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UNCERTAINTIES IN COMPARISON OF FLIR PERFORMANCE IN THE 3-5 AND 8-12 μm BANDS

Part 3 of
Effect of Weather at Hannover, Federal Republic
of Germany, on Performance of Electrooptical
Imaging Systems

Lucien M. Biberman

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Prepared for
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INSTITUTE FOR DEFENSE ANALYSES
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This paper addresses aerosol contributions to the atmospheric problem, the uncertainties in predicting electrooptical system performance through the atmosphere in both the 3-5 and 8-12 μm bands because of uncertainties about aerosol composition and size distribution, and the effects of both aerosol composition and size distribution.
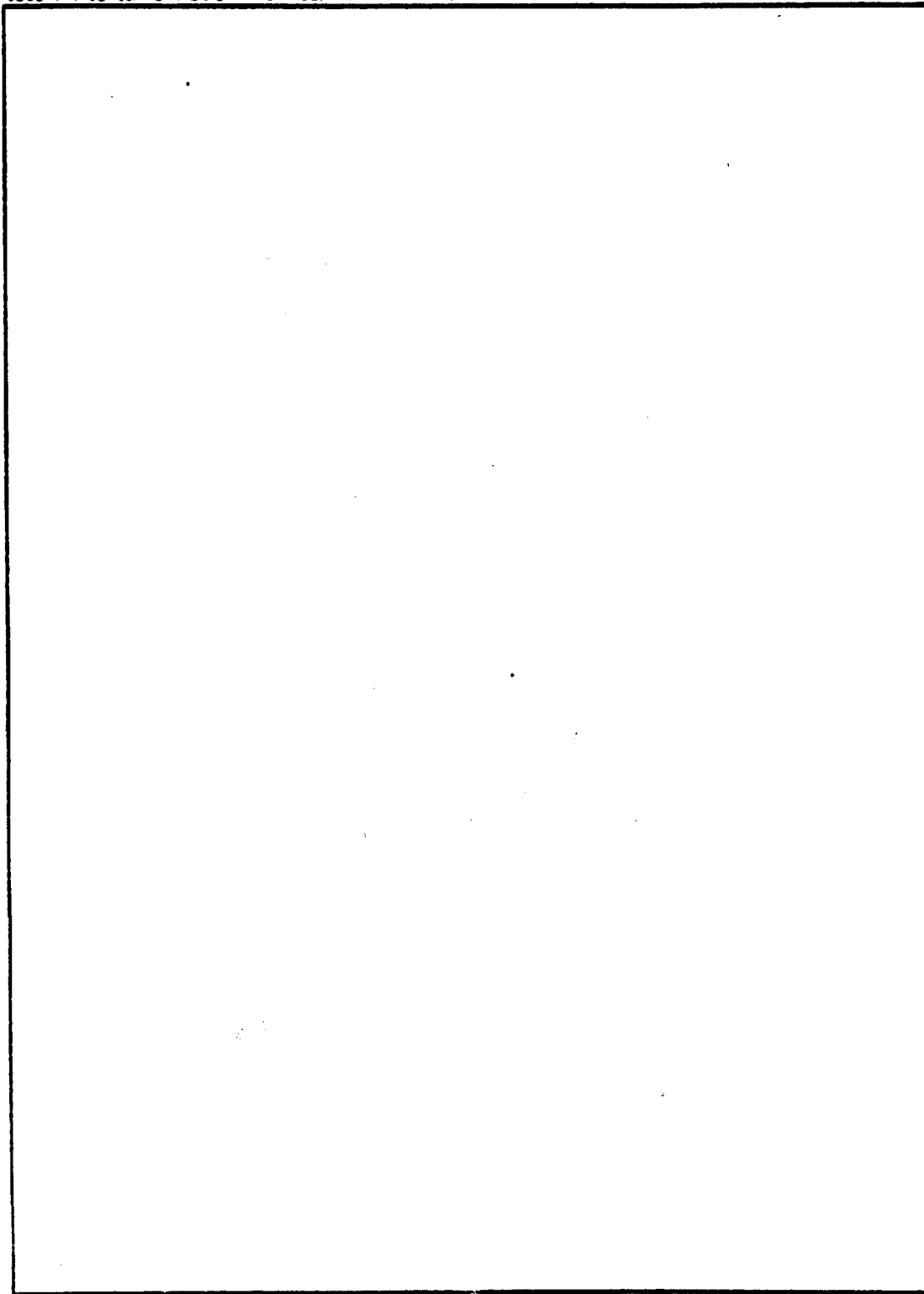
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CONTENTS

EXECUTIVE SUMMARY

The most serious difficulties in predicting electrooptical (EO) system performance in the field can be ascribed to our poor understanding of the classic problems of search and to the impact of atmospheric conditions in the locale where the EO system is used.

This paper addresses aerosol contributions to the atmospheric problem, the uncertainties in predicting electrooptical system performance through the atmosphere in both the 3-5 and 8-12 μm bands because of uncertainties about aerosol composition and size distribution, and the effects of both aerosol composition and size distribution.

The relative performances of more or less similar EO systems operating in the same spectral region can be computed fairly accurately. The relative performances of two such competing EO systems operating in different spectral bands, however, can be computed only if one can correctly assign a specific attenuation in each band to the given aerosol used in the computations, since the extinction coefficient due to aerosols varies both in magnitude and in spectral dependence. This is a task over which there can be much argument, depending upon the time, places, and recent weather history through which the aerosol may have passed. For this reason, we cannot believe *absolute* performance predictions in less than clear weather for any forward-looking infrared (FLIR) device.

In past studies we have shown that these aerosol uncertainties may exceed by two orders of magnitude the uncertainties due to the molecular effects of the atmosphere.

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We show our best estimates for aerosol models in and around North Central Germany and in the Mideast. The spread due to the choice of aerosol model is clearly undesirable even for horizontal paths.

The effect of altitude can be even more serious, yet but little data is available on which to build a confident understanding. Using what data we have from the data collection program called Grafenwöhr I, we show in Section IV a model that indicates, for conditions of low clouds, the effect of altitude on the extinction coefficient. From this very limited sample of winter aerosol data from Grafenwöhr we deduce that in the case of low cloud cover the aerosol extinction often gets exponentially more severe with altitude from ground level up to the base of the cloud. Further, we find the most important quantity is the ratio of target or sensor height to cloud-base height.

This exponential characteristic, which seems to be rather common, can have great impact on airborne weapon system applications and tactics. We would like to point out that our results indicate that both the surface extinction coefficient and the ratio of target height to cloud-base height are very important when clouds are low. The extinction coefficient of clouds is so large that we use the lower in a range of values. Anything more makes the results even more sharply defined. These calculations may show major operational significance if our results, deduced from a very limited data sample, prove to be more generally valid.

With but crude estimates of cloud height and surface aerosols, we can choose the altitudes for most favorable operation, but we cannot yet do even a reasonable job of forecasting absolute range performance, primarily because of aerosol-related uncertainties.

At first quick look it would appear we have two choices. We could accept the vagaries of weather and shrug them off, or

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we could make a concerted effort to understand the atmosphere and the weather.

Unfortunately, it is not clear that we will be able to gather enough good data on the factors that cause aerosol extinctions to be what they are to yield a useful predictive capability, though we may acquire knowledge of their general statistical effects on the performance of EO sensors through study of past data. It remains for those better trained in meteorology to assess these problems.

Whether or not a predictive capability can be gained, we suggest that the general impact of the vertical profile of the atmosphere on EO performance be studied, and that the results of such understanding as may be acquired therefrom be factored into a study of the tactics and utility of electrooptical weapons that must be used through the atmosphere at ranges up to a kilometer or so of altitude.

I. INTRODUCTION

In August 1976 IDA published the first volume of a five-part series on the *Effect of Weather at Hannover, Federal Republic of Germany, on Performance of Electrocptical Imaging Systems*. The work of Volumes 1 and 2 was done by IDA under its Central Research Program, while the fourth and fifth volumes were done for Task T-136 supported by OUSDRE(R&AT) of the Department of Defense. Note that we have accounted for only four of the five volumes in that series. Two drafts for the third volume were prepared only to be rejected as obsolete because our understanding of the atmosphere in regard to infra-red imaging systems was so rapidly changing.

We have recomputed the FLIR performance data and rewritten this paper once again only to become convinced that the aerosol data, often the most important factor in electrooptical system performance calculations, is not reliable enough to make absolute performance predictions. If the atmospheric extinction co-efficients are accurately known for each band, we can predict absolute performance for 3-5 and 8-12 µm FLIRs (Refs. 1-4). Unfortunately, the properties of the aerosol components of atmospheric extinction are not sufficiently well characterized to make such a quantitative assessment in general. Thus we can make relative predictions of competing FLIR performance with confidence if both operate in the same spectral band, but absolute predictions need better aerosol data. We have found, however, that if aerosols are a sizable factor in atmospheric extinction, the performance of the 3-5 µm system will usually suffer far more than that of the 8-12 µm system (Ref. 5). If

aerosols are present only to a trivial extent the 3-5 μm system can offer smaller size and simpler cooling for the same performancé, or longer range and higher resolution for size and complexity equal to the 8-12 μm system (Ref. 3).

One of the first classic analyses of FLIR performance which included weather-related factors such as atmospheric propagation was published in 1970 by H. Barhydt, D.P. Brown, and W.B. Dorr (Ref. 1). They found that at very short ranges in the absence of severe aerosol degradation essentially equivalent performance is obtained in the 3-5 and 8-12 μm regions. However, at very long ranges in humid atmospheres, the short-wavelength band is superior in the absence of haze. If operation in haze or light fog is desired, the longer wavelength band is preferable, because in this band atmospheric scattering causes less loss of signal.

In 1977 A.F. Milton, G.L. Harvey, and A.W. Schmidt of the Naval Research Laboratory published *Comparison of the 3-5 Micrometer and 8-12 Micrometer Regions for Advanced Thermal Imaging Systems: LOWTRAN Revisited* (Ref. 2). They considered both current- and future-technology thermal imaging systems for the marine environment. They found that for current systems with comparable-quality detectors, the 8-12 μm band gave superior performance. For future systems, the 3-5 μm spectral band was preferred for moderately high-visibility humid atmospheres, in agreement with the analysis of Barhydt et al. discussed above. Unfortunately, the selection of an optimal spectral band for poor-visibility marine conditions was totally dependent upon choice of aerosol model. In light of this uncertainty, they recommended an experimental verification of the extinction to be expected with maritime aerosols.

Both of these significant studies were dominated by the atmospheric models chosen for the studies. Barhydt et al. used the classical experimental data of Yates and Taylor, which was

the best available data for two decades but which suffered from a lack of absolute calibration. Milton et al. used the Air Force Geophysics Laboratory (AFGL) LOWTRAN 3b transmission code with its inherent uncertainty in aerosol modeling.

In his IDA Paper P-1281, *Effects of Focal-Plane Arrays, MTF, and Atmospheric Attenuation on Predicted Performance of FLIR Imaging Systems* (Ref. 4), A.D. Schnitzler did a more careful set of calculations for FLIRs of various degrees of complexity ranging from 2×10^2 detectors to 2×10^5 detectors in a focal plane. Schnitzler's calculations were for both Army and Navy tactical applications. He found that the expected improvement in performance between present and future sensors operating in the same spectral band is a factor of 1.5 to 2.0 independent of weather conditions and atmospheric models. He also determined that conditions of high humidity favor the 3-5 μm band in the absence of aerosol effects, again in agreement with previous studies.

An explanation of the clear-weather impact of humid environments is illustrated in Fig. 1. We have plotted blackbody sources corresponding to thermal targets with near-ambient temperatures. We have also shown the envelope of source radiation as transmitted through different path lengths for both a dry subarctic winter condition and a humid tropical condition. In the absence of water vapor and aerosols the 8-13 μm band transmits almost all the radiant power from a source for all the path lengths. As humidity is encountered the water vapor continuum is responsible for significant degradation in the 8-13 μm region. The 3-5 μm band, however, is affected to only a moderate degree by the change in water vapor content. Thus even for a thermal source with significantly more radiation near 10 μm, the continuum degradation for long path lengths through a humid atmosphere leads to a preference for the 3-5 μm band.
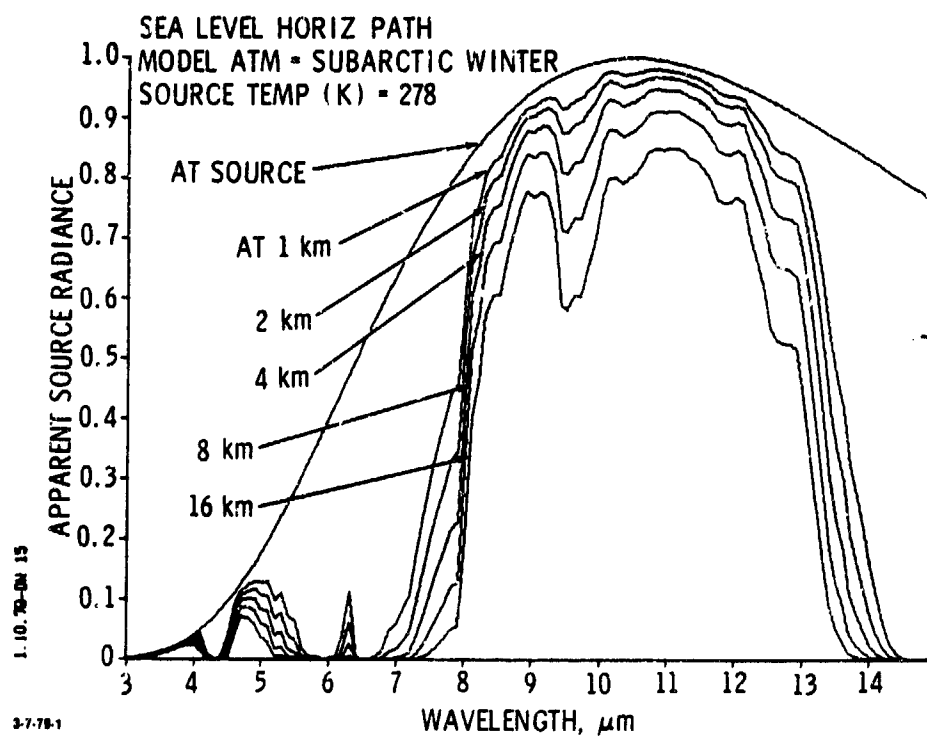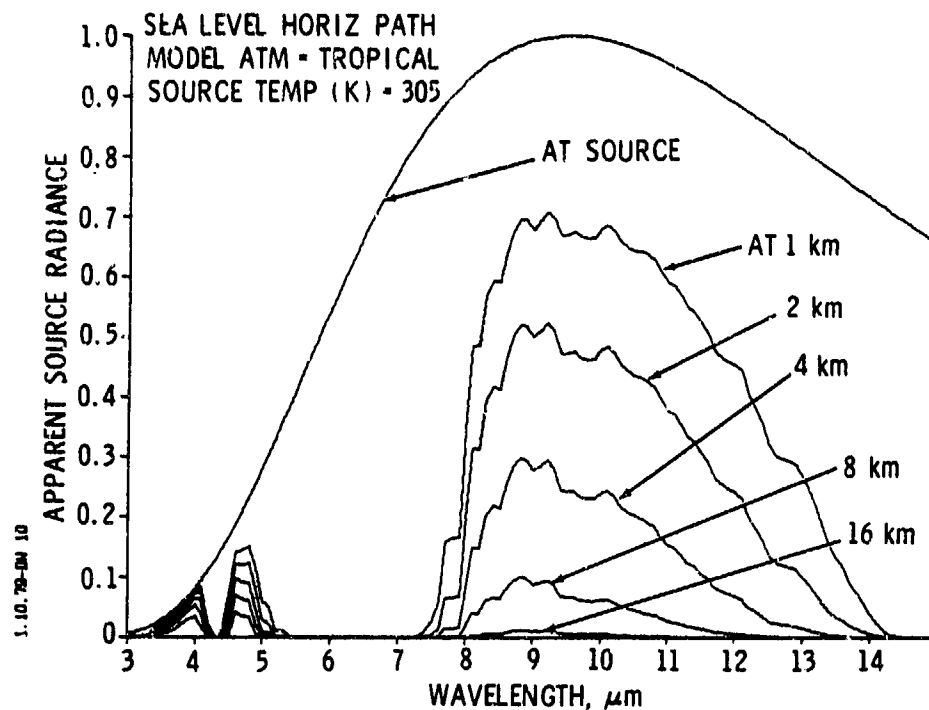
FIGURE 1. Effect of atmospheric water vapor and other gases on
spectral character of radiation transmitted over
tropic and subarctic paths of 1, 2, 4, 8, and 16 km
in total absence of aerosols.

For reduced visibilities, where aerosol attenuation plays a dominant role, the impact upon performance estimates in either a relative or an absolute sense is totally dependent upon the choice of aerosol model. In the remainder of this paper we shall discuss the selection of aerosol models together with the uncertainties inherent in their application.

II. DESCRIPTION OF ATMOSPHERIC AEROSOL EXTINCTION MODELS

One of the most useful parameters for the assessment of IR sensor performance is the atmospheric extinction coefficient, defined as $\beta_{atm} = \frac{1}{R} \ln \tau_{atm}^{-1}$, where R is the path length in kilometers and τ_{atm} is the transmission factor (Ref. 6).

The atmospheric extinction coefficient β_{atm} has two main components, that due to molecular absorption (β_{mol}) and that due to extinction by atmospheric aerosols (β_{aer}) such as smoke, haze, fog, and dust.[*] For most of our needs the molecular effects of atmospheric transmission or extinction are well predicted by a series of computer codes such as the AFGL LOWTRAN 4. This is not true for aerosol extinction. The details of that problem pertaining to the Central European environment are discussed in IDA Paper P-1330 (Ref. 3). The aerosol situation is still less well known if one considers the dry dust and blowing sand of some Mediterranean and Middle East countries rather than the hazes and mists of North Central Europe. The weather conditions at Beersheba, Cairo, Istanbul, and Tehran can scarcely be ascribed to the same sort of air mass one finds at Hamburg, Oslo, Poznan, and Prague. Thus, even though the original focus of this study was on the Hannover area, we became convinced that we needed a Middle East dust model as well as a model for the wet aerosols of North Central NATO Europe.

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[*] Aerosol contributions to extinction coefficients are usually derived from empirical models which employ subjectively determined atmospheric visibility as the key parameter.

A. CENTRAL EUROPEAN REGIONS

The LOWTRAN aerosol models provide a simple scaling rela-
tionship between the aerosol extinction in different spectral
regions and the subjectively measured meteorological visibility
range (Vis). For North Central NATO Europe we have used the
AFGL maritime aerosol model, which for the 8.5-11 μm region is
given by .

$$\beta_{aer} = \frac{0.85}{Vis} \quad .$$

For large visibilities—say, >20 km, β_{aer} becomes very small
(less than 0.04 km^{-1}) and is small even compared to the molecular
effects, β_{mol}. Only on very cold, dry winter days do such
aerosol effects exceed the molecular effects. Thus, for low-
altitude air-to-ground operations or for ground-to-ground
operations, aerosols can reasonably be ignored for visibilities
of about 20 km or more.

For visibilities below 1.5 or 2.0 km, our best empirical
fit (again in the 8.5-11 μm region) based upon transmission
measurements during a winter haze/fog at Grafenwöhr is

$$\beta_{aer} = \frac{1.84}{Vis^{2.36}} \quad .$$

In much of our work,* then, for the North Central German
Plain and the 8.5-11 μm band we used

$$\beta_{aer} = \frac{1.84}{Vis^{2.36}} \qquad Vis \leq 1.8 \text{ km}$$

$$\beta_{aer} = \frac{0.85}{Vis} \qquad Vis \geq 1.8 \text{ km} \quad .$$

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*See IDA Paper P-1330 (Ref. 3).

AFGL has a model for a continental air mass representative of urban manufacturing and heating by-products. For the 8.5-11 μm band this model has been represented by

$$\beta_{aer} = \frac{0.44}{Vis}$$

but has always seemed to underestimate the aerosol effects in a haze or fog environment. AFGL is modifying its aerosol models currently to represent the effects of relative humidity, which at higher levels should substantially increase the particle sizes in the aerosols, resulting in increased extinction.

B. DRY REGIONS AROUND THE MEDITERRANEAN

For the drier climates, where dust can blow or hang heavily in still air, the optical extinction effects would appear to be comparable to those of fogs, but certainly the particles are quite different from saltwater droplets or water-coated soot or fly ash.

In response to our request, James Lindberg of the Army Atmospheric Sciences Laboratory (ASL) examined a very limited collection of dry aerosol material and determined the refractive index and the size and shape parameters. Applying Mie theory to these data, Ronald Pinnick of ASL then computed extinction coefficients for us. From these we established a correlation between extinction at the mid-visible wavelength and each of the important infrared bands to produce a reasonable "dry aerosol" model.

The scaling relationships discussed above are shown in Table 1 for both bands of interest.

TABLE 1. SIMPLIFIED AEROSOL MODELS

	$\beta_{aer}^{3-5\mu m}$	$\beta_{aer}^{8-12\mu m}$
For North Central Europe (Moderate Humidity):		
AFGL Maritime	2.24/Vis	0.85/Vis
AFGL Rural	0.42/Vis	0.43/Vis
AFGL Urban	0.60/Vis	0.41/Vis
IDA Grafenwöhr	$2.12/\text{Vis}^{2.00}$	$1.84/\text{Vis}^{2.36}$
For Dry Climates*	1.76/Vis	0.95/Vis

*NOTE: These values were obtained for the single wavelengths 3.8 and 10.6 μm. For our calculations we assumed they would apply approximately over the 3-5 and 8-12 μm bands, respectively.

III. STATISTICAL DATA FOR COMPUTING FLIR
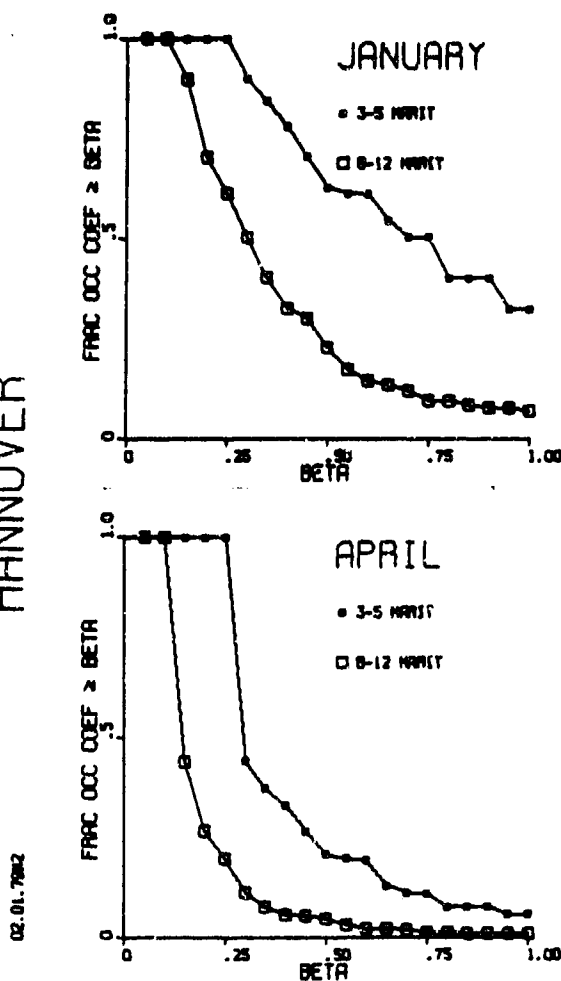## PERFORMANCE NEAR HANNOVER

A. EXTINCTION STATISTICS

If we accept the LOWTRAN maritime aerosol model as an im-
perfect but useful model for Central Europe, we can compare the
extinction coefficients in the 3-5 and 8-12 μm bands month by
month. We have done so for the Hannover area in Fig. 2 for
each hour of four seasonally representative months, plotting
the fraction of time that the extinction β equals or exceeds
some value. Note the broad, gentle slope of the curves for the
winter month compared to those for spring, summer, and fall,
when the frequency of occurrence of higher values of extinction
drops sharply and then trails off.

For the meteorological data we employed, the extinction
computed for the 3-5 μm region was always significantly larger
than that for the 8-12 μm region. In no single month in this
North Central German region was the 3-5 μm band a more trans-
parent window. This fact arises from the moderately high level
of aerosols and from the aerosol model used. If we use one of
several other models, the results tend to be similar in the
relationship between the two bands, but the slopes and shapes
of the curves can be markedly different.

However, our results are not in very good agreement with
those emerging from some early analysis at the OPAQUE (Optical
Properties of Atmospheric Quantities in Europe) data-collection
station in Meppen, FRG. The Meppen data tend to agree with our
previous analysis of Grafenwöhr data for high values of β_{aer},
but the extinctions in the two bands shown (3-5 and 8-12 μm)
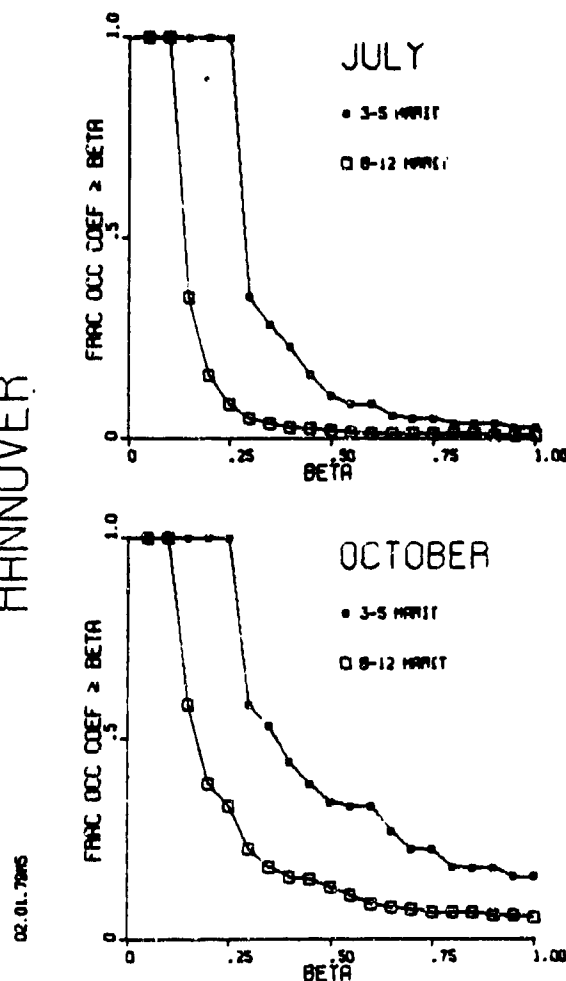nearly coincide for the lower values. In a practical sense this

FIGURE 2. Comparison of computed extinction statistics for
Hannover, 1970, for maritime models in the 3-5
and 8-12 μm bands.

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means that when the weather is not severe the two bands give nearly equal performance for equivalent FLIRs.

B. FLIR PERFORMANCE STATISTICS

To the extent that the extinction data from which we plotted the curves of Fig. 2 are valid, we can use the individual values of extinction or transmission hour by hour to show the frequency with which the probability of detection or recognition of a front-aspect tank will equal or exceed 50%. This is shown in Fig. 3, where again we use the maritime model for illustrative purposes. Here again we see the 8-12 μm statistics are much more favorable than the 3-5 μm data.

In viewing these data one must keep in mind the strong reservations from the previous discussion of extinction co-efficient validity. Further, we must note that though we do not have much doubt about the general form of the plots in Fig. 3, we would expect from the OPAQUE data that the merged parts of the curves extend to the right a bit farther before they separate into 3-5 and 8-12 μm curves.
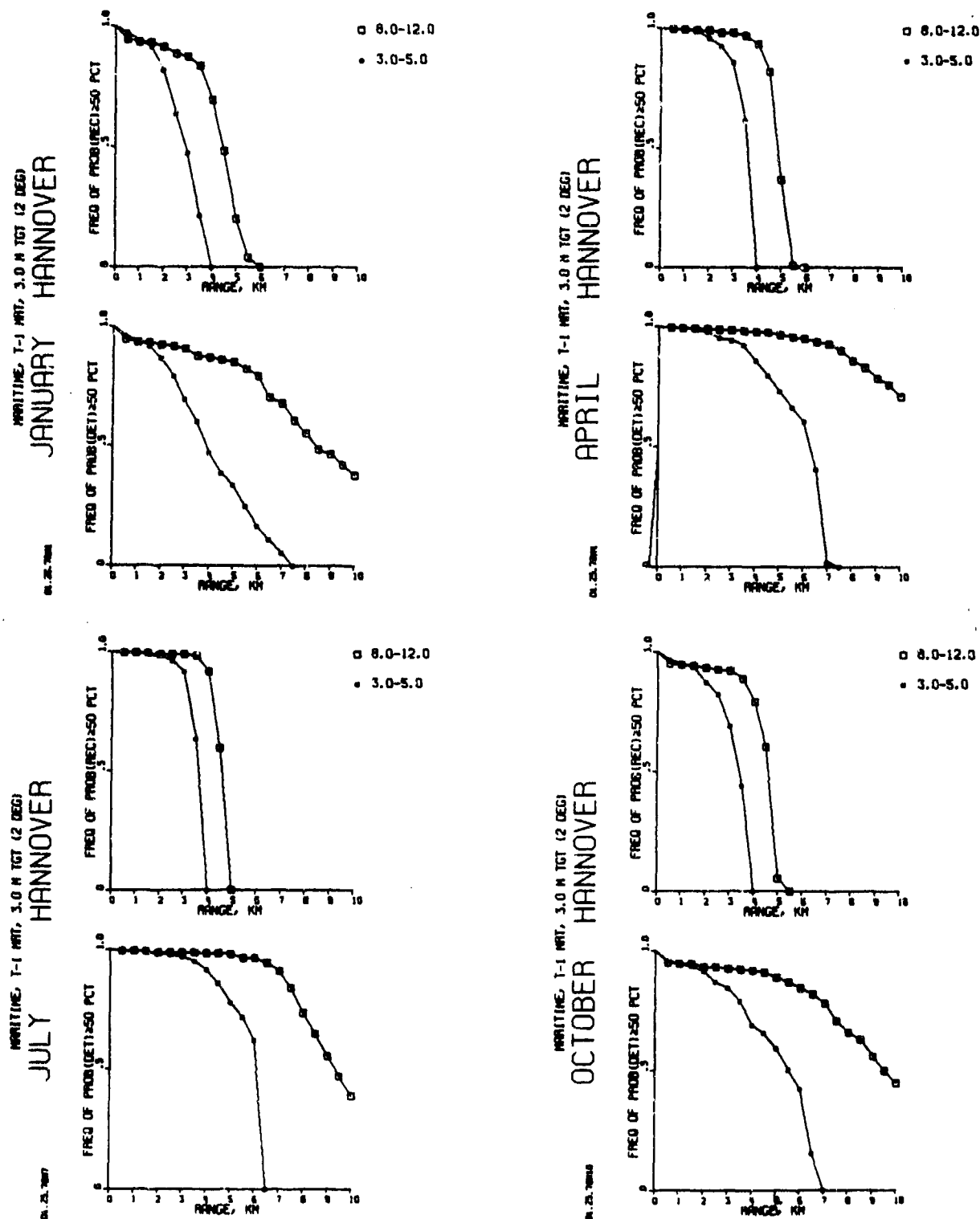
FIGURE 3. Seasonal probabilities of detection and recognition of tank in front aspect by 3-5 and 8-12 μm FLIRs, assuming maritime aerosol model.

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IV. OTHER RESERVATIONS CONCERNING AEROSOL MODEL UNCERTAINTIES

A. VERTICAL DISTRIBUTIONS OF AEROSOLS

The most serious problem plaguing electrooptical system applications from an atmospheric viewpoint is our lack of knowledge concerning slant-path aerosol degradation. Most of our aerosol models assume that for low-altitude platforms ground-path conditions prevail. This is hardly the case, as demonstrated by the work of Roberts or Lindberg et al. (Ref. 7) for Central European conditions. Their measurements indicate the strong extinction at altitudes of 100 to 300 meters or so is often found to be several orders of magnitude worse than prevailing ground conditions. See Fig. 4 by Roberts.

In many discussions of weather effects on airborne attack systems the assumption is made that the atmosphere below clouds is homogeneous and uniformly attenuating, and that the effect of aircraft altitude is a very small factor in range computations. In fact, some commonly used models assume a homogeneous atmosphere below clouds and a totally opaque one above the cloud base. For weather in North Central Europe this is decidedly not true for low-level cloud conditions.

Actually but few detailed studies of this problem have been made. Our data are from a set of trials called "GRAF I." These data are from extensive measurements of weather effects on electrooptical systems in December and January of 1975-76 at Grafenwöhr, FRG.

It had been often said that weather effects in North Central NATO Europe were largely due to ground fogs, but no real supporting
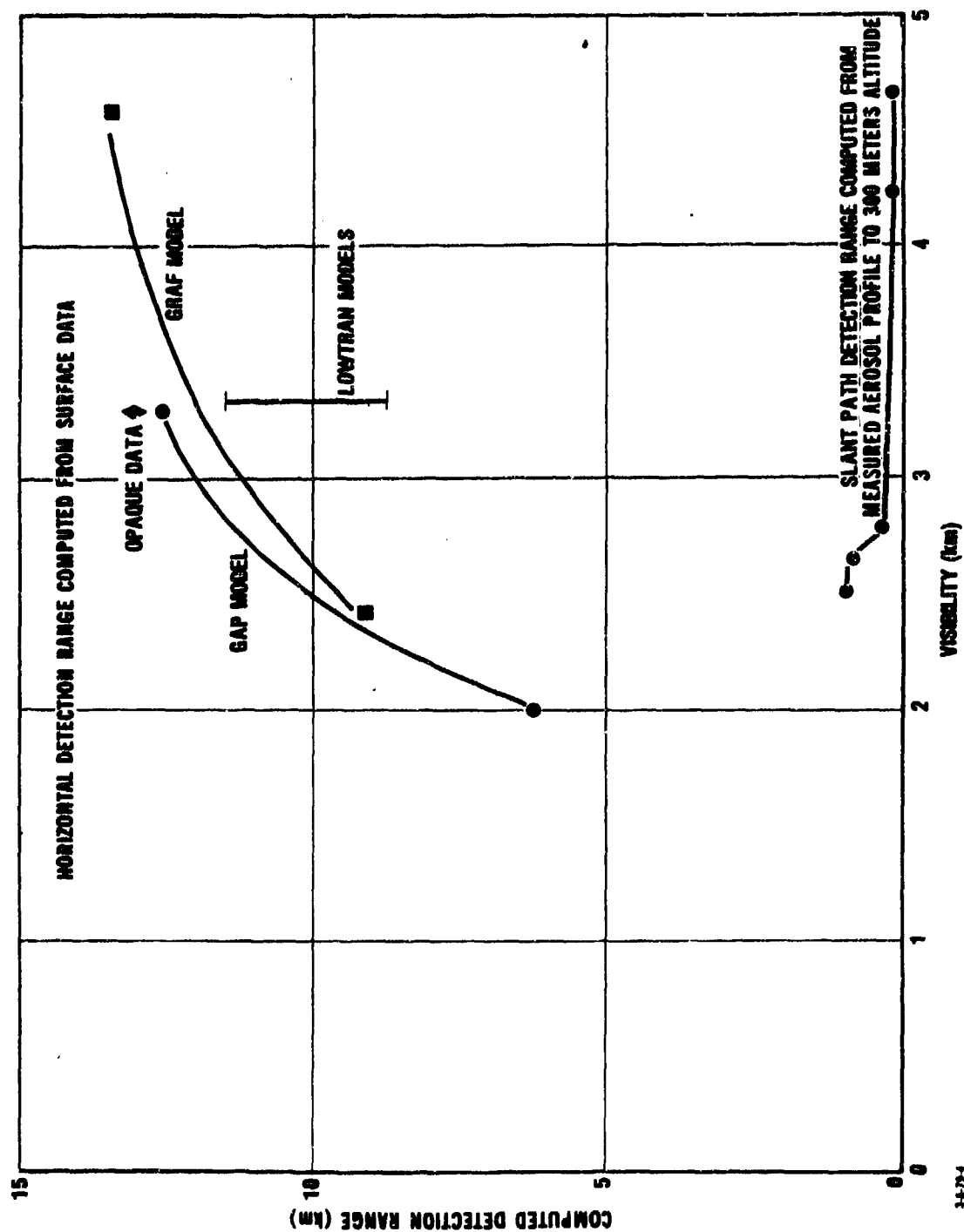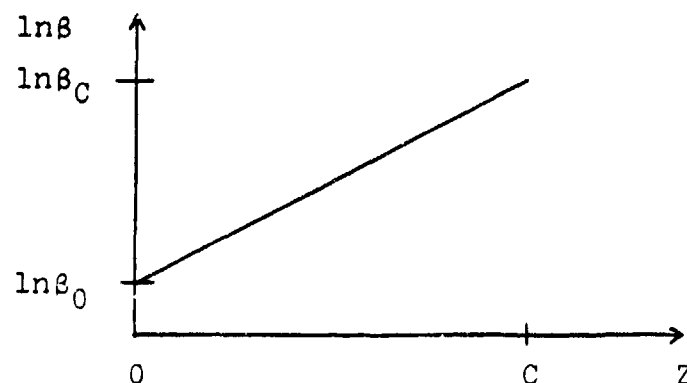
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FIGURE 4. Comparison of computed horizontal detection ranges based on surface measurements with slant-path detection range from 300 m altitude based on aerosol profile measurements.

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evidence was available. Thus, as part of the GRAF I operation, a series of tethered balloon ascents was made to obtain atmospheric data as a function of altitude.

The results showed that for conditions of relatively low cloud ceilings the aerosol concentrations increased exponentially from values at ground level to those at the lower edges of the clouds. Some samples are shown in Fig. 5. Note the major increase in extinction coefficient β--as much as three orders of magnitude in the aerosol extinction coefficient from ground to 300 meters in altitude. Since the total atmospheric extinction never is zero even when the aerosol effects are nearly zero, the spread in total extinction coefficient can vary from about 0.2 to about 5.0 km^{-1} or, in worst cases, to 10.0 km^{-1} near terrain, and from about 20 to 150 km^{-1} at the lower edges of a cloud.

On the basis of that data, one can construct a set of equations that describes the atmospheric extinction and thus transmission, and from that one can forecast system performance for the given conditions.

Assume that the extinction coefficient β increases exponentially with height, from $\beta = \beta_0$ at ground level ($Z = 0$) to $\beta = \beta_C$ at the ceiling ($Z = C$). On a semilog plot this is:

$$\ln\beta = \frac{(\ln\beta_C - \ln\beta_0)}{(C - 0)} Z + \ln\beta_0 = \ln(\beta_C/\beta_0)\frac{Z}{C} + \ln\beta_0 \ .$$
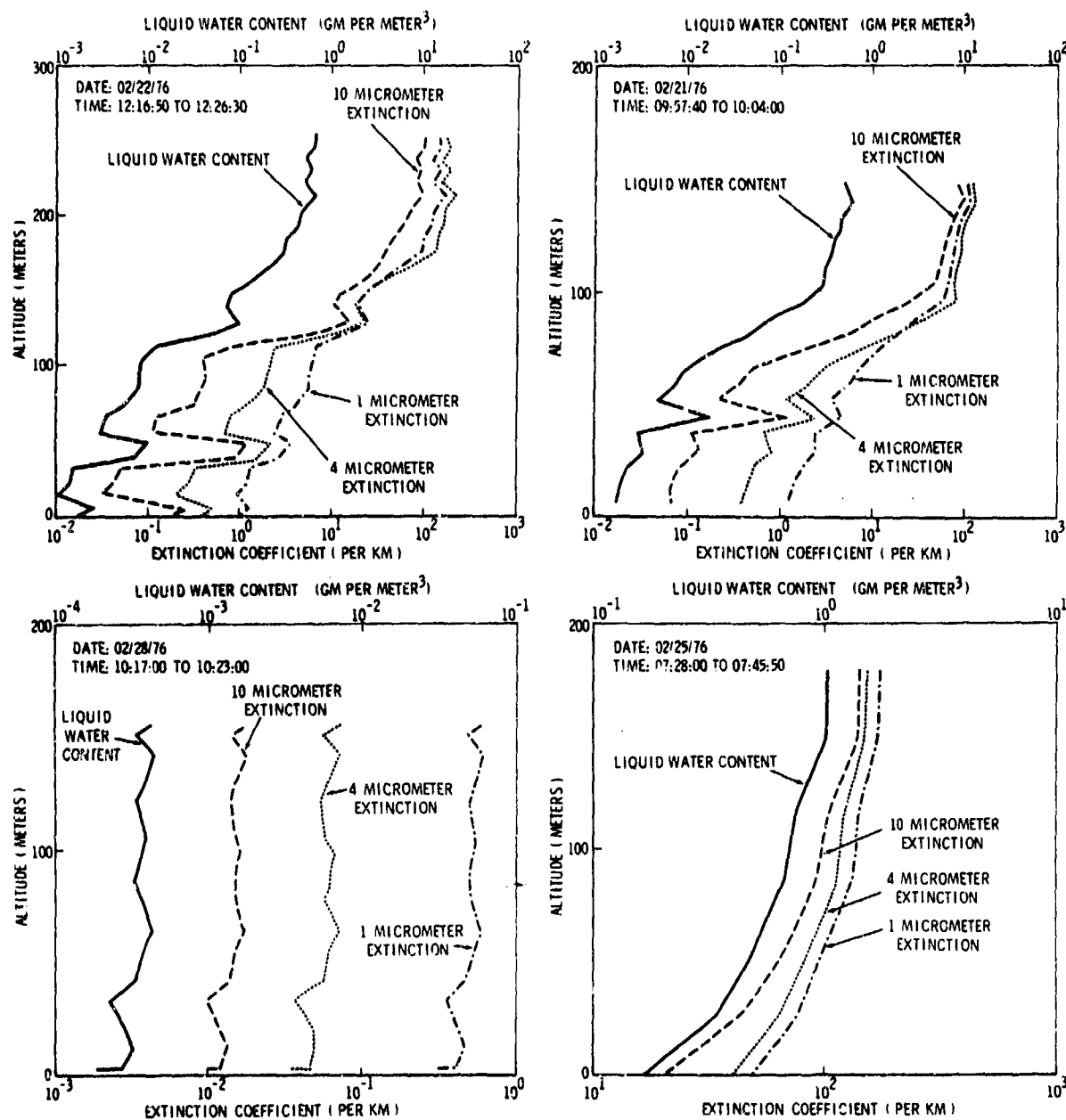
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FIGURE 5.   Effect of altitude upon computed extinction coeffic-
            ients of aerosols. Curves show four sets of measured
            data, indicating the variability of the vertical pro-
            file. Three of these cases indicate marked increased
            extinction with altitude. The jagged breaks are due
            to thin fractus clouds.

Thus we have

$$\beta(Z) = \beta_0 \, e^{\frac{Z}{C}\ln(\beta_C/\beta_0)} \quad .$$

To determine the effective extinction coefficient β_{eff} for a slant path from ground to altitude Z, we must integrate $\beta(Z)$ along the slant path:
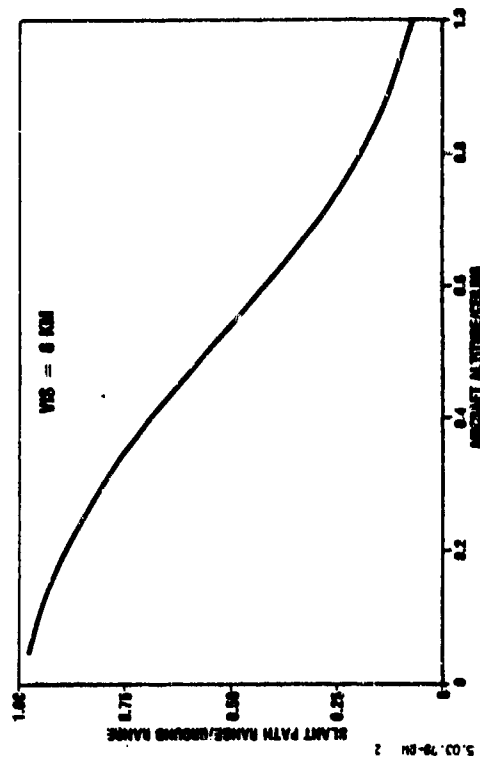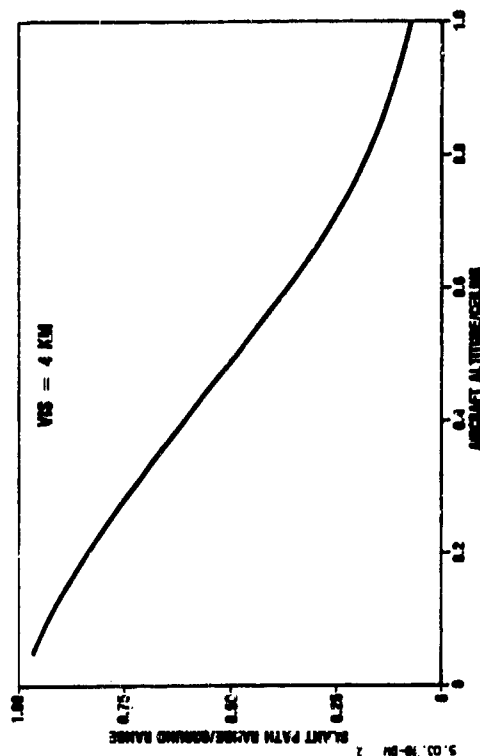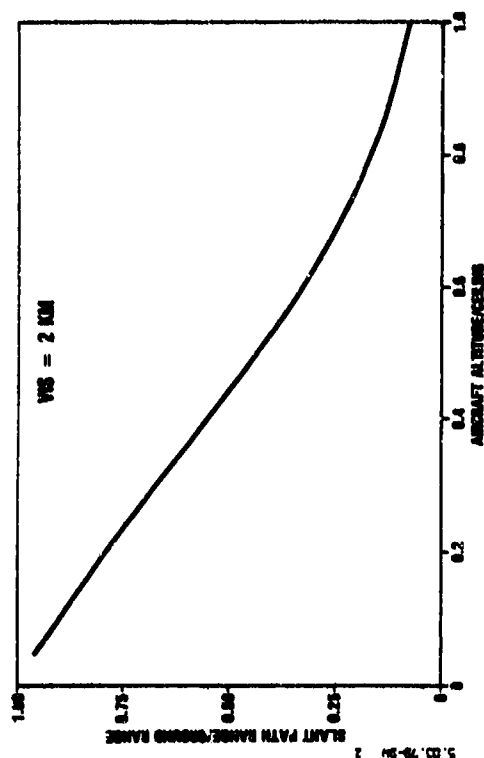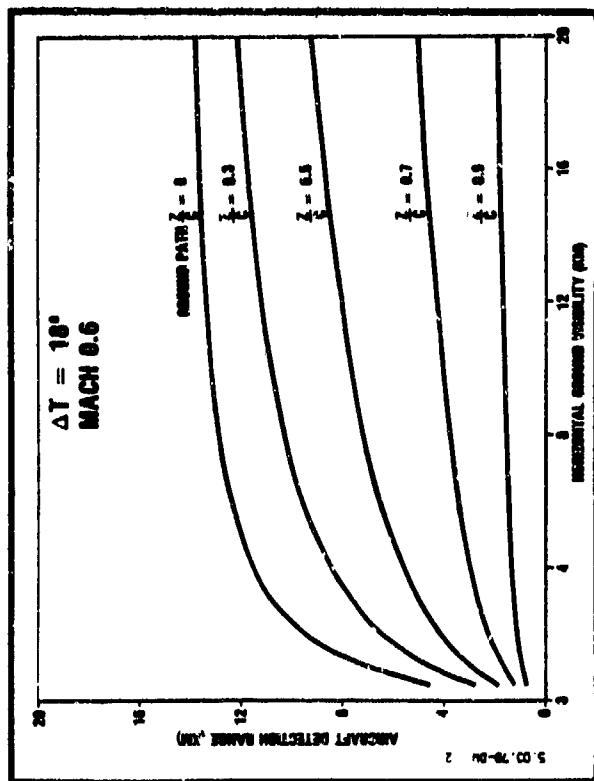
$$\beta_{eff} = \frac{1}{Z}\int_0^Z \beta(Z)dZ = \frac{1}{Z}\int_0^Z \beta_0 \, e^{\frac{Z}{C}\ln(\beta_C/\beta_0)}dZ$$

$$= \frac{\beta_0}{Z}\int_0^Z e^{\frac{Z}{C}\ln(\beta_C/\beta_0)}dZ$$

$$= \frac{\beta_0}{Z} e^{\frac{Z}{C}\ln(\beta_C/\beta_0)} \, \frac{C}{\ln(\beta_C/\beta_0)} \, \Big|_0^Z$$

$$= \frac{\beta_0}{\frac{Z}{C}\ln(\beta_C/\beta_0)} \left(e^{\frac{Z}{C}\ln(\beta_C/\beta_0)} - 1 \right) \quad .$$

Let $X = \frac{Z}{C}\ln(\beta_C/\beta_0)$;

then

$$\beta_{eff} = \frac{\beta_0}{X}(e^X - 1) \quad .$$

Figure 6 shows the use of the equations derived above to compute the detection of a Mach 0.6 aircraft by a modern ground-based FLIR.

FIGURE 6. Ground-based FLIR detection of attack aircraft below low clouds. Aerosol extinction β computed as $\beta = 0.85$/visibility at surface. β at lower edge of cloud equals 20 km^{-1}. FLIR parameters: $MRT_0 \cong 0.01$, $d(\ln MRT)/ds = 0.6$.

B. VISIBILITY DATA

As discussed in Chapter II of this report, the aerosol extinction coefficients are based upon visibility as the primary input parameter. Later models will also use relative humidities to modify the extinction coefficient.

The USAF Environmental Technical Applications Center provided weather data including relative humidity and visibility recorded hourly over each month of the year 1969 for several locations around the world. Examining the relative humidity data, we find a fairly smooth and reasonable distribution, as shown in Figs. 7 and 8 for two examples (Ankara, Turkey, in December and Aviano, Italy, in November). Unfortunately, the visibility data does not match that smooth spread. This inconsistency casts doubt upon the validity of visibility data alone as input to an aerosol model.

Much can be said about the quality of visibility data or lack thereof. The quality of the data is dependent to some extent upon the quality of the observed markers, and to some extent upon the motivation of the observers. Even dedicated teams located at different, though nearby, sites can disagree markedly (Fig. 9). Visibility is determined from a series of daytime sightings of silhouetted objects against the sky. As the atmosphere gets hazy, the dark object against the bright sky gets "filled in" by scattered light that reduces the contrast of the dark target against the sky. At some degree of haziness the scattered light renders the object undetectable or just on the threshold of detection. To make estimates one should have a series of such objects at known distances more or less evenly spaced throughout the range span of interest.

In some locations there are few such objects, and no additional special markers are installed. As a result, the data tend to bunch about the ranges at which an observer has a known
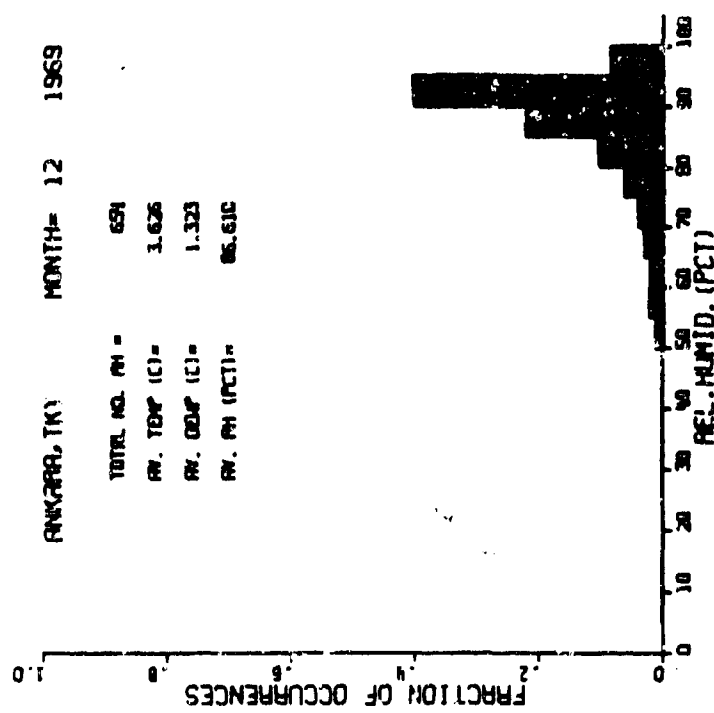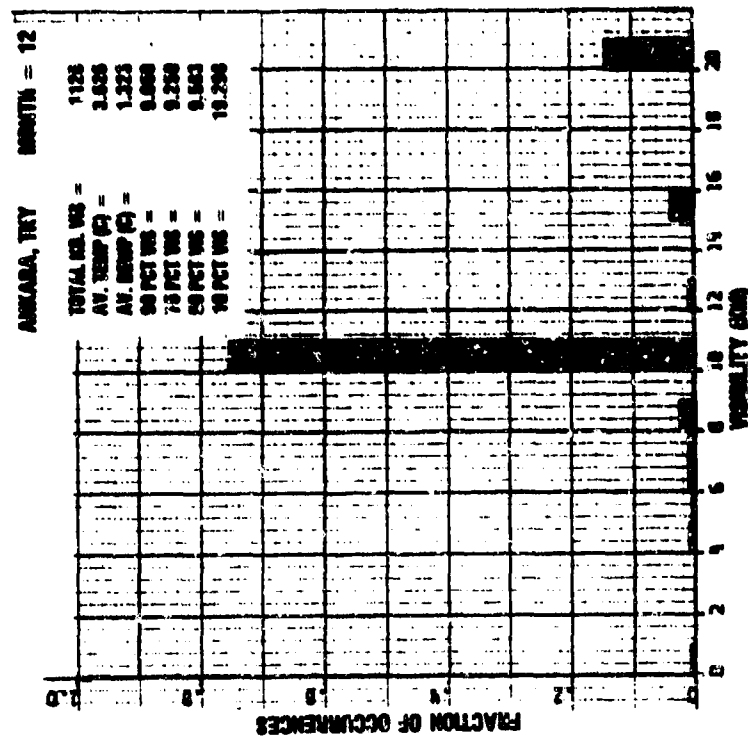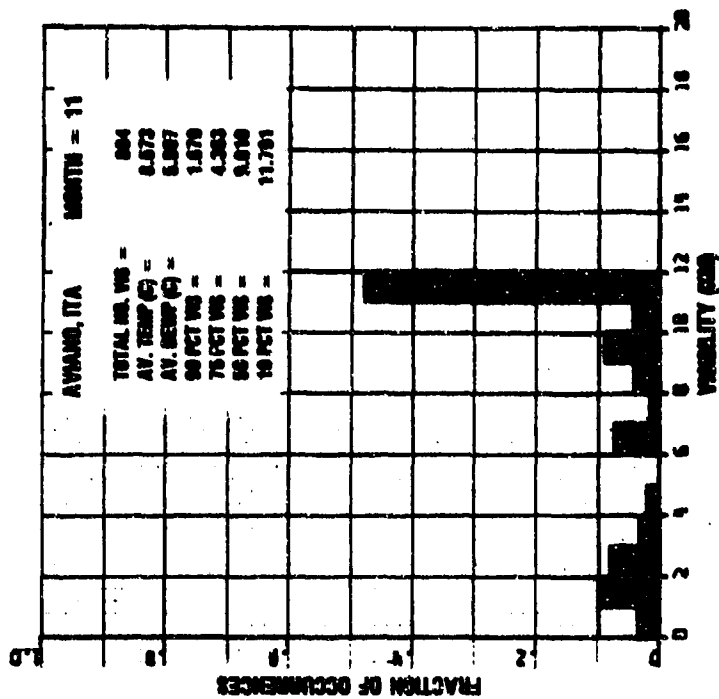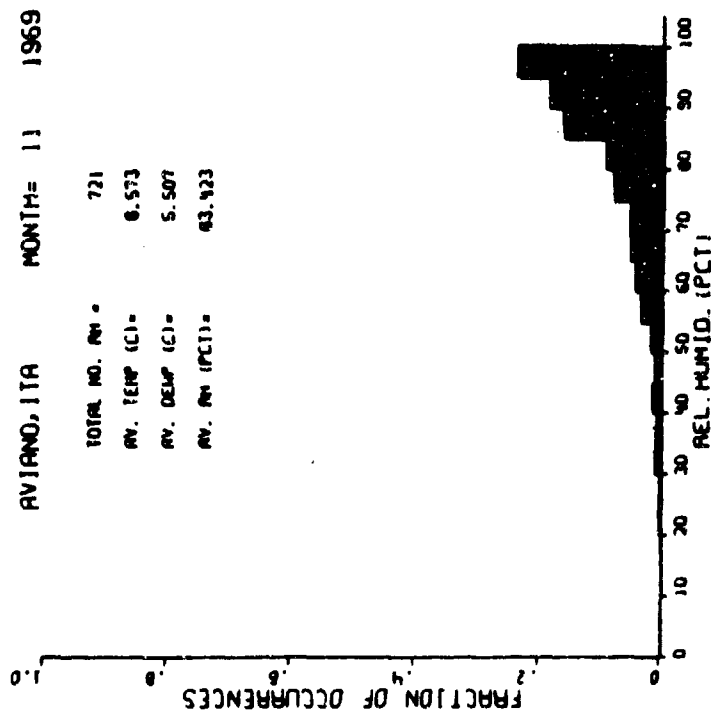
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FIGURE 7. Relative humidity and visibility statistics, Ankara, Turkey.

FIGURE 8. Relative humidity and visibility statistics, Aviano, Italy.
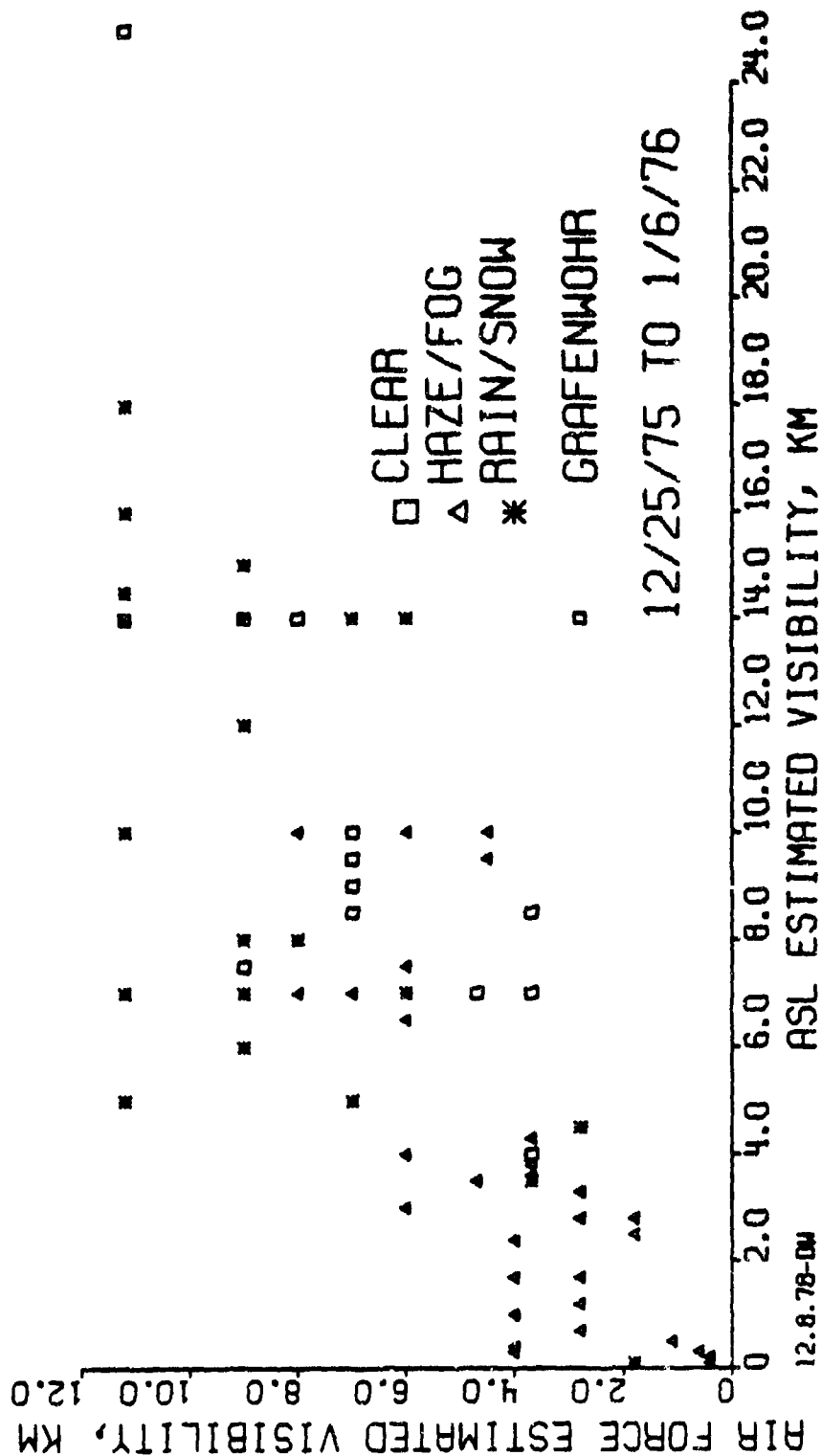
FIGURE 9. Comparison of visibility estimates. Each data point is an Air Force meteorology team estimate plotted versus an ASL meteorology team estimate. (See Section IV-A, pp. 19-20.)

marker, and no observation can be made where there is no such marker.

U.S. weather stations run by the Air Force tend to find or to provide markers. It has been suggested that the visibility data shown in Fig. 9 are more representative of the available silhouetted features of the observing-site skyline than of the turbidity of the atmosphere. These are nevertheless the only visibility data available.

By international convention, visibilities exceeding 10 km are usually reported as infinite in aviation weather data, but there are deviations from this practice. Thus, some observers may report anything over 10 km as infinite, while others--even at the same station--may actually report a specific marker at, say, 11 or 16 or 20 km, if one exists and is just visible. These variations in the reporting of visibility are of little help when it comes to solving

$$\beta = \frac{\text{factor}}{\text{visibility}} \quad .$$

V. CONCLUSIONS

In this paper we have discussed the difficulties associated with assessing the impact of aerosol effects upon 3-5 and 8-12 μm FLIR performance.

Although the 8-12 μm band has proven superior under most limited visibility conditions, the valid prediction of individual performance ranges for each system is not possible in a deterministic sense with current aerosol models. The four major uncertainties in making such a prediction are:

1. The visibility required as input to the aerosol models is not reliably measured.

2. It is unrealistic to expect any simple scaling model to pertain to all atmospheric conditions.

3. The LOWTRAN aerosol models are primarily useful for ground-level paths. For air-to-ground cases, significant differences occur due to vertical structure which cannot be predicted by these models.

4. Preliminary models of the vertical lapse of aerosol extinction have been put forth by Roberts and Turner of IDA and by Lindberg of ASL. Although these need careful validation, until something better is put forth these are the only models for estimating EO performance through slant paths containing aerosols.

We therefore believe that a final assessment of FLIR performance requires a yet unavailable, statistically valid experimental data base for infrared transmission, such as OPAQUE may in time provide.

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