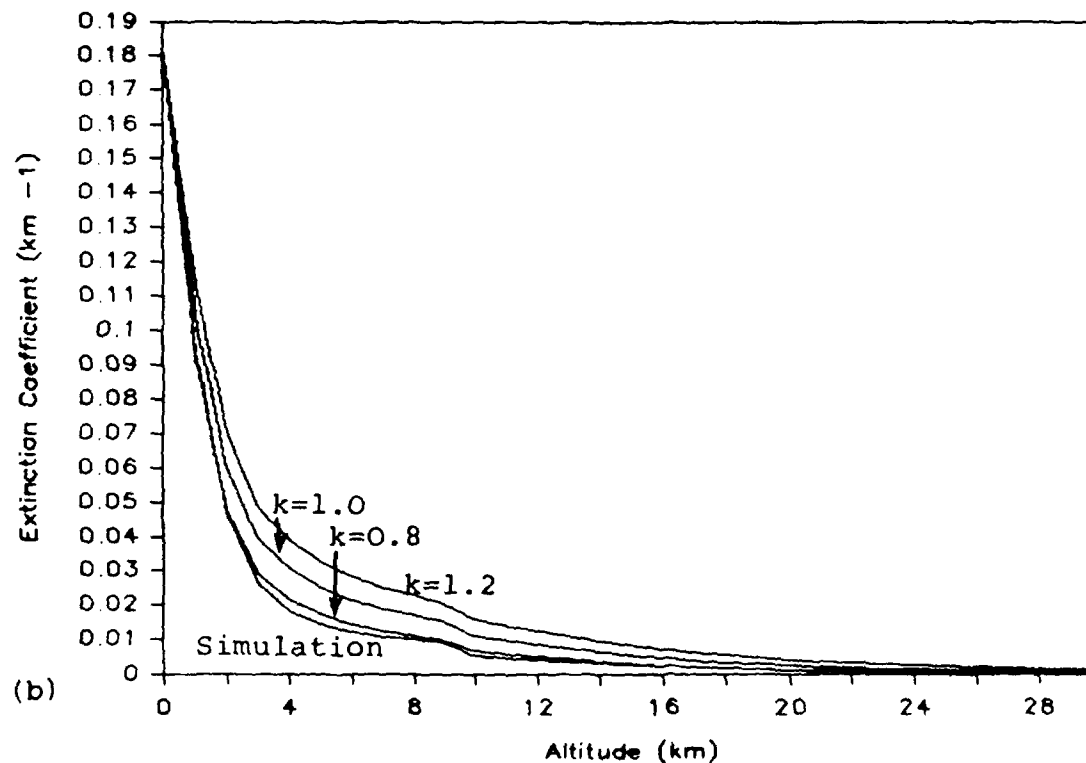
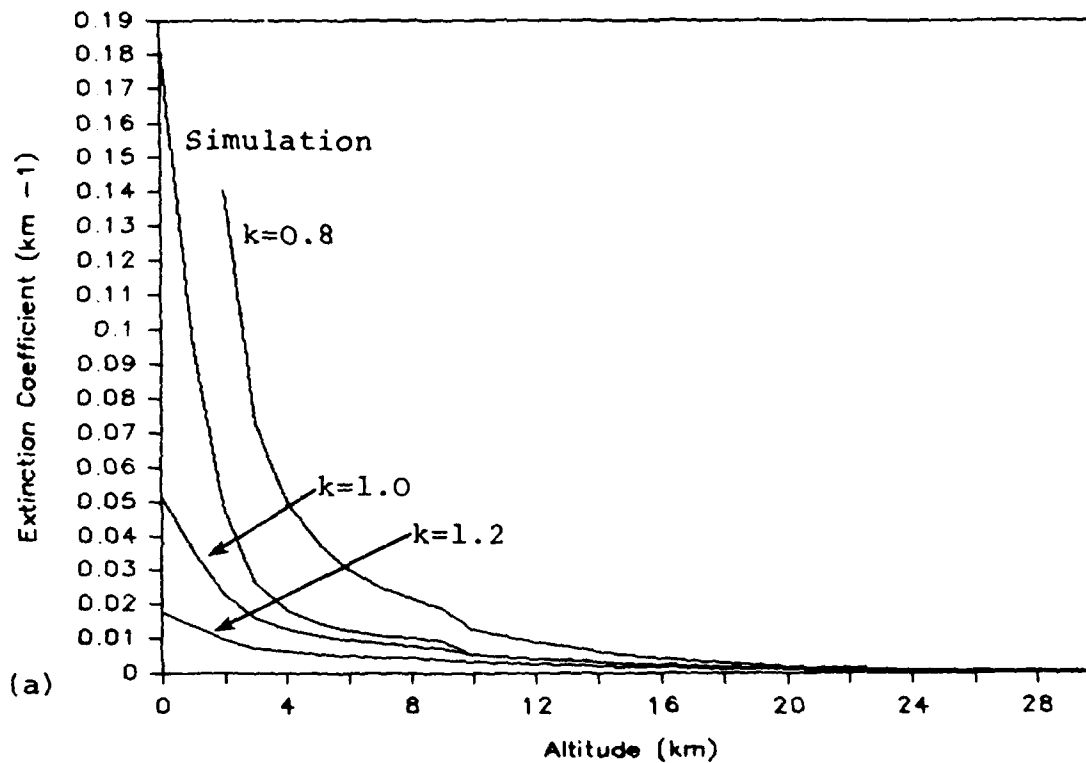


Figure 19. Comparison of Simulated and Inverted Data at 514.5 nm for Case 4 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

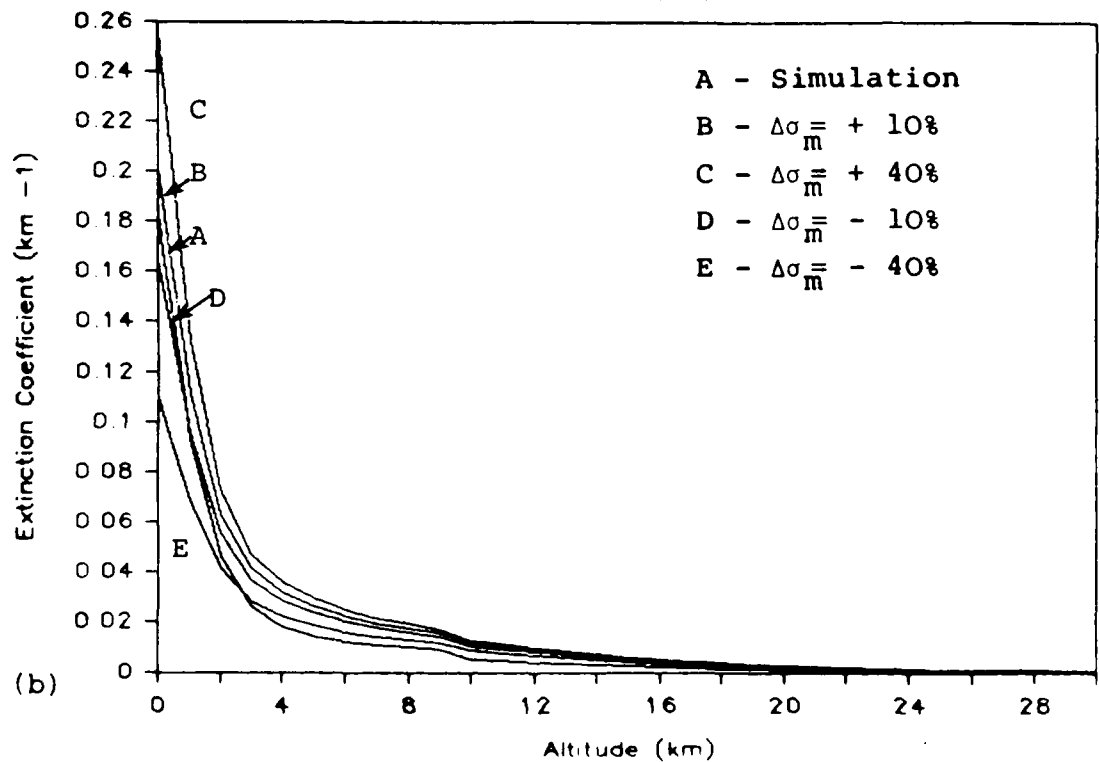
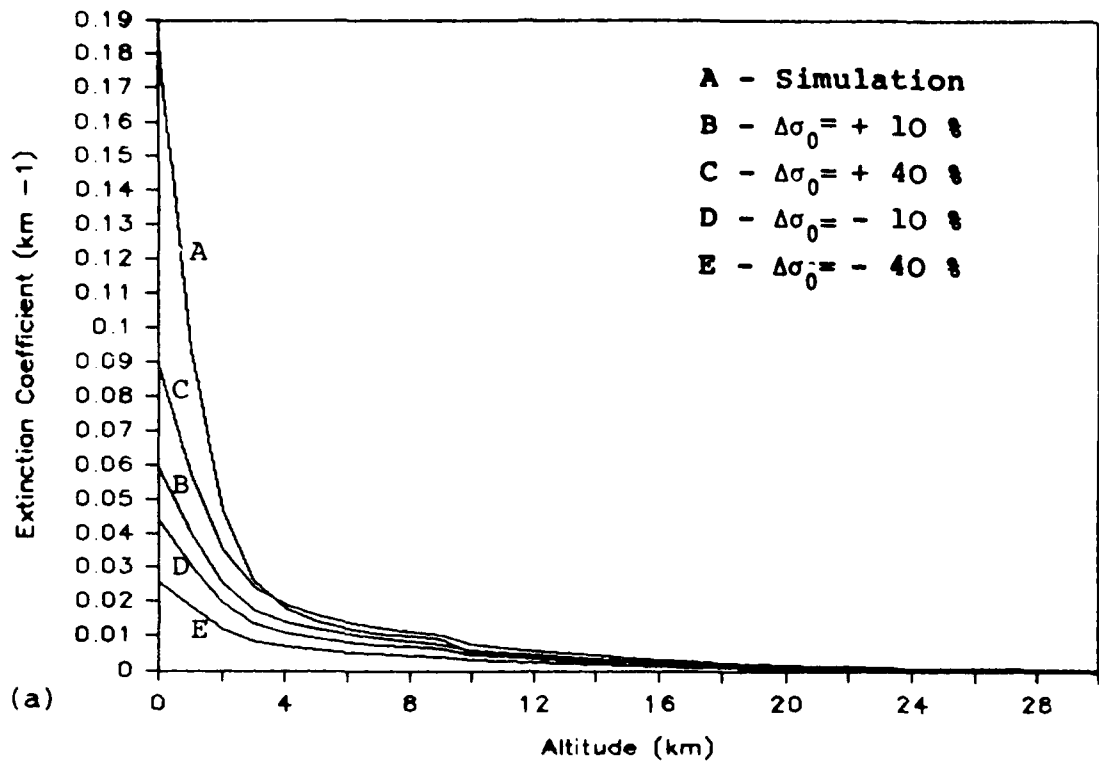


Figure 20. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 4 for the (a.) Near-field and (b.) Far-field Solutions

Tropospheric + Stratospheric Aerosols

Wavelength - 514.5nm

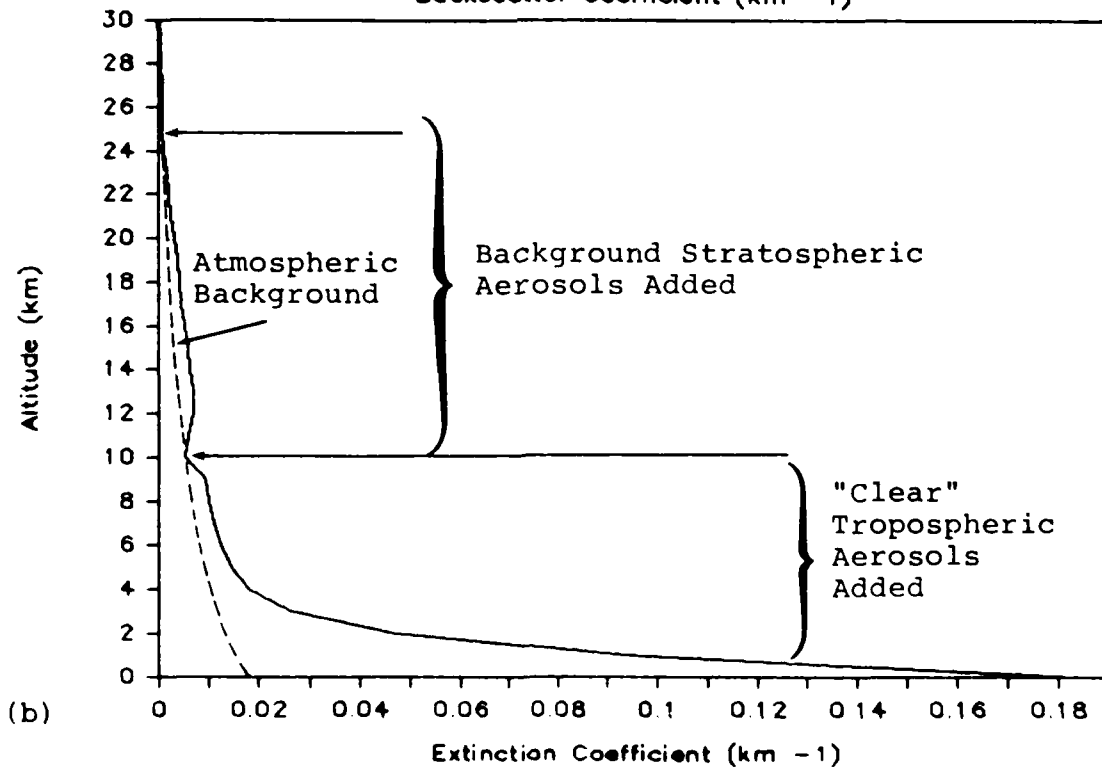
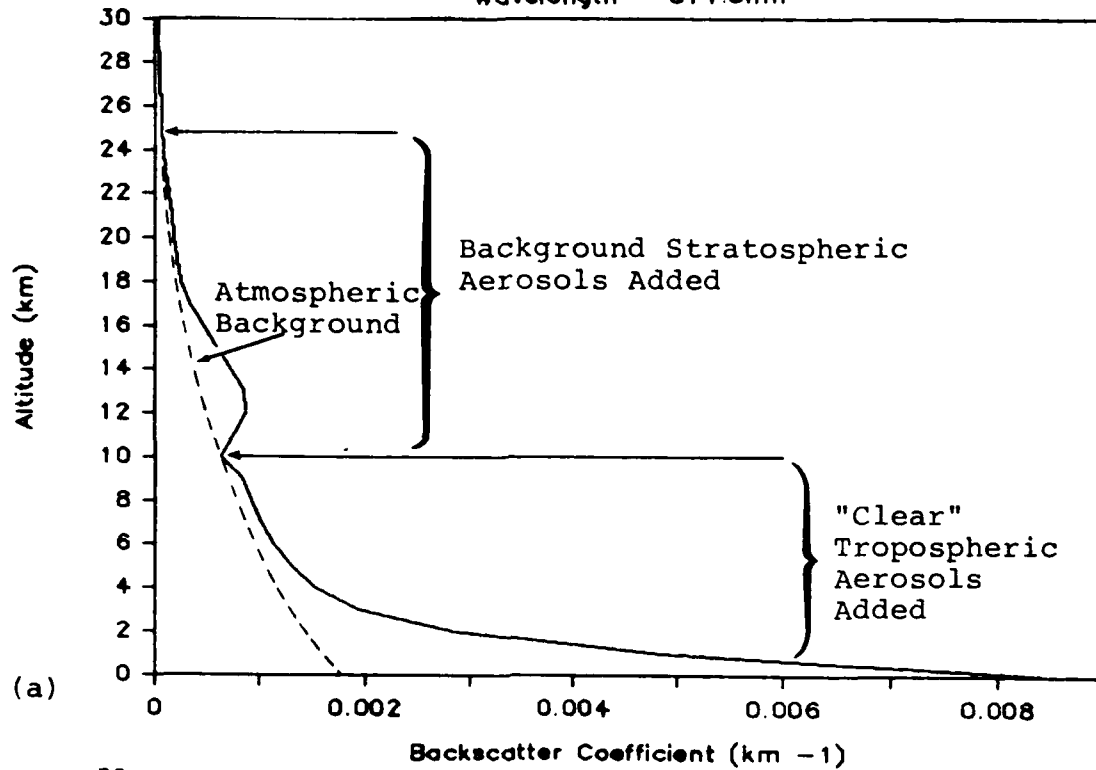


Figure 21. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Background Stratospheric and "Clear" Tropospheric Aerosols

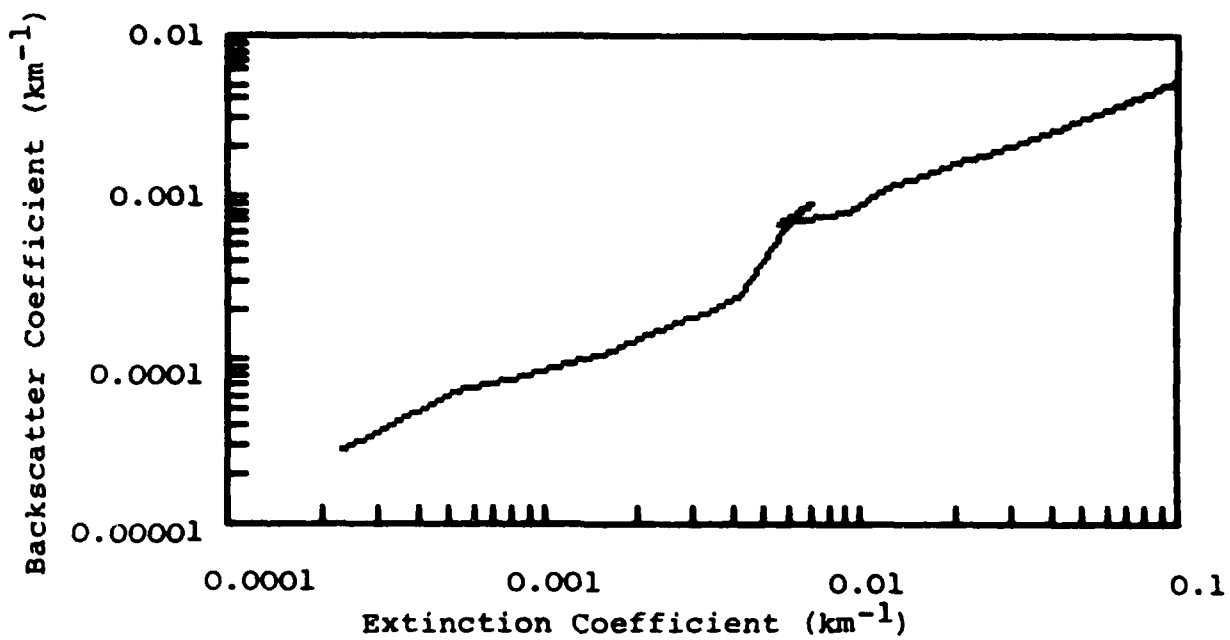


Figure 22. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Background Stratospheric Aerosols and "Clear" Tropospheric Aerosols

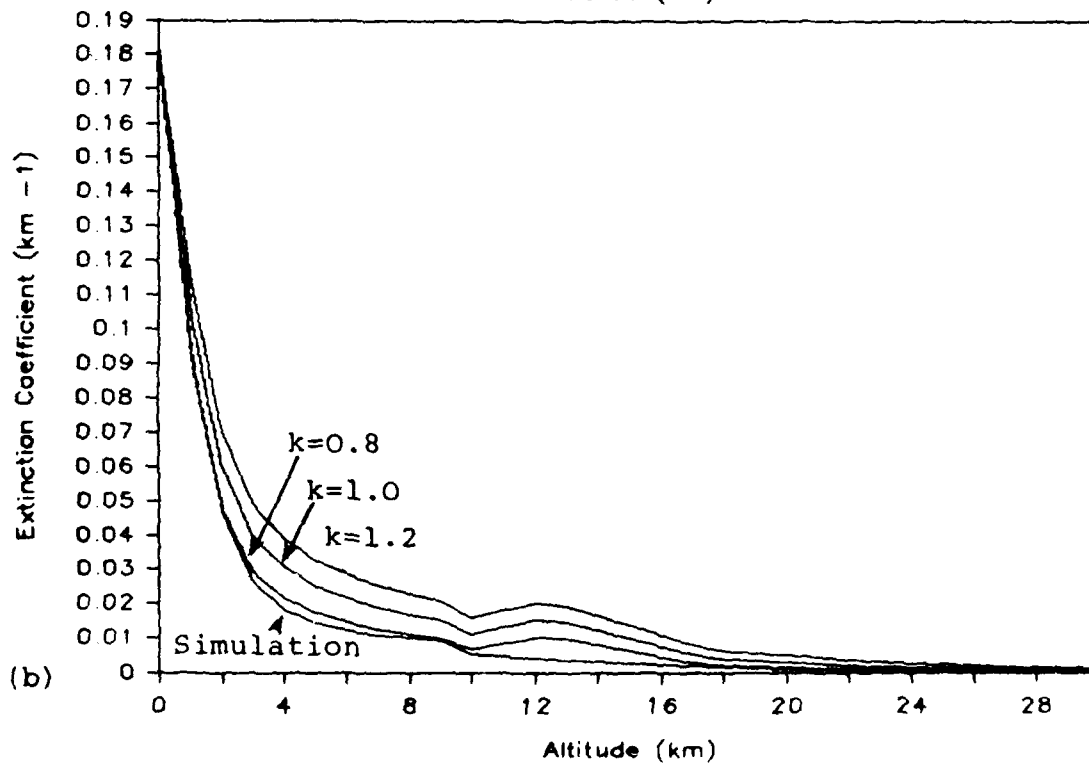
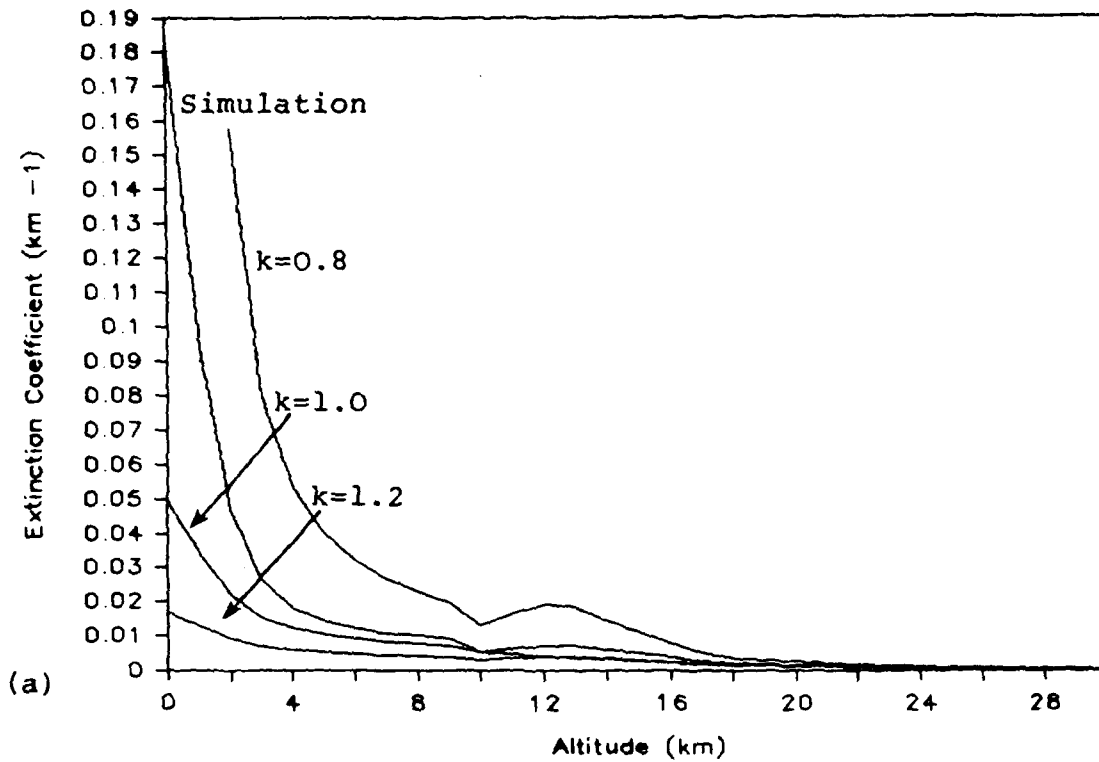


Figure 23. Comparison of Simulated and Inverted Data at 514.5 nm for Case 5 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

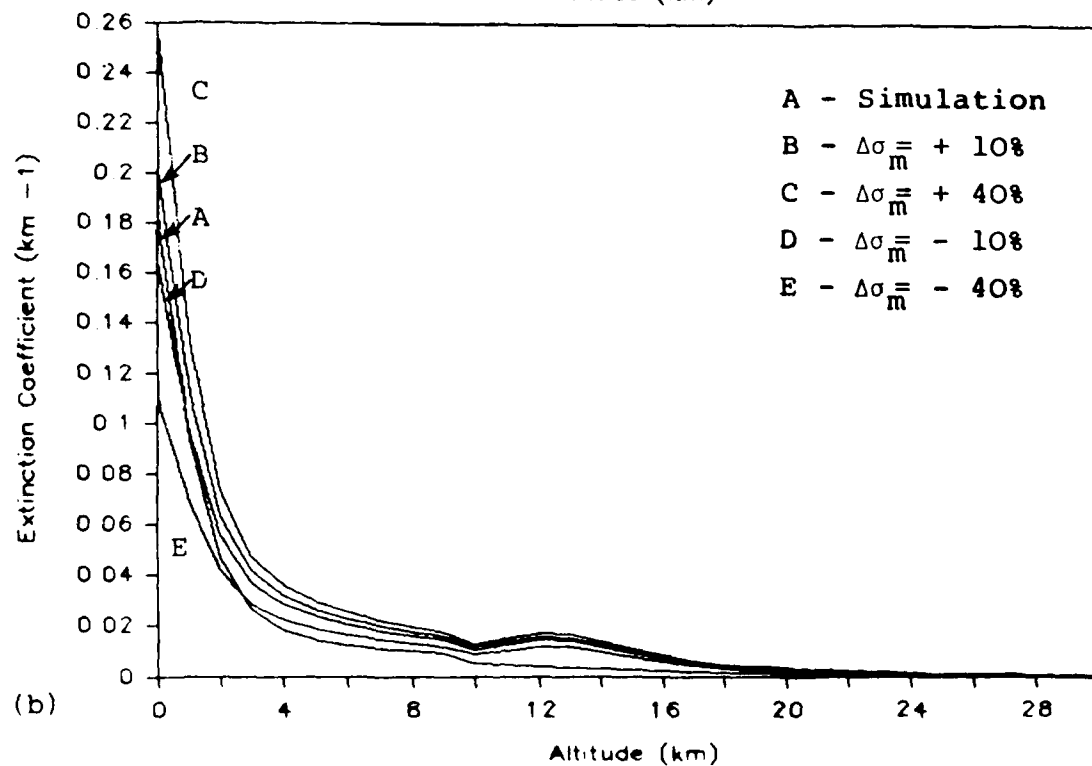
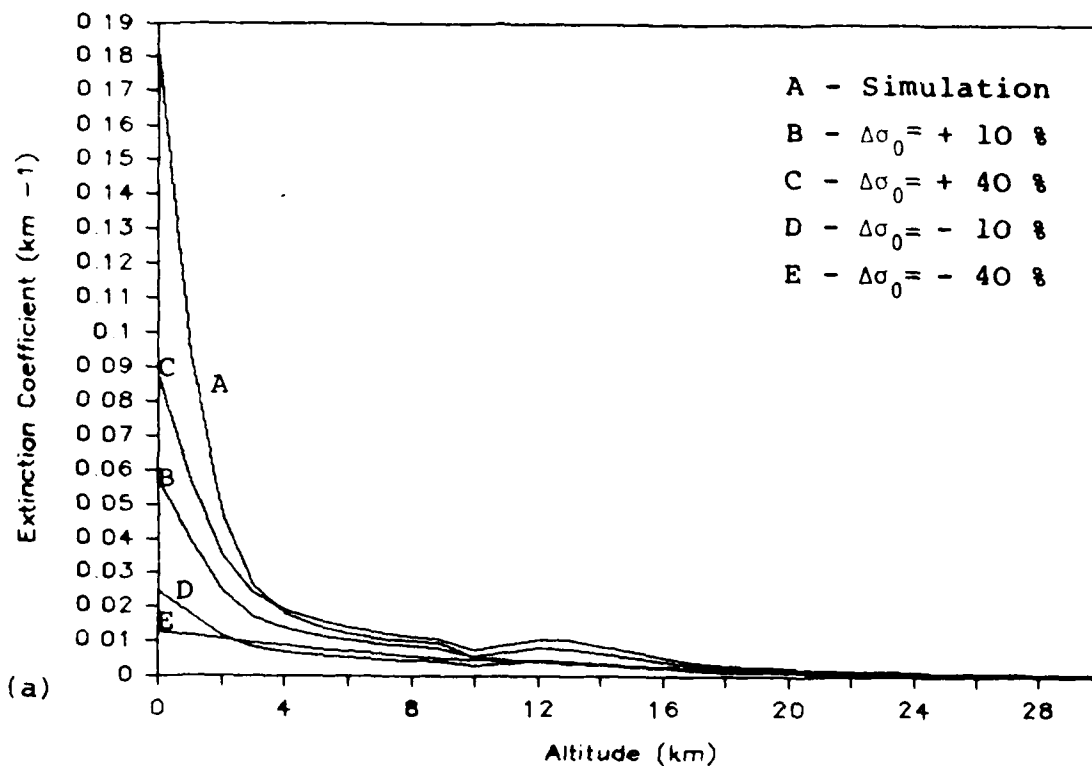


Figure 24. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 5 for the (a.) Near-field and (b.) Far-field Solutions

None of the k values tried yielded an acceptable fit to the simulated data. A value of k of 0.8 gave a reasonable fit to the far-field solution for altitudes below 10 km but an unacceptable fit above 10 km. This agrees with the results for the individual aerosols layers (see Sections 3.1.4 and 3.1.5). One can conclude from this, that one power law cannot represent an atmosphere with distinct aerosol layers.

3.1.6 Case 2 Plus Aged Volcanic Aerosols

Figures 25 (a.) and (b.) show the backscatter and extinction coefficients as a function of altitude for an atmosphere with aged volcanic aerosols added to an aerosol-free background. The backscatter and extinction coefficients, as shown in Figure 26, are those in LOWTRAN 6 [Shettle, private communication, 1986].

Figures 27 (a.) and (b.) give the results from the inversions with different values of k and Figures 28 (a.) and (b.) give the results from the variation in the boundary conditions with $k=1$. As with the background stratospheric aerosol results (e.g. Figure 15), a power law with $k=1$ will reproduce the aerosol-free parts of the atmosphere but not those with aerosols present.

3.1.7 Case 2 Plus Fresh Volcanic Aerosols

Figures 29 (a.) and (b.) show the backscatter and extinction coefficients as a function of altitude for an atmosphere with fresh volcanic aerosols added to an aerosol-

Rayleigh + Aged Volcanic

Wavelength - 514.5nm

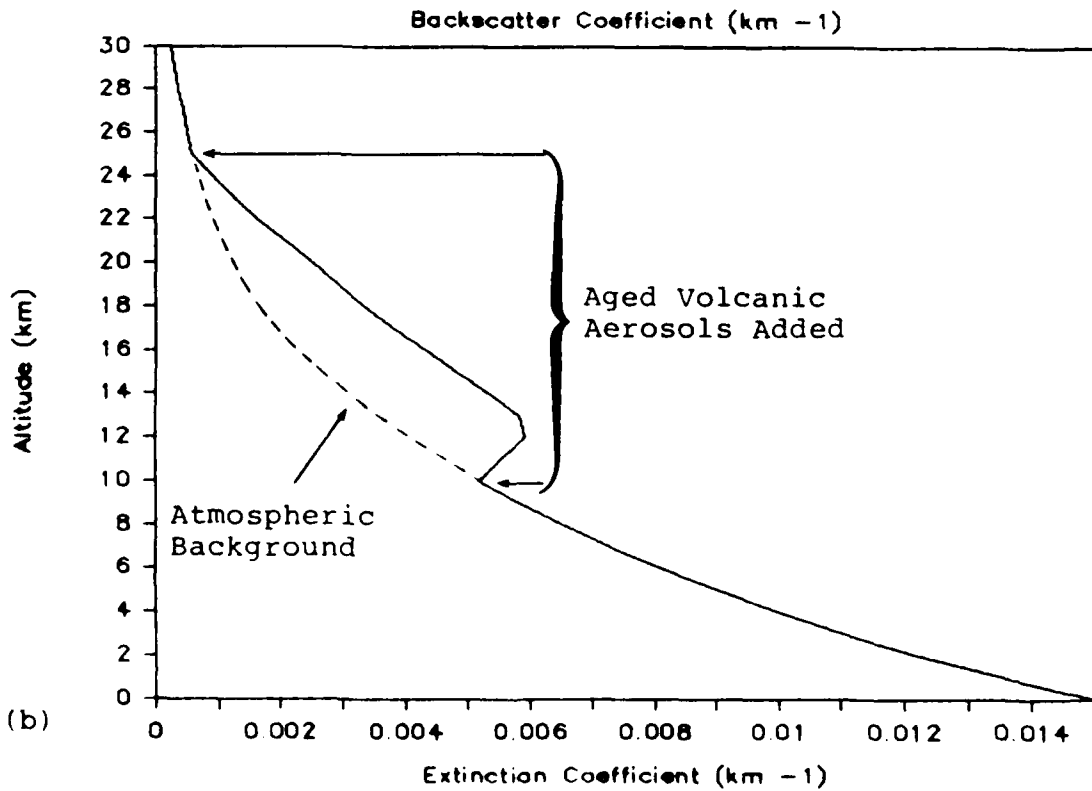
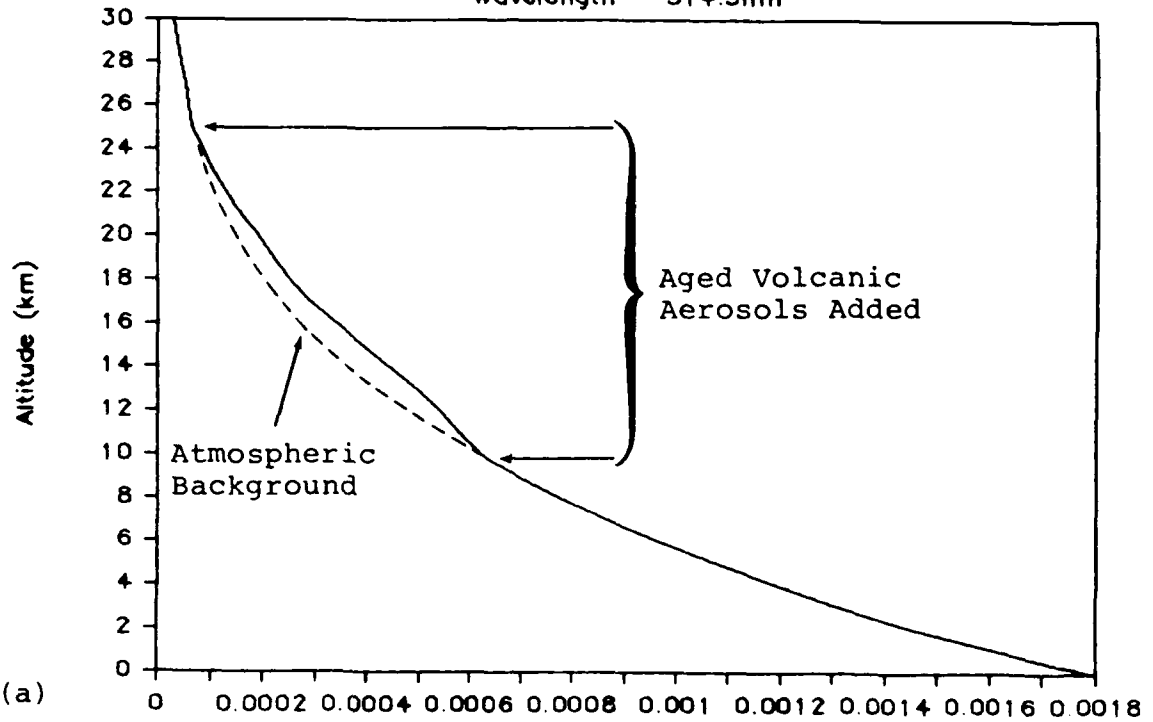


Figure 25. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Aged Volcanic Aerosols

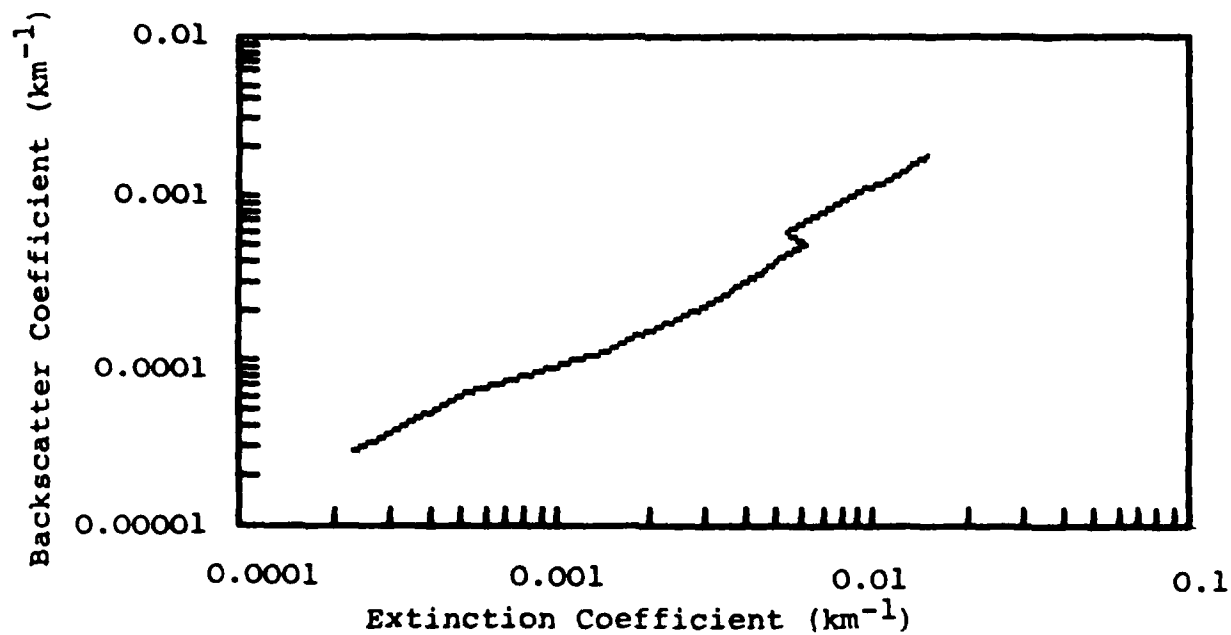


Figure 26. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Aged Volcanic Aerosols

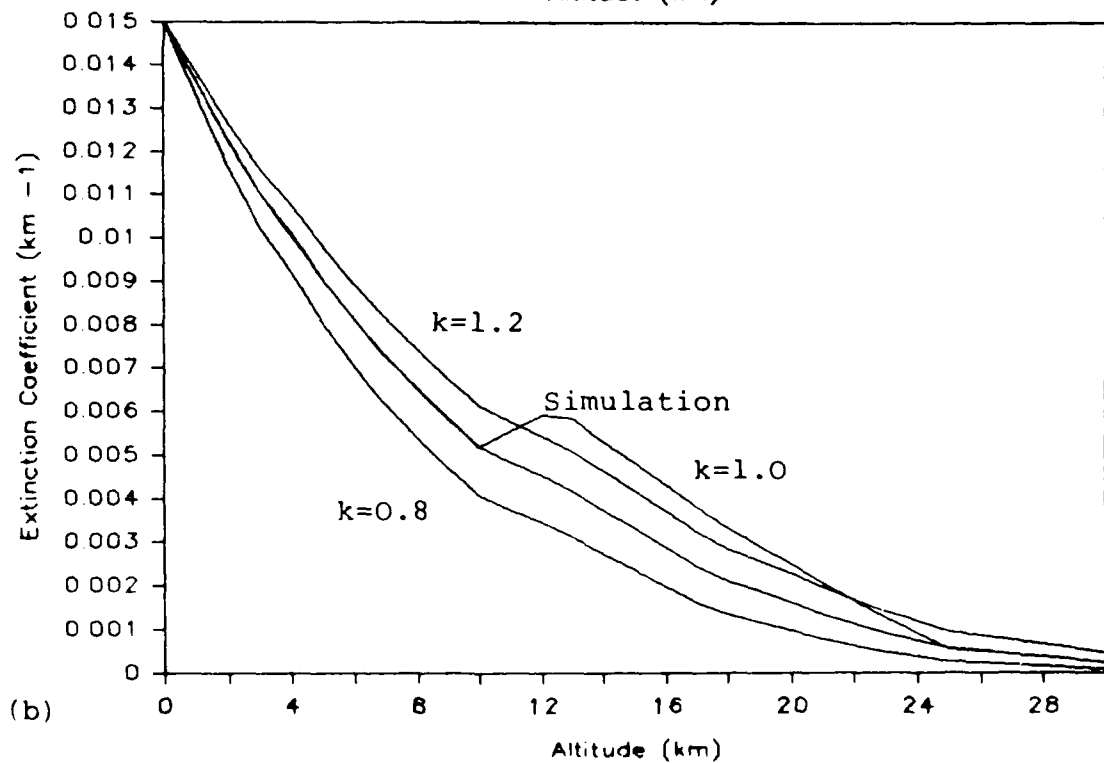
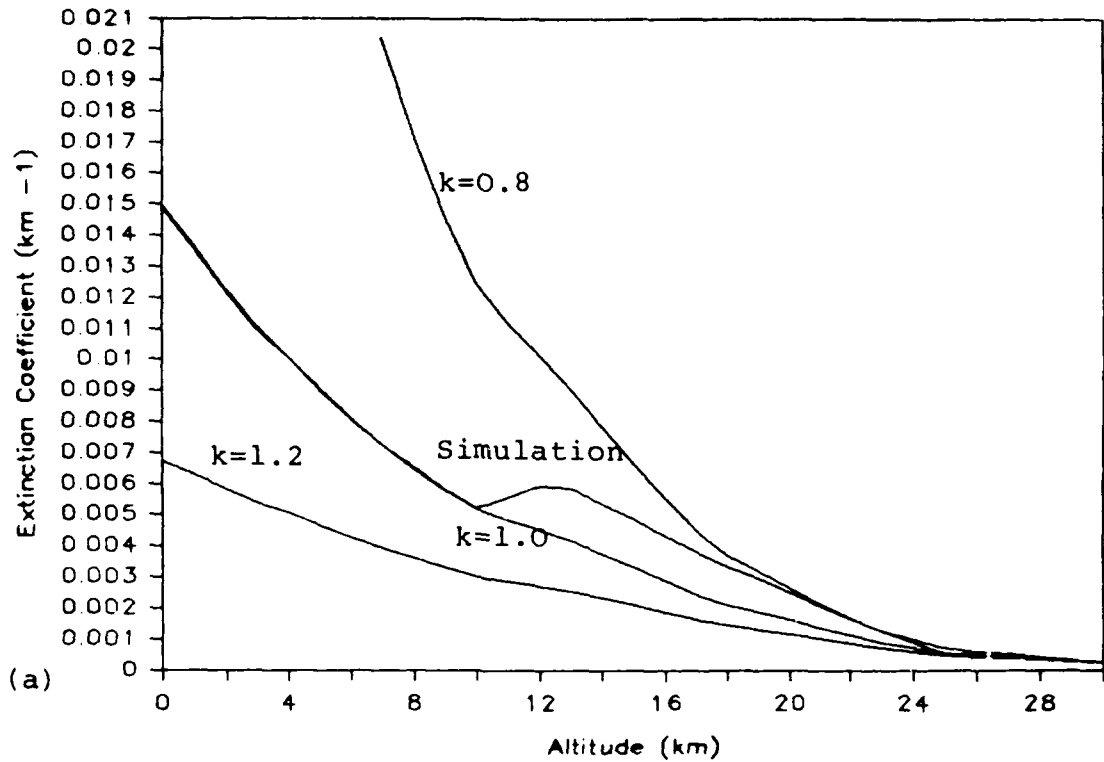


Figure 27. Comparison of Simulated and Inverted Data at 514.5 nm for Case 6 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

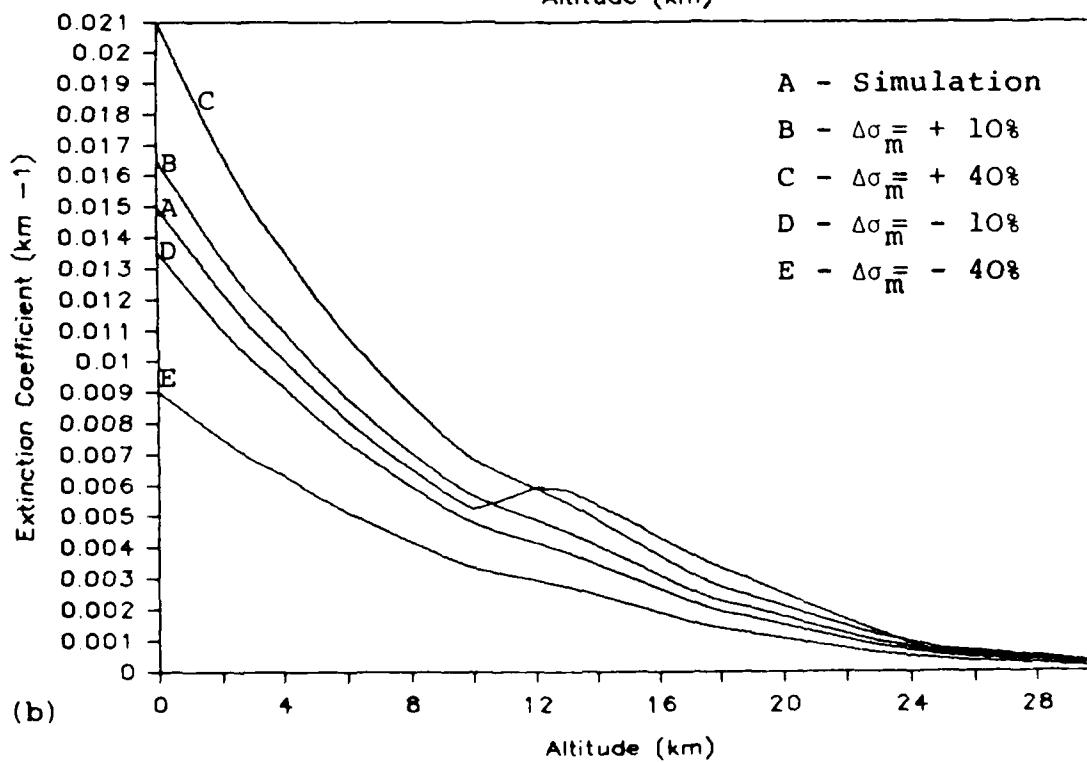
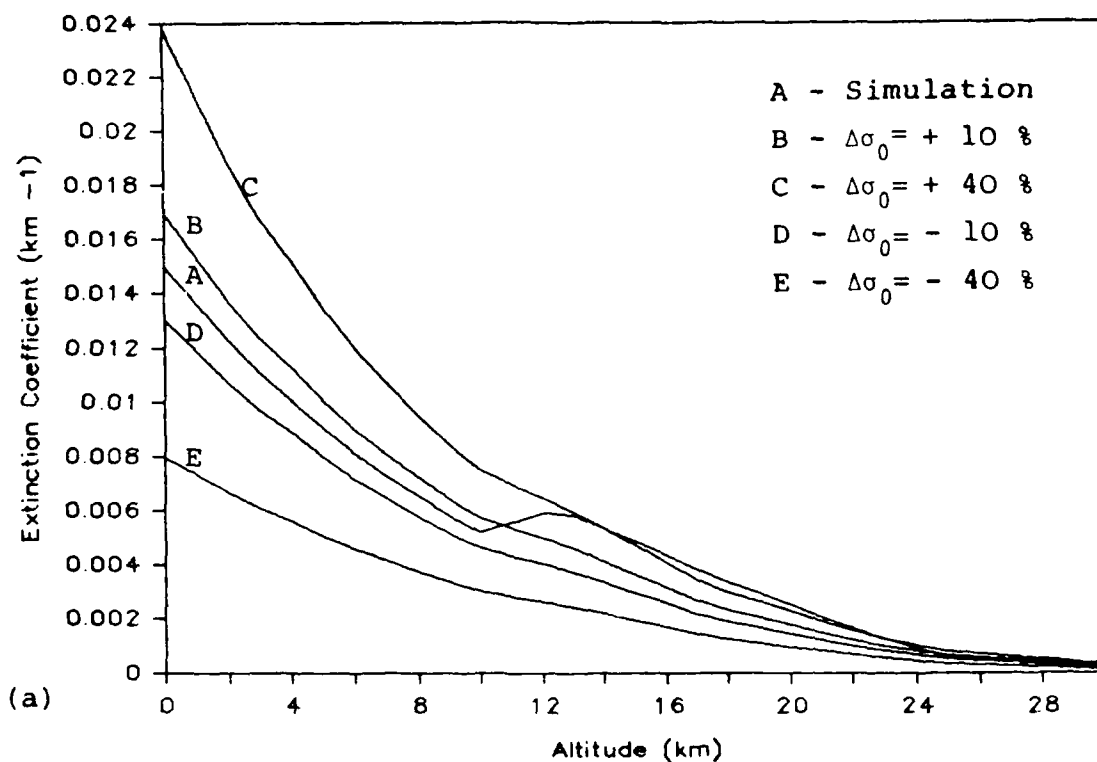


Figure 28. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 6 for the (a.) Near-field and (b.) Far-field Solutions

Rayleigh + Fresh Volcanic

Wavelength - 514.5nm

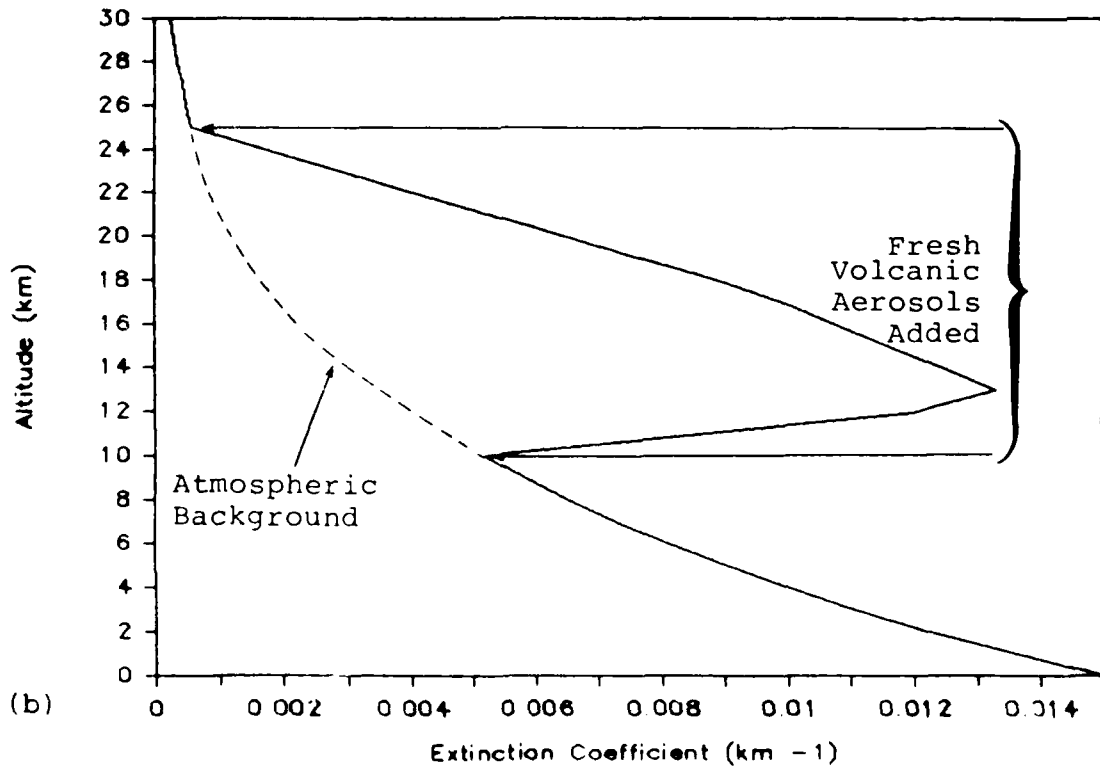
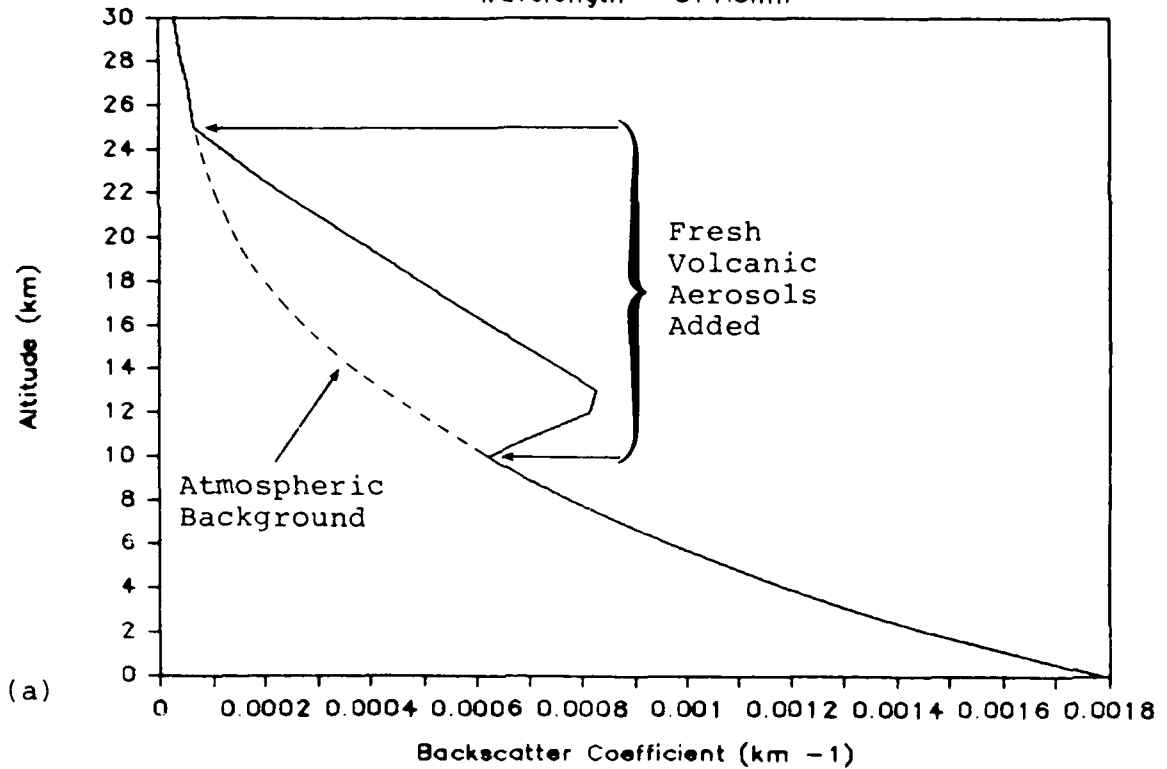


Figure 29. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With Fresh Volcanic Aerosols

free background. The backscatter and extinction coefficients, as shown in Figure 30, are those in LOWTRAN 6 [Shettle, private communication, 1986].

Figures 31 (a.) and (b.) give the results from the inversions with different values of k and Figures 32 (a.) and (b.) give the results from the variation in the boundary conditions with $k=1$. As with the background stratospheric aerosol results (e.g. Figure 14), a power law with $k=1$ will reproduce the aerosol-free parts of the atmosphere but not those with aerosols present.

3.1.8 Case 2 Plus Combined Background Stratospheric and Fresh Volcanic Aerosols

Figures 33 (a.) and (b.) show the backscatter and extinction coefficients as a function of altitude for an atmosphere with 50 % background stratospheric and 50 % fresh volcanic aerosols added to an aerosol-free background. Figure 34 displays the backscatter and extinction coefficients.

Figures 35 (a.) and (b.) give the results from the inversions with different values of k and Figures 36 (a.) and (b.) give the results from the variation in the boundary conditions with $k=1$. Under these conditions, a power law with $k=1$ does a reasonable job of reproducing the simulated data.

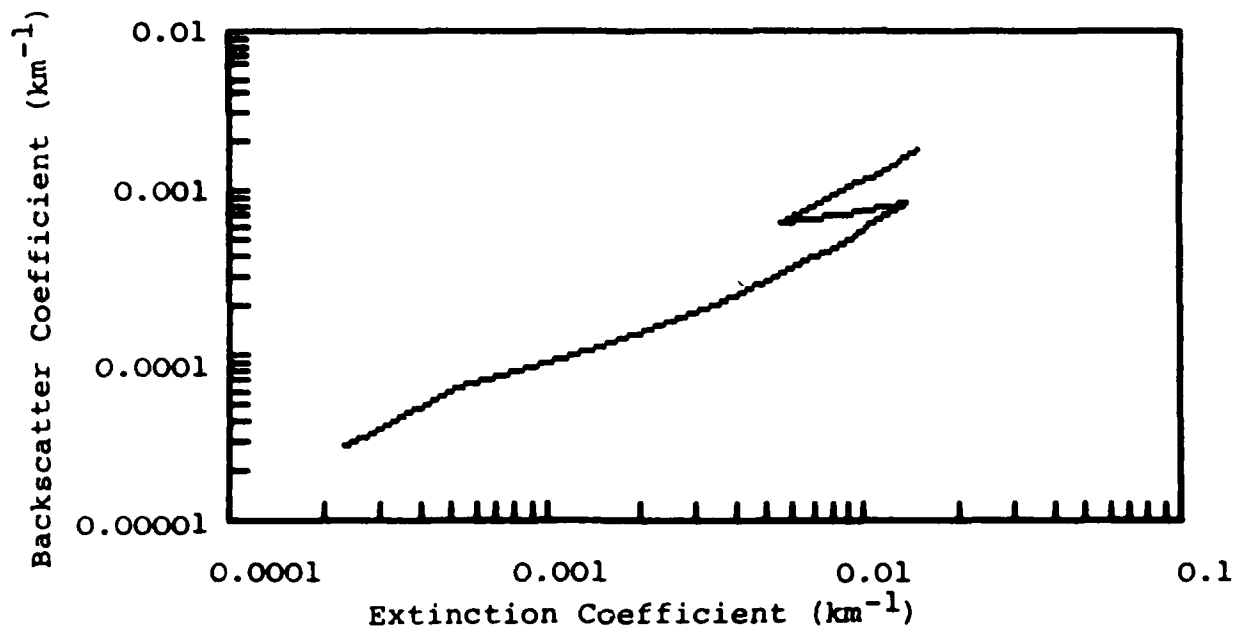


Figure 30. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Fresh Volcanic Aerosols

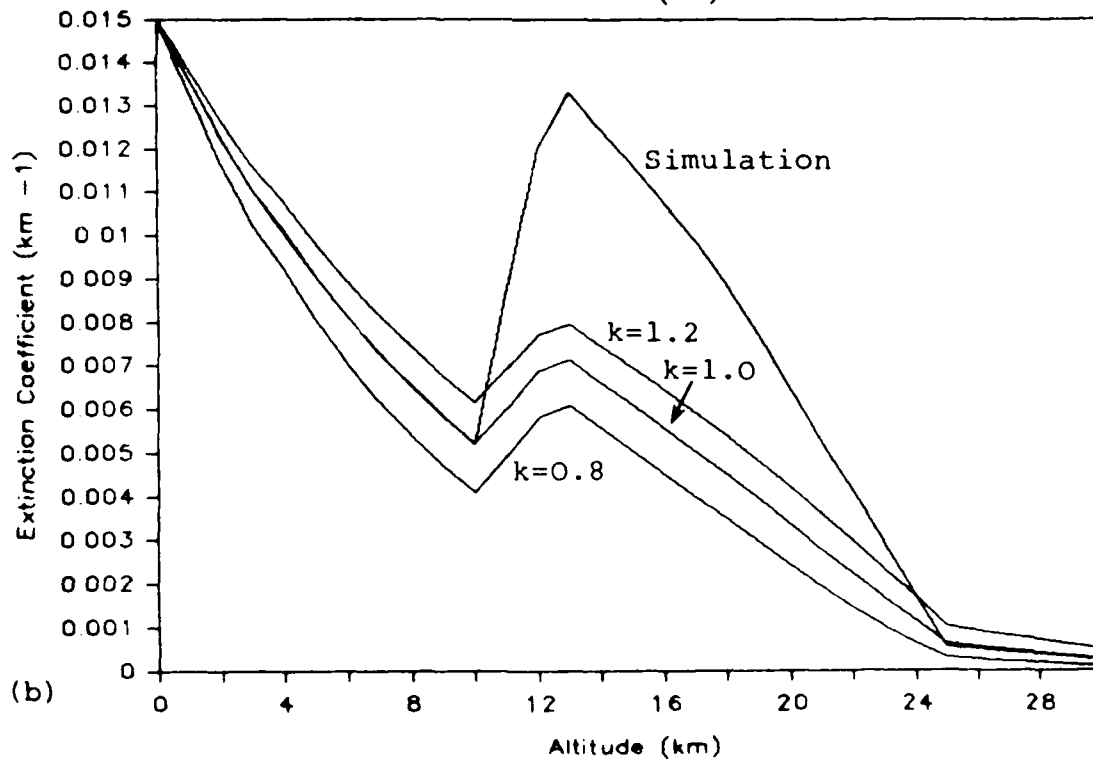
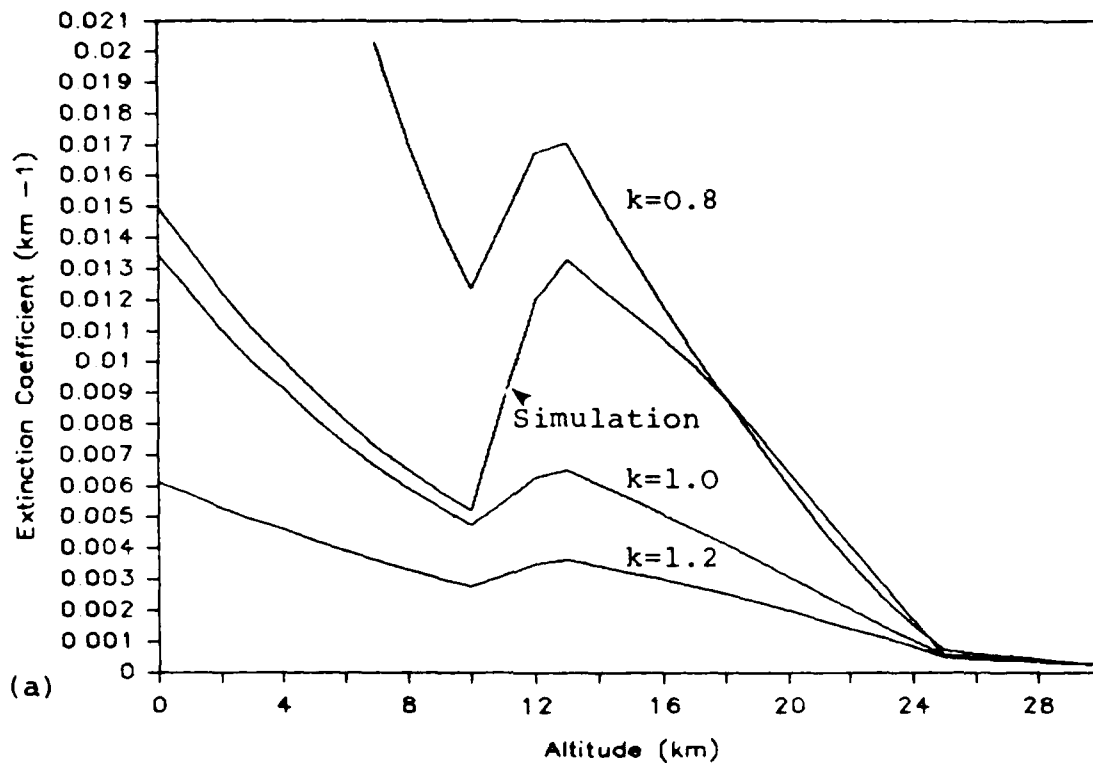


Figure 31. Comparison of Simulated and Inverted Data at 514.5 nm for Case 7 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

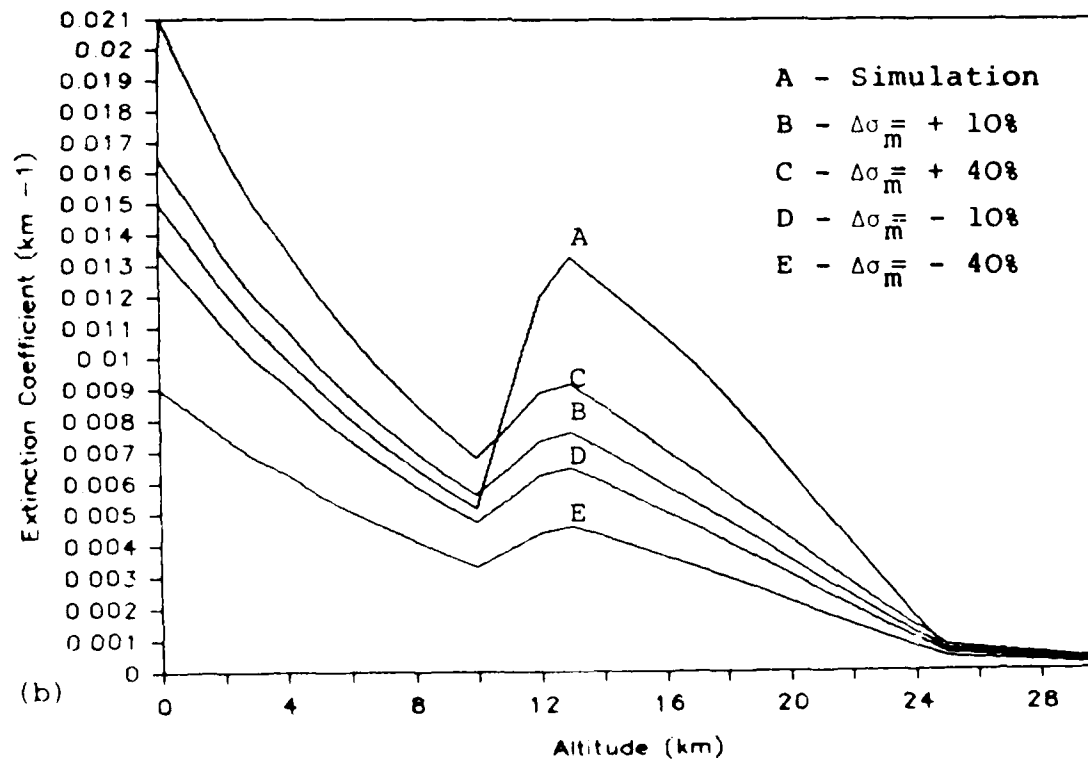
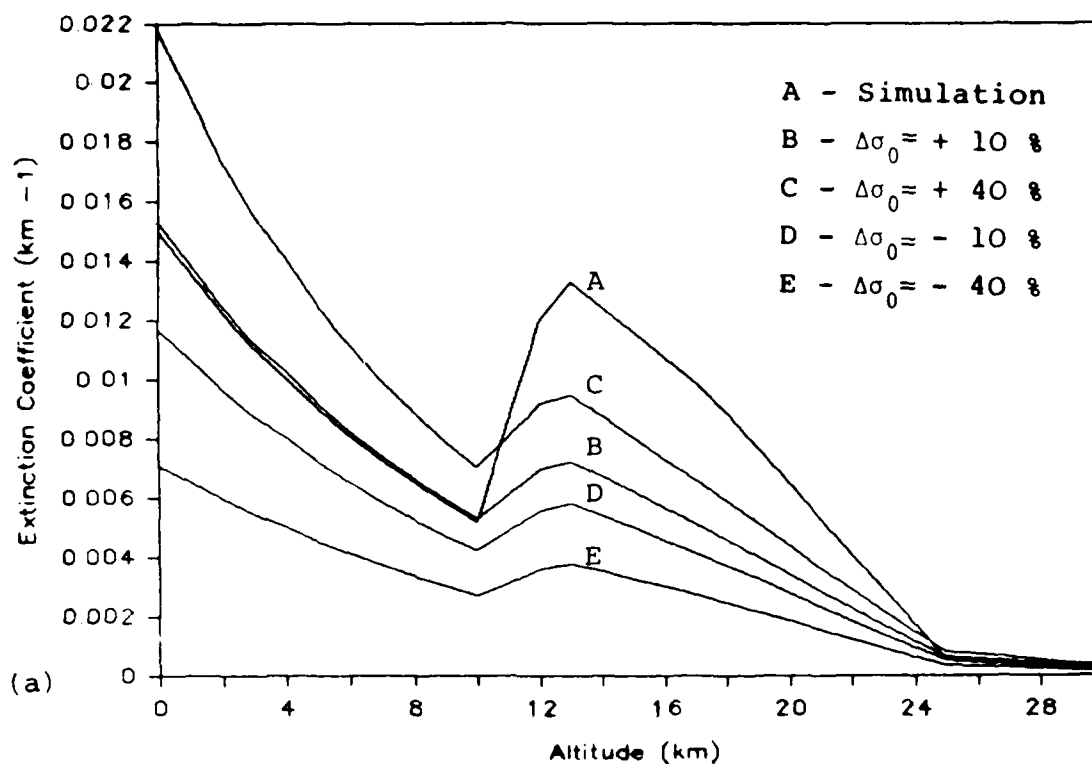


Figure 32. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 7 for the (a.) Near-field and (b.) Far-field Solutions

Rayleigh + Background + Fresh Volcanic

Wavelength - 514.5nm

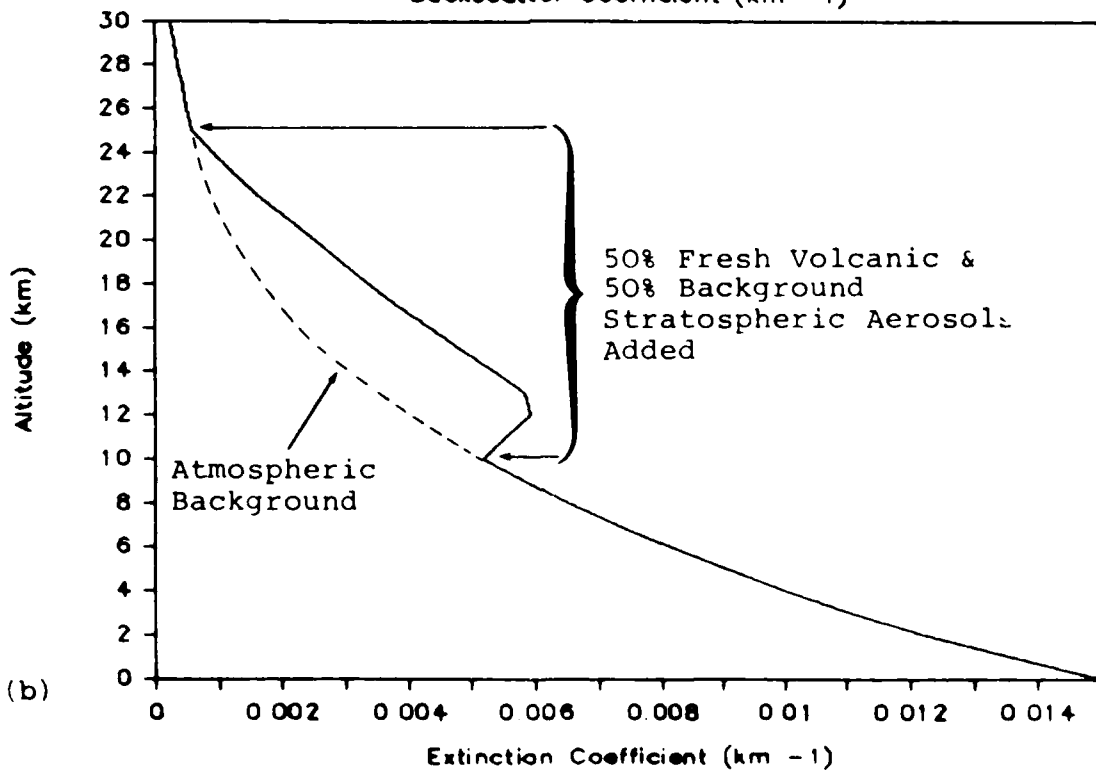
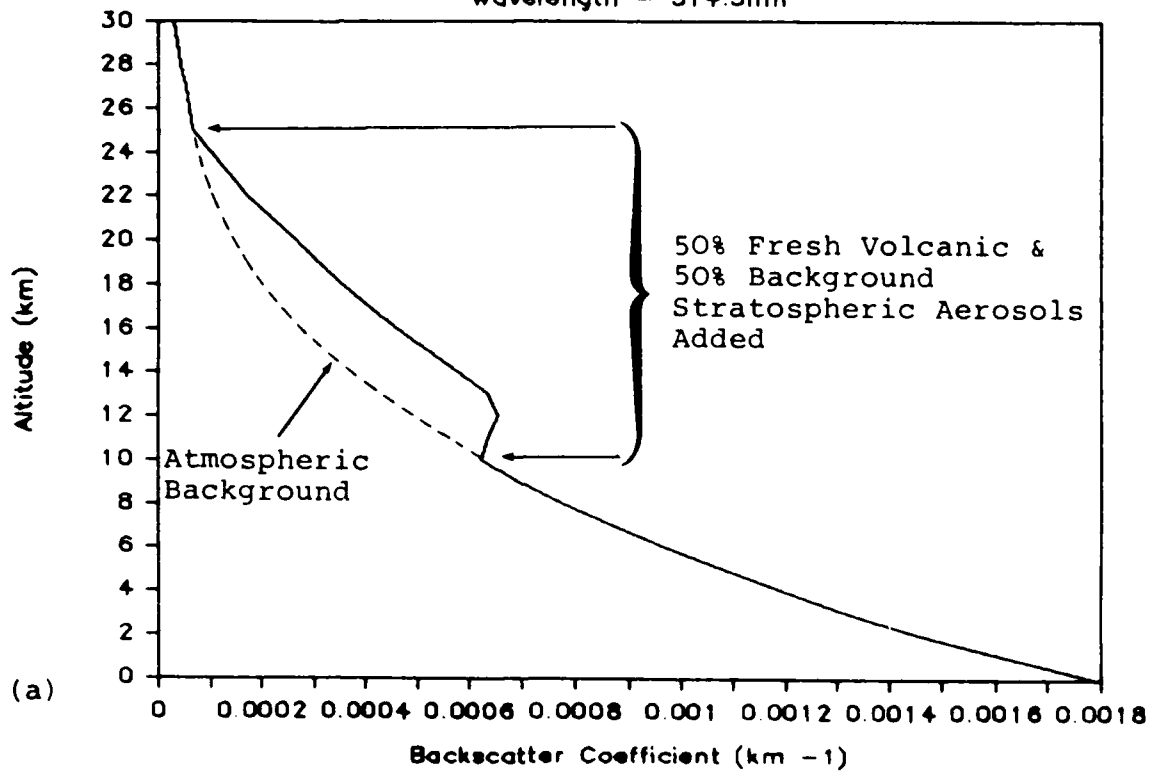


Figure 33. (a.) Backscatter and (b.) Extinction Coefficients As A Function of Altitude for a Midlatitude Summer Atmosphere at 514.5 nm With 50 % Background Stratospheric and 50 % Fresh Volcanic Aerosols

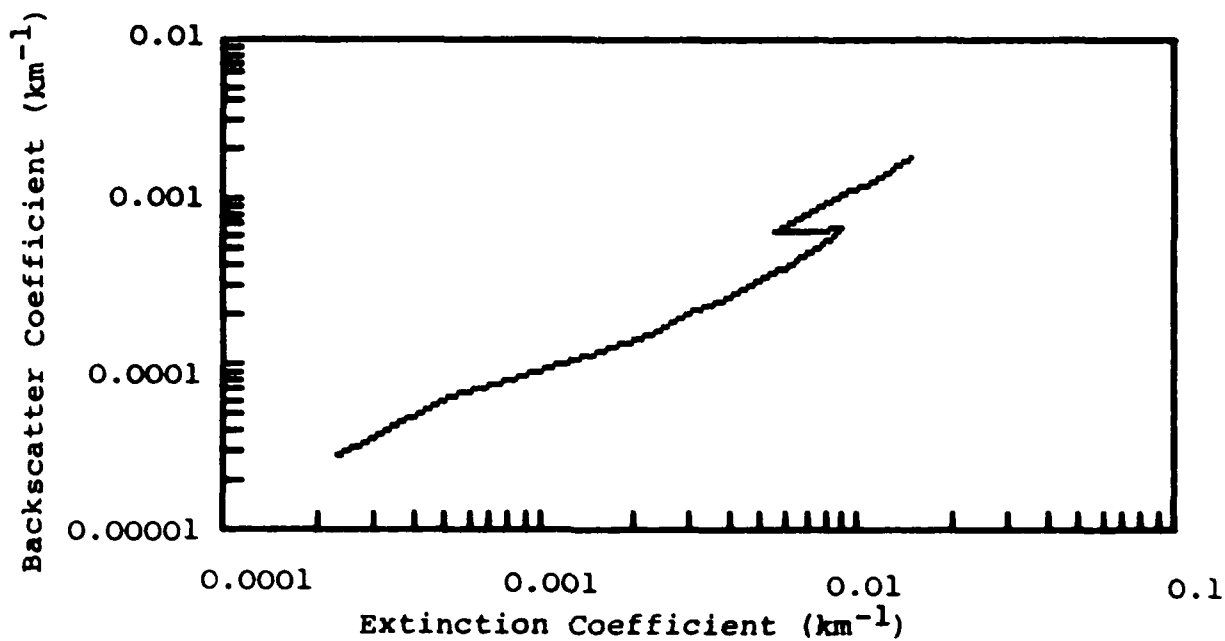


Figure 34. Backscatter Coefficients As A Function of Extinction Coefficients at 514.5 nm For A Midlatitude Summer Atmosphere With Background and Fresh Volcanic Aerosols

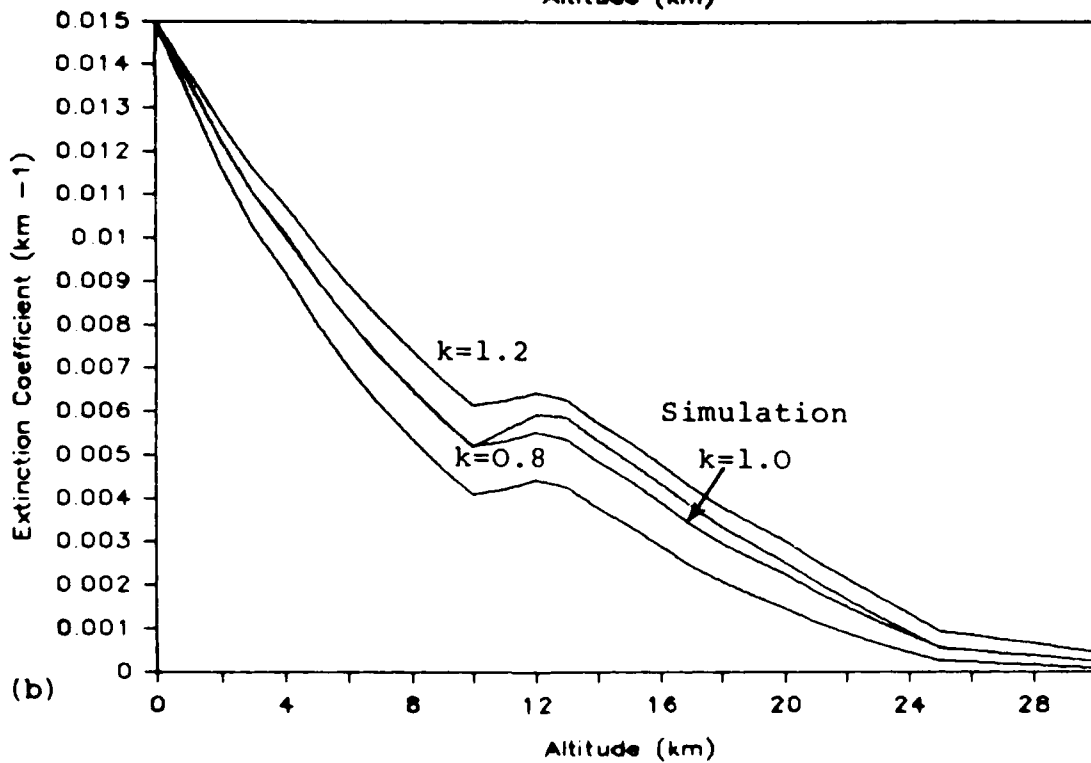
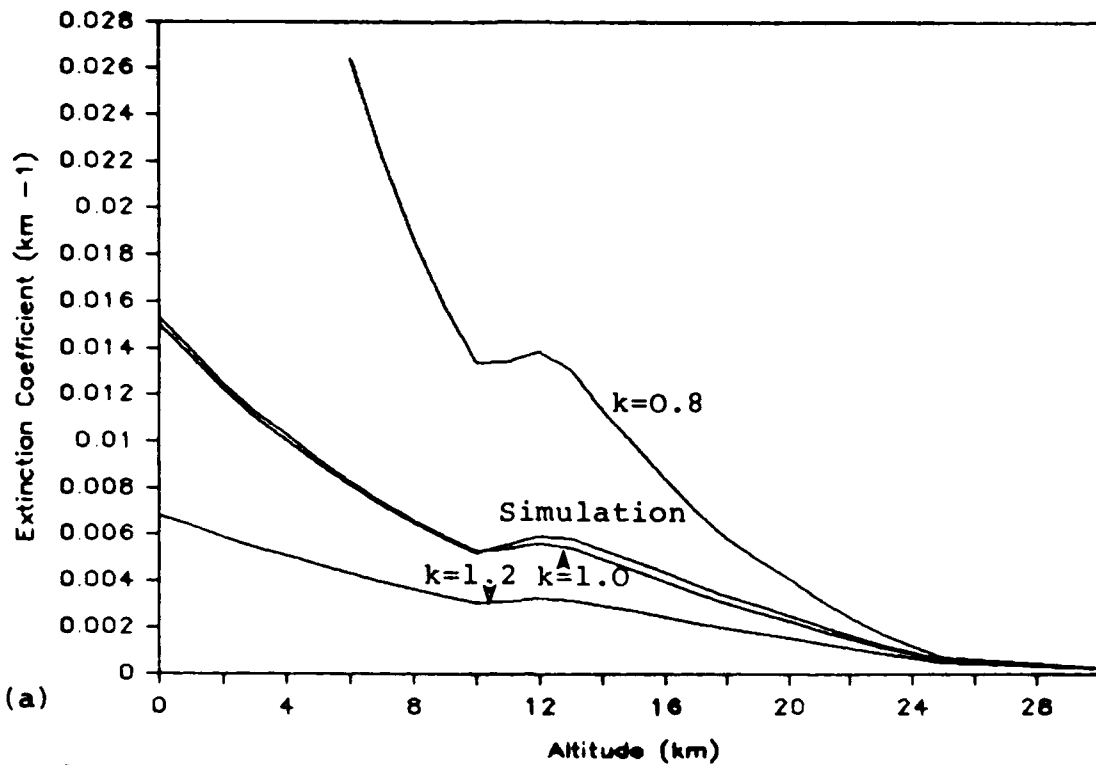


Figure 35. Comparison of Simulated and Inverted Data at 514.5 nm for Case 8 For Various Values of k for the (a.) Near-field and (b.) Far-field Solutions

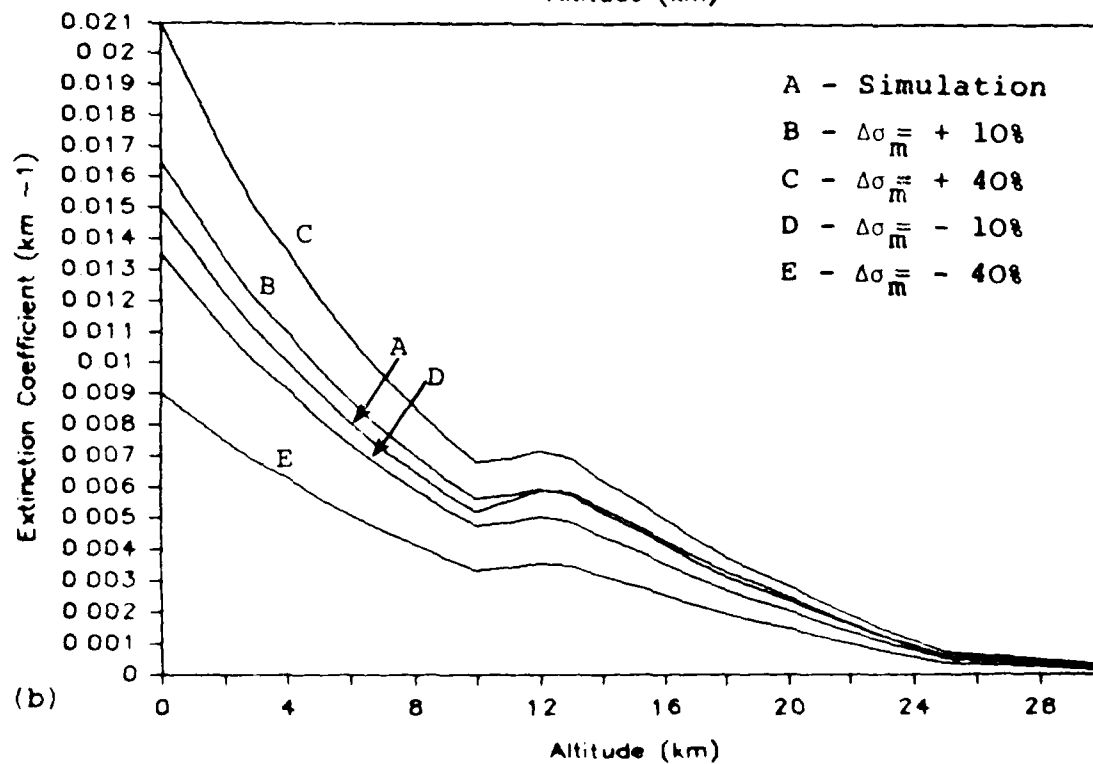
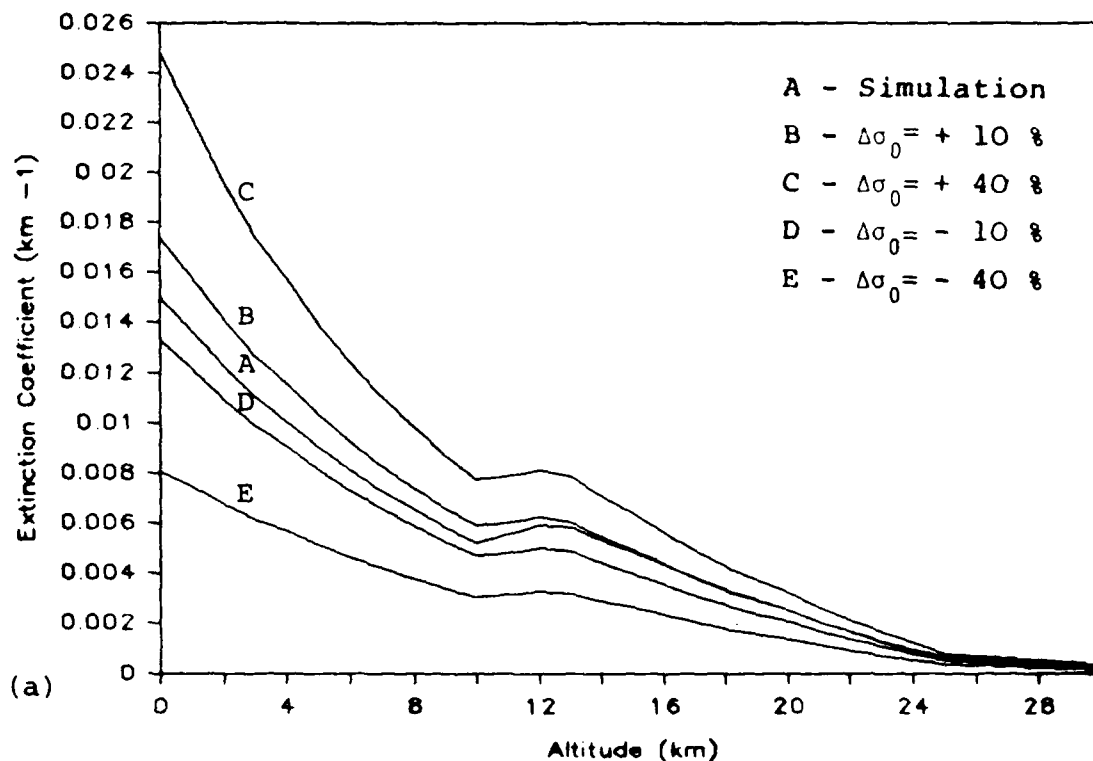


Figure 36. Inverted Results at 514.5 nm with Variations in the Boundary Conditions Considered for Case 8 for the (a.) Near-field and (b.) Far-field Solutions

3.2 Evaluating the Boundary Conditions in a "Real World" Situation

In the preceding sections, it was assumed that the boundary conditions were known. Then, it was shown that inaccuracies in the boundary conditions could have a significant impact on the inverted results. It is fair to ask the question, "Can the boundary conditions be known accurately?"

If one were using the far-field solution approach, the extinction coefficients at or near the surface would be required. If the visibility is known, the extinction coefficient at visible wavelengths can be evaluated from the Koschmieder formula

$$\sigma = 3.912 / V \quad (13)$$

where V is the meteorological range. If the observer visibility, V_{obs} , is known, then V can be approximated as

$$V = (1.3 \pm 0.3) V_{\text{obs}} \quad (14)$$

The observer visibility is not an exact measure of the transmission properties of the atmosphere and can vary greatly from one observer to another. Even with observer errors ignored, it is a quantity that can vary greatly during the day.

Over the ocean or uninhabited land areas, one would not have a way to calculate the extinction coefficient boundary conditions. Even if a surface extinction coefficient clima-

tology existed, it would still not be accurate enough for the inversion of lidar data.

For the near-field solution, the boundary condition represents the extinction at a high altitude, presumably in an altitude region well above any aerosol or cloud layers. In this case, the Rayleigh scattering values can be used for the boundary conditions. Assuming that the laser line was one in which little or no molecular absorption occurred, the assumption would be valid. Seeing that the Rayleigh scattering is primarily dependent upon the wavelength (there is a minor dependence of pressure and temperature upon the atmospheric index of refraction), the near-field boundary conditions could be evaluated utilizing Rayleigh scattering coefficients. The net effect is that the near-field boundary conditions can be evaluated with an accuracy that can not be achieved for the far-field solution.

3.3 Summary of Results Utilizing A Power Law Inversion Approach

The calculations just presented have demonstrated that a power law inversion approach can accurately invert an atmosphere that only consists of Rayleigh scatters. The real atmosphere is rarely free of aerosols and, as demonstrated, a power law approach does not accurately invert the optical properties of a Rayleigh and non-Rayleigh atmosphere. To complicate matters, the atmosphere contains mixtures of different kinds of aerosols. Therefore, even if a power law could invert the optical properties for a given

aerosol, one would have to know in advance what kind of aerosol was being probed so as to select the correct value of k . This requirement coupled with the lack of a physical justification for the power law assumption forces one to conclude that a power law inversion approach cannot be used for the inversion of data from a spaceborne lidar system. An alternate approach can be recommended that is rooted in the physics of radiative transfer. The alternate approach will now be presented in the next chapter.

4. AN ALTERNATE INVERSION APPROACH FOR A SPACEBORNE LIDAR SYSTEM

Assuming that one can measure the atmospheric density profile, an expected profile of signal returns can be calculated (eg. Equation 1) for an atmosphere of pure Rayleigh scatterers, P_{Ray} . From this profile for a pure Rayleigh atmosphere, one can calculate a profile of the ratio of the actual lidar returns to that expected from a Rayleigh atmosphere, $R(r)$

$$R(r) = \frac{P_{actual}(r)}{P_{Ray}(r)} \quad (15)$$

The atmospheric extinction profile consists of molecular and aerosols components,

$$\sigma(r) = \sigma(r)_{Ray} + \sigma(r)_{Aer} \quad (16)$$

Expressing Eq (15) in its component terms gives

$$R(r) = \frac{\beta_{BS,Ray}(r) + \beta_{BS,Aer}(r)}{\beta_{Ray}(r)} \exp\left[-\int 2\sigma_{Aer} dr'\right] \quad (17)$$

where $\beta_{bs,Aer}$ and $\beta_{bs,Ray}$ are, respectively, the aerosol and Rayleigh backscatter coefficients.

The single scattering albedo, ω_0 , can be given as the ratio of the total scattering to extinction coefficients

$$\omega_0 = \beta_S / \sigma \quad (18)$$

The single scattering albedo can also be given in terms of the phase function, $p(\Omega)$,

$$\omega_0 = \frac{1}{4\pi} \int p(\Omega) d\Omega \quad (19)$$

Substituting Equation (18) into Equation (17) gives

$$R(r) = \frac{\beta_{BS, Ray}^{(r)} + \beta_{S, AEF}^{(r)} p(180)}{\beta_{Ray}^{(r)}} \exp\left[-2 \int \beta_S dr' / \omega_0\right] \quad (20)$$

Equation 20 can be solved numerically with an iterative method, such as the Newton-Raphson technique²², to solve for the total scattering coefficient.

A sample inversion using this alternate technique is given in Figure 37. The sample calculations were made using the aged volcano parameters of Case 6. The calculations assumed a constant single scattering albedo of 0.9519. The inversion result is quite good, with a maximum difference between the actual profile of about 8 %. Figures 38 (a) and (b.) show, respectively, the impact of variations in the single scattering albedo and fraction of scattering into the backwards direction. In both cases, the values were perturbed by + and - 10 %. The results for this case indicated that the inversion was somewhat less sensitive to variations in the single scattering albedo. A full set of sensitivity calculations should be performed utilizing other assumed aerosol models before any general conclusions can be made concerning what are the most sensitive parameters in this alternate inversion technique. For example, one must have the profile of Rayleigh scattering extinction

22. Dahlquist, G. and A. Bjorck (1974) Numerical Methods, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 222-227.

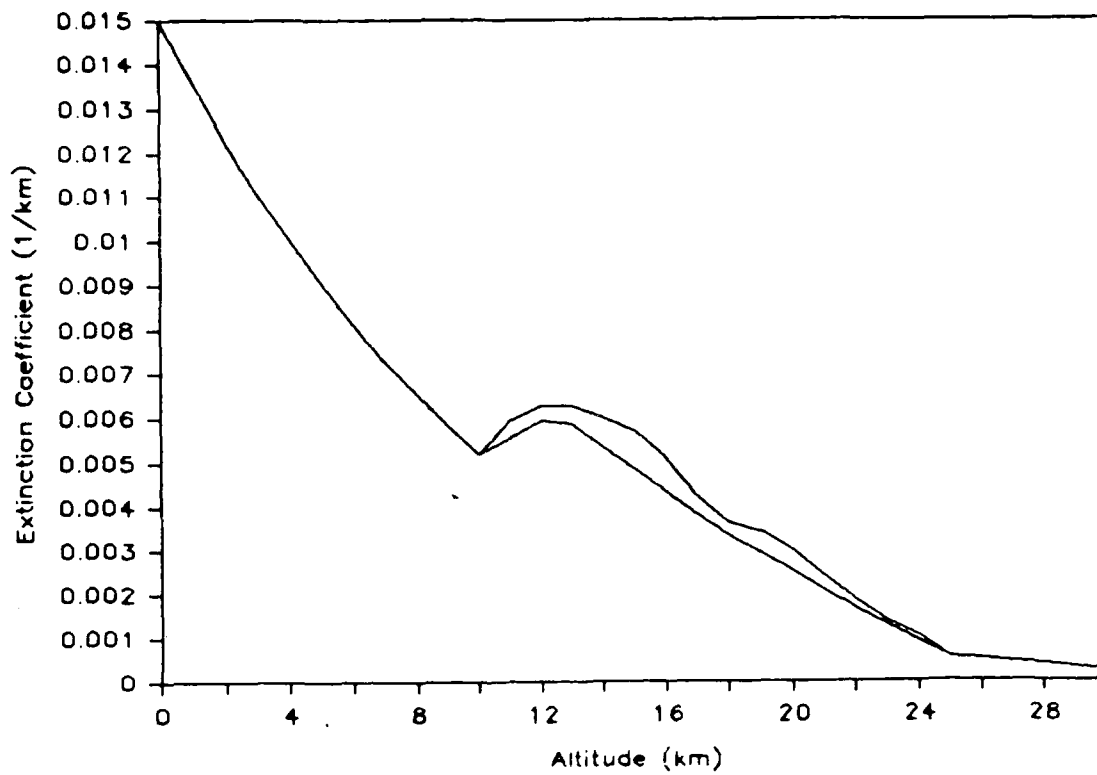


Figure 37. Inverted Results at 514.5 nm with the Alternate Inversion Techniques for a Simulated Atmosphere with Aged Aerosols

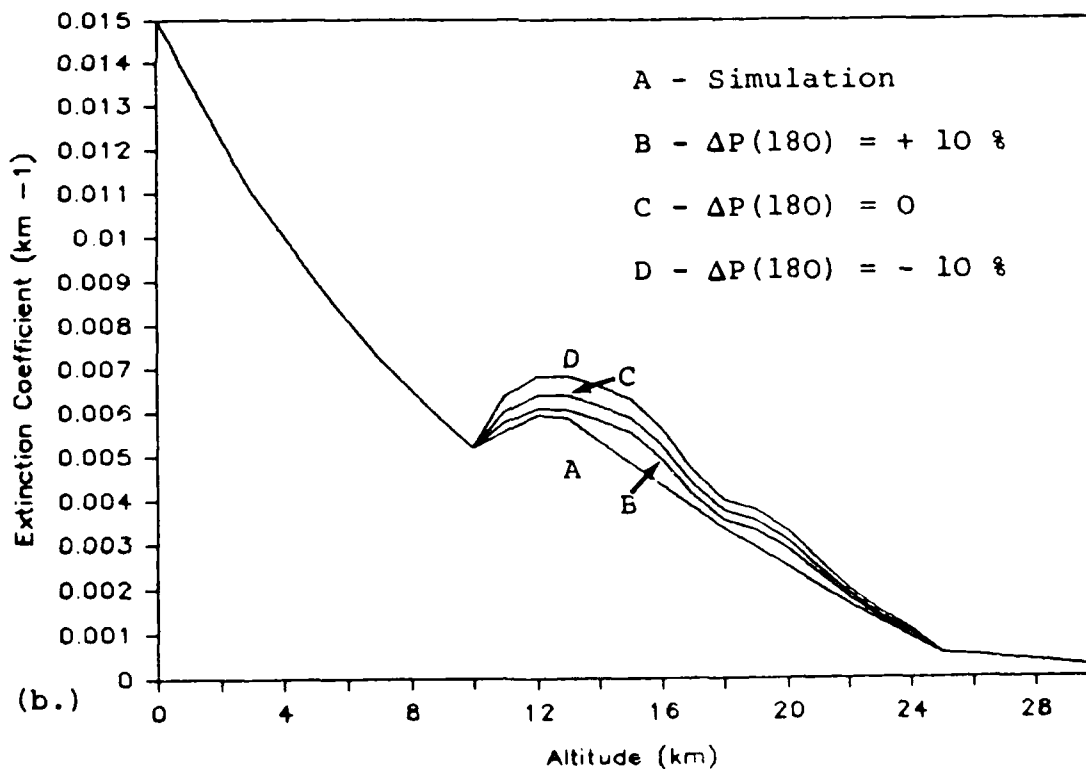
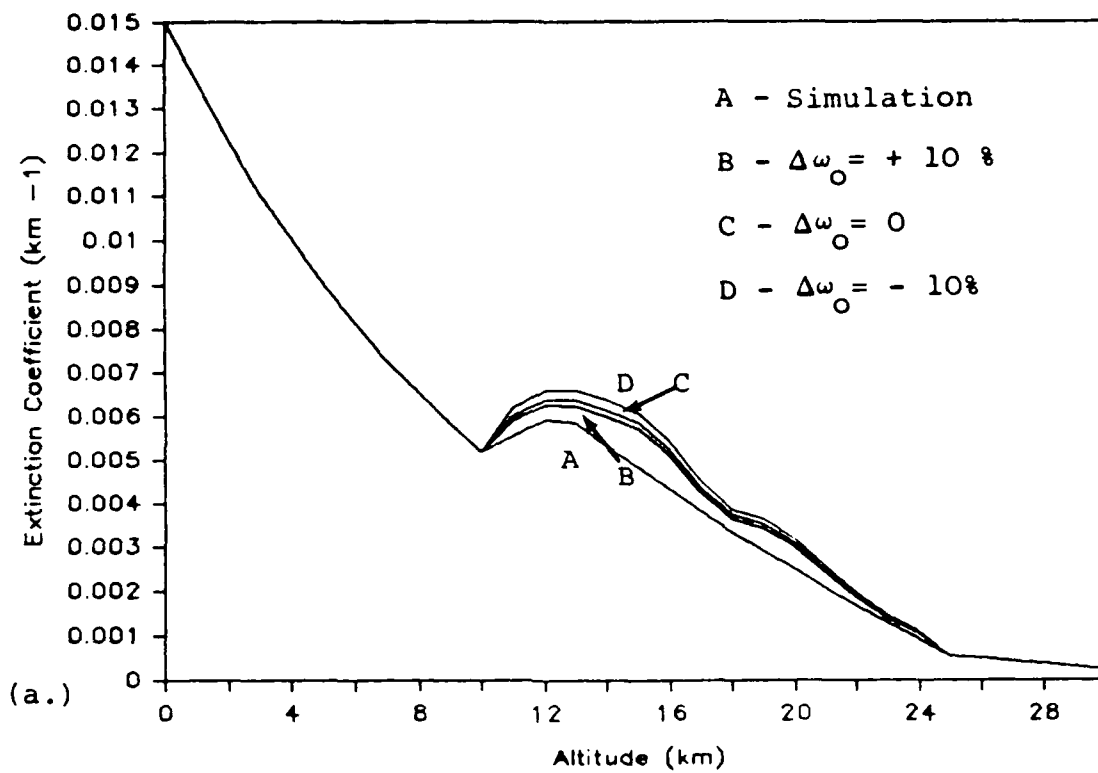


Figure 38. Inverted Results at 514.5 nm with Variations in (a.) the Single Scattering Albedo and (b.) the Fraction of Backscattered Radiation

coefficients and to do this one must know the atmospheric density profile. Also, one must have some information about the single scattering albedo and the fraction of backscattered radiation. One can obtain these either from the literature or from detailed sets of Mie calculations. In order to utilize that information, one must be willing to limit the range of possible values by assuming some knowledge about the aerosol layer. For example, one could say that if the returns are from a specific altitude region they must be from a certain type of aerosol. Also, using the latitude and longitude of the satellite track one could say whether or not the returns are from an urban or rural type of aerosol. The point to stress is that the alternate technique still requires some knowledge of the aerosol, primarily a guess of what type of aerosol is causing the return.

5. SUMMARY OF INVERSION TECHNIQUES AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Summary of Results

An examination of inversion techniques applicable for a spaceborne lidar system has been performed. The purpose of the examination has been to recommend a technique that could be used with the lidar system under development by AFGL.

In a purely Rayleigh atmosphere with no or minimal gaseous absorption, a power law relationship between back-scattering and extinction exists in which $k=1$. In an atmosphere with aerosols and clouds, the assumption of a power law relationship is tenuous at best. Although popular with researchers, the examination of the literature leads us to conclude that the power law relationship has no physical basis to support its extensive use. For any application probing different regions of the atmosphere and different types of aerosols, one cannot assume a single set of power law parameters for the entire atmosphere.

An alternate inversion approach has been presented based on the fundamental radiative transfer characteristics of the atmosphere. The approach is rooted in fundamental physics but, still, does not eliminate the problem of more unknowns than equations. For the approach to be used, one must still make an assumption about the type of aerosol responsible for the lidar signal.

5.2 Recommendations for Future Research

The alternate inversion approach that has been presented should be researched further to investigate its sensitivity to variations in the input parameters. This sensitivity study would help to establish the accuracy requirements of the input data.

The alternate inversion approach requires information on the phase function and the single scattering albedo of the aerosols. A review of the literature should be performed to determine what measurement database exists for the type of aerosols that would most likely be encountered by a spaceborne lidar system. Where measurements are lacking, calculations should be performed or results from previous calculations assembled.

Finally, the alternate inversion technique should be tested against the lidar data obtained from the recent test flight. This would help to establish the usefulness of the technique in the "real world" rather than the highly unrealistic situation in which the actual profiles are known.

References

1. Murray, E. R., M. F. Williams and J. E. van der Laan (1978) Single-ended Measurement of Infrared Extinction Using Lidar, Applied Optics, 17:296.
2. Collis, R. T. H. (1966) Lidar: A New Atmospheric Probe, Q. J. R. Meteorol. Soc. 92:220.
3. Viezee, W., E. E. Uthe and R. T. H. Collis (1969) Lidar Observations of Airfield Approach Conditions: An Exploratory Study, J. Appl. Meteorol. 8:274.
4. Kohl, R. H. (1978) Discussion of the Interpretation Problem Encountered in Single-Wavelength Lidar Transmissometers, J. Appl. Meteor., 17:1034.
5. Brown, Jr., R. T. (1979) Comments on "Discussion of the Interpretation Problem Encountered in Single-Wavelength Lidar Transmissometers, J. Appl. Meteor., 18:711.
6. Kohl, R. H. (1979) Reply, J. Appl. Meteor., 18:712.
7. Klett, J. D. (1981) Stable Analytical Inversion Solution for Processing Lidar Returns, Applied Optics 20:211.
8. Klett, J. D. (1985) Lidar Inversion with Variable Backscatter/Extinction Ratios, Applied Optics 24:1638.
9. Hughes, H. G., J. A. Ferguson and D. H. Stephens (1985) Sensitivity of a Lidar Inversion Algorithm to Parameters Relating Atmospheric Backscatter and Extinction, Applied Optics, 24:1609.
10. Bissonnette, L. R. (1986) Sensitivity Analysis of Lidar Inversion Algorithms, Applied Optics, 25:2122.
11. Ferguson, J. A. and D. H. Stephens (1983) Algorithm For Inverting Lidar Returns, Applied Optics, 22:3673.
12. Mulders, J. M. (1984) Algorithm for Inverting Lidar Returns: Comment, Applied Optics, 23:2855.
13. Curcio, J. A. and G. L. Knestrick (1958) Correlation of Atmospheric Transmission and Backscattering, J. Opt. Sci. Am., 48:686.
14. Twomey, S. and H. B. Howell (1965) The Relative Merit of White and Monochromatic Light for the Determination of Visibility by Backscattering Measurements, Applied Optics, 4:501.

15. Fenn, R. W. (1966) Correlation Between Atmospheric Backscattering and Meteorological Range, Applied Optics, 5:293.
16. Pinnick, R. G., S. G. Jennings, P. Chylek, C. Ham and W. T. Grandy, Jr. (1983) Backscatter and Extinction in Water Clouds, J. Geophys. Res., 88:6787.
17. Shettle, E. P. (1985) Backscattering by Atmospheric Aerosols, Presented at the IAMP/IAPO Joint Assembly, Honolulu, Hawaii, 5-16 August 1985.
18. Evans, B. T. N. (1986) Sensitivity of the Lidar Ratio to Changes in Size Distribution and Index of Refraction, Thirteenth International Laser Radar Conference, NASA Conference Publication 2431, National Aeronautics and Space Administration, Code NIT-4, Washington, D. C.
19. DeLuisi, J. J., Schuster, B. G. and Sato (1975) Separation of Dust and Molecular Scattering Contributions to the Lidar Observation: A Method, Applied Optics 14:1917.
20. Kastner, M. and H. Quenzel (1986) The Usefulness of Klett's Inversion Algorithms to Simulated Satellite Lidar Returns, Thirteenth International Laser Radar Conference, NASA Conference Publication 2431, National Aeronautics and Space Administration, Code NIT-4, Washington, D. C.
21. McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Volz and J. S. Garing (1972) Optical Properties of the Atmosphere, Air Force Cambridge Research Laboratories, Hanscom Field, Bedford, Massachusetts, AFCRL-72-0497, AD753075.
22. Dahlquist, G. and A. Björck (1974) Numerical Methods, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 222-227.

END

10-87

DTIC