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Environmental Standards for Electro-Optical Systems

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20. ABSTRACT (cont'd)

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The definitions of standards are based on an extension to system operability of the definitions given for physical survivability in Army Regulation AR 70-38, Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions. The objective is to have a procedure for determining the probability of successful performance of signal links of weapon systems that can be affected by environment.

> Data presented here include those environmental parameters that affect the performance of electro-optical links of military systems. These parameters include transmission and reflectance data. Transmission data are provided for visibility, ceiling, rain and snow rates, and humidity. These data are provided in terms of risk that a given level will be exceeded, based on the definitions of AR 70-38.



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CONTENTS

	<u>Page</u>
EXECUTIVE SUMMARY	7
1. INTRODUCTION	15
1.1 Background of EO Signal Links	15
1.2 Tasking	16
2. ENVIRONMENTAL EFFECTS ON SIGNAL LINKS	18
2.1 Weapon Systems with Signal Links	18
2.2 EO Parameters	19
2.3 Battlefield Conditions	20
3. DEFINITION OF STANDARDS	22
3.1 Mathematical Bases for Standards	22
3.2 Existing Standards for Natural Phenomena	22
3.3 Application to Sensor Standards	25
3.4 Definitions of Risk	27
3.5 Data Requirements	27
4. NATURAL ENVIRONMENTAL CONDITIONS	28
4.1 Data Package	28
4.2 Visibility Data Collection	31
4.2.1 Threshold of Contrast	31
4.2.2 The Data Package	32
4.3 Fulda Area Natural Environment	33
4.3.1 Visibility	33
4.3.2 Ceiling and Cloud Cover	37
4.3.3 Rain Intensity	38
4.3.4 Snow Intensity	39
4.3.5 Absolute Humidity	39
4.4 Composite Effects	40
4.5 Target Signatures	41
4.6 Target Reflectance	43
5. STATUS OF CURRENT EFFORTS	44
5.1 Natural Environment	44
5.2 Battlefield- and Enemy-Induced Environments	45
5.3 Comparisons with Other Efforts	46
5.4 Status Summary	46

CONTENTS (Cont'd)

	<u>Page</u>
ACRONYMS	49
LITERATURE CITED	50
DISTRIBUTION	81

APPENDICES

A.--EXTINCTION COEFFICIENT MODELS	53
B.--VISIBILITY MEASUREMENT AND EXTINCTION COEFFICIENT	65
C.--DEFINITIONS OF REFLECTANCE FOR ELECTRO-OPTICAL APPLICATIONS	75

FIGURES

1. Locations of selected weather stations, Federal Republic of Germany	30
2. Visibility versus frequency of occurrence, by month, seven-station average, all hours	33
3. Visibility versus frequency of occurrence, by month, seven-station average, morning hours (0600, 0700, 0800)	34
4. Visibility versus frequency of occurrence, worst months, best months; seven stations, all hours	35
5. Visibility versus frequency of occurrence, worst months, best months, seven stations, morning hours (0600, 0700, 0800)	35
6. Visibility versus frequency of occurrence, Wasserkuppe. Data are for worst month and best month, all hours and morning hours	36
7. Visibility versus frequency of occurrence, comparison of extreme cases	37
8. Frequency of occurrence versus ceiling height	38
9. Frequency of occurrence versus rain rate	39
10. Frequency of occurrence versus snow rate	40
11. Frequency of occurrence of absolute humidity greater than that indicated, by month, all hours, seven-station average	41
12. Visibility versus meteorological parameters, seven-stations July, all hours (● = average value and - = standard deviation)	42

FIGURES (Cont'd)

	<u>Page</u>
13. Visibility versus meteorological parameters, seven stations, September, all hours (● = average value and - = standard deviation)	43
14. Bidirectional reflectance, M48 tank; reflectance angular range: 0 to 60 deg	44

TABLES

1. Natural Environments	29
2. Weather Stations Around Fulda	29
3. Environmental Data for Natural Factors	47

EXECUTIVE SUMMARY

1. BACKGROUND

In the development of weapon systems that use signal links, there is a need for a better procedure for estimating the probability of proper performance. Standards and definitions of environmental conditions are needed by modelers and others who assess performance capabilities of materiel under nonideal atmospheric conditions that are natural or induced by the battlefield on the enemy. Currently, such standards are lacking and there is no common basis for comparison of assessments that use different data bases. This report is a first step to systematically approaching such standards.

Current Army standards, as defined in MIL-STD-210-B¹ and AR 70-38,^{2,3} are materiel functional standards for some natural environmental conditions. These standards are designed to ensure the physical survivability of primarily, mechanical materiel in such an environment. However, standards relating to signal transmission are required for estimating a probability of proper performance of weapons employing sensors in signal links.

This report provides some background on the existing definitions for standards, and it outlines the way in which they fail to satisfy the requirements for determining a probability of operation on a realistic battlefield. An extension is proposed for the existing definitions so that they will be useful for estimating a probability of signal link performance degradation or failure, and available data are reduced and presented in a uniform format, specifically for use with electro-optical (EO) systems.

The U.S. Army Materiel Development and Readiness Command (DARCOM) and the U.S. Army Training and Doctrine Command (TRADOC) were tasked by the Vice Chief of Staff, Army (VCSA), to develop standard conditions for the assessment of battlefield obscurant effects on weapon performance. All signal links, and especially links in weapon systems, must operate in three kinds of environments: natural, battlefield-induced, and enemy-induced. "Operate" means both that the equipment will hold up while waiting to be operated and that it will operate successfully when finally used. The tasking recognized that no one knows where future battles will be fought, but that there is knowledge of where U.S. forces plan to be ready to fight and that data exist on the natural environment in those locations.

¹Military Standard, MIL-STD-210B, Climatic Extremes for Military Equipment, Department of Defense (15 December 1973).

²AR-70-38, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

This report provides the background, the rationale, and representative reduced data on battlefield environmental conditions believed necessary to lead to the selection of environmental sensor standards for use in analyses, research and development (R&D), and training. No attempt is made to explicitly set new standards, but only to statistically quantify those environmental factors that are critical to system performance, from which standards can be set by the user. It is shown that data on these environmental factors can be reduced and presented in a format equivalent to those currently used for mechanical survivability, as in MIL-STD-210-B¹ and AR-70-38.^{2,3} Other procedures for defining standards that have been considered have advantages and disadvantages when compared with the proposed definitions. In many cases, the proposed standards tend to employ near-worst-case data bases, as do the mechanical survivability standards, and thus tend to be conservative in estimating performance degradation on a realistic battlefield. However, such data bases for the proposed standards can be assembled, provide for a performance safety factor, and avoid the complexity of attempting to weight the area-wide environmental conditions by the expected probability of occurrence. For the effort reported here, available data that apply to the EO signal links of weapon systems are so presented. Future effort is needed to extend the data collection and reduction to those factors necessary to evaluate other weapon performance elements that can be affected by realistic battlefield conditions.

This procedure then provides a methodology for setting standards in terms of a risk probability that the system will not function as designed. The data are provided in a format equivalent to that used in AR-70-38,^{2,3} with provision for setting a variable risk, depending on the materiel need. From the proposed methodology, the developer can define standard conditions for particular environments. Based on the environmental data of the type presented, the equipment developer can use these data to set sensor standards for a system which can then be used in analyses, R&D, and training.

2. DEFINITIONS

A standard is set up and established by authority as a rule for the measure of limits or definitive levels of a physical parameter. An Army objective is to have a force that "routinely thinks in terms of realistic battlefield environmental conditions and can operate successfully when subjected to them." To help satisfy that objective, this report proposes that sensor standards be based on the probability of occurrence of those battlefield environmental conditions that could degrade the performance of a system employing signal links from the level that would be obtained in a clear environment.

¹Military Standard, MIL-STD-210B, Climatic Extremes for Military Equipment, Department of Defense (15 December 1973).

²AR-70-38, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

Such sensor standards will have two basic applications: (1) to set performance requirements for new or improved weapons that will be used in analyses, R&D, and training and (2) to support assessments for the probability of achieving a desired level of performance for any weapon system used in a designated scenario. A corollary to the latter application is for the user to be able to predict for what fraction of the opportunities a weapon is likely to succeed, or the probable success in a given opportunity.

Because of the form in which the basic data are available and the way in which they will be used, it is proposed that standards be defined separately for natural, battlefield-induced, and enemy-induced environments. A natural environment is characterized by the indigenous conditions on a battlefield such as fog, rain, and wind. A battlefield-induced environment is characterized by conditions resulting from a battle, such as battlefield dust and smoke, and by the applicable properties of weapons and targets in such an environment, such as target signatures. An enemy-induced environment is characterized by enemy use of agents designed to deliberately alter the environment, such as smoke.

Normally, materiel is designed, developed, and tested to operate under both natural and induced conditions less severe than the absolute extremes that may occur within the areas of intended use. This limitation implies that there will be some risk of an inability to operate at a desired opportunity. Given the statistics of occurrence of each of these environmental conditions, a design limit or design value can be specified for which this risk can be set at any desired level.

The risk of inability to operate (operational risk) should be kept as low as possible, consistent with other design constraints such as cost, operability in the entire range of battlefield environments, and state of the art. The potential failure rate that will be acceptable in a given set of conditions is a function of the importance to the outcome of the battle of achieving success and the availability of alternative equipment that can function under such conditions.

The sensor operational risk is an extension to the mechanical function risk definitions given in AR-70-38.^{2,3} It is proposed that the methodology for defining risk and the risk philosophy be equivalent to that in AR-70-38. Risk is defined in AR-70-38 in terms of a percentage risk policy, in which the design limit or standard selected is the value exceeded not more than some selected percentage of the hours in the most extreme month in an average year at the most severe location for that natural factor or parameter. These limits can be expressed as percentages, and when applied collectively they are

²AR-70-38, *Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions*, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, *Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions*, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

referred to as a percentage risk policy. This definition needs to be modified in two ways for defining sensor standards. First, time of day may be specified because of (1) the predictable diurnal variation of some elements and (2) the known enemy tactics of taking advantage of such predictable conditions whenever possible. Second, the use of the most severe location in a region for a given EO link may not be reasonable if that location is not militarily significant or important to the operability of a particular type of EO equipment.

The actual risk percentage to be specified is a function of the particular military requirements for functional operability of specific equipment. As stated in AR-70-38, "Although this [risk percentage] is a convenient short designation, it can be misleading to those who are not aware of this specific definition."^{2,3} Further, it is stated that there is no way to quantify, with any degree of accuracy, the probability that materiel will be required to operate at the extreme conditions and that any such specification of risk, when applied over a more extended region, will necessarily be very conservative. To the extent possible, this should be taken into account in accepting an acceptable risk.

The use of risk based on a time distribution of occurrence applies only to the natural environment. For battlefield- and enemy-induced environments, some measure of probability of occurrence will be necessary other than elapsed time. It is proposed that the criteria for performance be defined as follows:

Natural environment.--The design value will be defined, in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the hours at the most extreme time of day and month in an average year at the most severe location for that element.

Battlefield-induced environment.--The design value will be defined, for a specified scenario, in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the events affecting a weapon element.

Enemy-induced environment.--The design value will be defined, for a specified threat, in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the events affecting a weapon element.

²AR-70-38, *Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, Headquarters, Department of the Army (5 May 1969).*

³AR-70-38, *Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).*

3. DATA REQUIREMENTS

The performance of EO signal links of weapon systems is affected by one or more of the following natural environmental factors that can affect the transmission and the scattering of the link signal and, where needed for operation of a particular system, the target signature and target reflectivity:

- Visibility (including effects of natural haze, dust, smoke, etc.)
- Ceiling
- Cloud cover
- Rain intensity
- Snow intensity
- Humidity

The following battlefield-induced factors can affect the performance of EO signal links of weapon systems:

- Battlefield dust
- Battlefield smoke

These conditions can affect the transmission and the scattering of the EO link signal and, to some extent, can affect some target signatures and target reflectivity.

The principal enemy-induced environmental factors that can degrade the performance of EO signal links are chaff, deliberate smoke, and other aerosols. For this report, performance degradation that can be caused by other countermeasures such as high-energy laser or counterfire is not included because it does not affect the EO signal link directly. Smoke also may affect some target signatures through its impact on contrast, and therefore these environmental factors are included for both battlefield and enemy-induced environments.

4. APPLICATION

Care must be taken in setting system performance requirements based on the sensor standards to be defined. First, the effects may be nonadditive. For example, data on signal attenuation in fog alone and in battlefield dust alone may not permit an estimate to be made of signal attenuation in a combined fog and dust environment. Such a requirement may have to be met by use of appropriate composite models or by use of data taken in the combined environment to accurately quantify the complex composite battlefield. Few such composite data are currently available.

Second, the standards to be applied to different EO links of a system must reflect likely environmental combinations. For example, target reflectivity and target signature data in rain must be used with signal attenuation for an equivalent rain rate. Also, a low temperature standard should not be used with a standard that is inappropriate, such as a high absolute humidity standard.

Third, the environmental conditions must be related in context to battle-field operations. That is, input data to environmental standards should include data taken only under conditions during which significant military operations can be conducted or would not be extremely risky to be attempted. Thus, any weather limitations that apply to mechanical function in a combat situation should be applied also to weapon performance in that environment.

5. REPRESENTATIVE DATA

Some typical data on probability distributions of battlefield environmental conditions have been reduced. The transmission data are based on Environmental Technical Applications Center (ETAC) data for stations around Fulda, Federal Republic of Germany. The selection of standards, based on risk factors, must take into account the area of use and operability requirements for specific weapon systems. For natural environmental conditions, the data are presented on the assumption of use of the proposed definition of percentage risk as being the value exceeded not more than the selected percentage of the hours in a particular period at the specified locations for that factor.

The data are typical point estimates based on the definition of risk and the probability of occurrence data reduced to date. However, for any other numerical level of a particular EO parameter selected, a corresponding risk level can be defined. Similarly, if a risk level is given, the corresponding numerical values of the various EO parameters appropriate to that level of risk can be found.

All conditions, except for target reflectance, are considered to be natural environmental conditions, and the assessment of risk is based on the variation with time of each factor. Target reflectance is considered to be a battlefield-induced condition, and the assessment of risk is based on data for militarily significant intercept conditions.

6. TYPICAL RISK FACTORS

Visibility.--For a 500-m visible range, the risk is 60 percent based on probability of occurrence data for the hilltop observation station of Wasserkuppe (in December early morning hours). Also, for the same 500-m visible range, the risk is 19 percent based on average probability of occurrence data for seven Fulda area low-altitude stations (in September early morning hours).

Ceiling.--For a 300-m ceiling above station level, the risk is 53 percent based on probability of occurrence data for Wasserkuppe (in December). For the same 300-m ceiling above station level, the risk is 16 percent based on average probability of occurrence data for Fulda area low-altitude stations (in December).

Rain rate.--For a 5-mm/hr rain rate, the risk is 3 percent based on probability of occurrence data for Wasserkuppe (in May). For the same 5-mm/hr rain rate, the risk is 1 percent based on average probability of occurrence data for seven Fulda area low-altitude stations (worst month).

Snow rate.--For a 4-mm/hr equivalent rain rate, the risk is 3 percent based on probability of occurrence data for Wasserkuppe (in December). For the same 4-mm/hr equivalent rain rate, the risk is 0.5 percent based on average probability of occurrence data for seven Fulda area low-altitude stations (in December).

Absolute humidity.--For an absolute humidity of 12 g/m³, the risk is 24 percent based on average probability of occurrence data for seven Fulda area low-altitude stations (July and August).

Target reflectance.--For a reflectance of 5 percent, the risk is 20 percent for a dry tank based on equal weighting of test data using an M48 tank as a target at 1.06 μ m, for bistatic angles from the illumination ranging from -30 to 60 deg. For the same 5-percent reflectance, the risk is 15 percent for a wet tank under the same test conditions.

7. SUMMARY AND CURRENT STATUS

Definitions for standards applicable to the EO signal links of weapon systems are proposed here based on extension of existing definitions. Some available data, mostly for central European (Fulda) environmental conditions, have been gathered and reduced to a form in which the risk associated with specific environmental conditions can be estimated. These data are in a format that can be used in existing and projected weapon performance models to estimate the probability of successful performance for specified scenarios.

Given that these definitions are acceptable, much additional work is necessary. Environmental conditions are categorized as natural, battlefield induced, and enemy induced. For the last two, the assembling of statistics for estimation of risk requires the selection of a standard battlefield scenario. Additional data are needed both for regions other than the Fulda area and for other environmental factors and EO parameters affecting weapon performance. This need is strong for target-to-background contrast data for both thermal sights (8 to 14 μ m) and microwave radiometric contrast sensors. Target detection, recognition, and identification for thermal sights are determined in part from the difference between target and background temperatures. For these sights, the large number and variation of environmental factors and EO parameters make the determination of a probability distribution function depend heavily on scenario and weather. Partly because of a lack of a scenario, no data are presented here on a probability distribution function of vehicle thermal contrast temperatures.

The proposed concept of risk as a tool for setting battlefield sensor standards can apply to equipment other than EO signal links of weapon systems. Possible extensions include specifications for other influences on such weapon systems such as the effect of wind shear on lift surfaces, which can increase the miss distance. Standards may be developed using this concept to apply to specification of performance of systems operating in other portions of the electromagnetic spectrum, where such performance can be affected by battlefield environmental conditions, induced both by natural causes and by the enemy.

1. INTRODUCTION

An objective of the Army is to have a force that "routinely thinks in terms of realistic battlefield environmental conditions and can operate successfully when subjected to them."* To meet this objective in part, the Harry Diamond Laboratories (HDL) was tasked to help develop standard environmental conditions for training, research, development, and analysis.

This report specifies those environmental factors of a realistic battlefield that can affect the performance of guided weapon systems using electro-optical (EO) sensors in signal links. Nature, the battlefield, and the enemy can affect how electromagnetic energy is transmitted through the atmosphere and how target signatures behave, since the target also interacts with the environment.

Standards for environmental conditions are defined in a way that is comparable to those given for mechanical survivability in AR-70-38¹ which can be extended to apply to signal link performance. The objective is to have a means to determine the probability that signal links of a weapon system will perform successfully on a battlefield in natural, battlefield-induced, and enemy-induced environments.

1.1 Background of EO Signal Links

For several years, the Army has been greatly concerned about how smoke and obscurants affect the performance of EO links in guided weapon systems.^{4,5} The Army's concern follows a long period of relative neglect of obscurants. This neglect can probably be attributed to the emphasis on the development of radar during and after World War II and the dependence on radar for target location. Even though location by radar is generally not precise enough to bring direct fire on a target, it was a great technological advance and is very useful on the battlefield.

After World War II, guided missile technology advanced rapidly, and with it advanced the technology of EO signal links. Track to line-of-sight (LOS) weapons became feasible, resulting in development of antitank guided weapons such as Shillelagh, which uses an infrared (IR) guidance link, and TOW (Tube-Launched Optically Tracked Wire-Guided Missile), which uses wire guidance and IR tracking technology. However, only after the 1973 Middle East war was analyzed did the Army fully recognize the effectiveness of these weapons, especially TOW.

¹Military Standard, MIL-STD-210B, Climatic Extremes for Military Equipment, Department of Defense (15 December 1973).

⁴Smoke as an Optical Countermeasure (U), Report of the Ad Hoc Committee on Optical Countermeasures of the Army Scientific Advisory Panel (November 1976). (CONFIDENTIAL)

⁵U.S. Army Management of Electro-Optical Countermeasure Hardening of Major and Non-major Weapon Systems (U), Report of the Ad Hoc Committee on Optical Countermeasures of the Army Science Board (May 1978). (CONFIDENTIAL)

*TWX from Gen W. T. Kerwin, Subject: The Use of Realistic Battlefield Environmental Conditions Throughout the Army DAMO-RQS (25 November 1977).



At that time, the Army had highly effective antiarmor weapons, but they could be degraded or defeated by obscurants. It became important to evaluate EO weapon performance in probable battlefield environments. Studies indicated that EO weapons can be seriously degraded in a limited visibility environment.⁶⁻⁸ Further, limited visibility environments are of frequent natural occurrence in central Europe and can be expected to be induced on the battlefield anywhere.

In response to the realization of the potential degrading effects of obscurants, the Office of Project Manager (PM) Smoke/Obscurants was established to develop smoke munitions and assess weapon effectiveness in smoke and obscurant environments.⁹ General W. T. Kerwin called for increased awareness and the development of standards for conditions to assess obscurant effects.* General J. R. Guthrie added emphasis to that call and clarified certain responsibilities within DARCOM.[†] W. J. Perry defined certain responsibilities among the three Services.‡

1.2 Tasking

The present tasking grew out of a briefing on battlefield aerosols to the Under Secretary of the Army on 15 November 1977. The PM Smoke/Obscurants made it evident that there were many unknowns and much confusion about obscurants. Several tasks in obscurants were generated by the DARCOM Battlefield Systems Integration Office (BSI) in cooperation with Headquarters, TRADOC.^{§, ¶}

⁶William H. Pepper (editor), *Limited Visibility Operations Assessment (Phases I and II)*, Harry Diamond Laboratories HDL-TM-79-16 (December 1977). (SECRET-NOFORN)

⁷W. H. Pepper and R. G. Humphrey, *Limited Visibility Operations (U)*, Proceedings of the 39th Military Operations Research Symposium, U. S. Naval Academy, 28, 29, 30 June 1977. (CONFIDENTIAL)

⁸W. H. Pepper and R. G. Humphrey, *Effect of Smoke on Ground Force Operations (U)*, Proceedings of 16th IRIS Symposium on Infrared Countermeasures, 4, 5, 6 April 1978. (CONFIDENTIAL)

⁹Dominick A. Giglio and Robert G. Humphrey, *A Proposed Army Structure for the Assessment of Smoke Effectiveness*, Harry Diamond Laboratories HDL-TM-77-15 (December 1977).

*TWX from GEN W. T. Kerwin, Subject: *The Use of Realistic Battlefield Environmental Conditions Throughout the Army*, DAMO-RQS (25 November 1977).

†Letter from GEN J. R. Guthrie, Subject: *Evaluation of Electro-Optical Systems in Degraded Visibility Conditions*, U.S. Army Development and Readiness Command Battlefield Systems Integration Directorate (DRCBSI) (13 February 1978).

‡Letter, Subject: *DoD Plan for Atmospheric Transmission, Research, and Development*, Under Secretary of Defense, Research and Engineering (16 March 1978).

§TWX, Subject: *The Use of Realistic Environmental Conditions Throughout the Army*, Commander, U.S. Army Development and Readiness Command (DRCBSI) (26 January 1978).

¶TWX, Subject: *The Use of Realistic Battlefield Environmental Conditions Commanders*, U.S. Army Development and Readiness Command and U.S. Army Training and Doctrine Command (30 December 1977). (CONFIDENTIAL)

(a) Balance smoke munitions inventory against adjusted requirements (PM-Smoke/Obscurants).

(b) Develop small unit scenarios described completely enough for appropriate agencies to evaluate the impact of aerosols and smoke on the systems for which they are responsible. The first scenario will relate to the Soviet breakthrough (Army Materiel Systems Analysis Activity--AMSAA--and TRADOC Systems Analysis Activity--TRASANA).

(c) Develop standard environmental conditions for training, research, development, and analysis (Headquarters, TRADOC and Electronics Research and Development Command--ERADCOM--through HDL).

(d) Prepare a handbook with environmental, aerosol, and system data (AMSAA and TRASANA).

(e) Solve one problem first--develop the concepts and the technical recommendations for U.S. reaction to enemy use of massive smoke. A how-to-fight manual and training literature on operating in limited visibility environments will flow from this effort (TRADOC and Combined Arms Center--CACDA).

Task c, reported here, is concerned with definitions from which standards for environmental conditions can be specified and the collection and reduction of data required to set such standards.

Within ERADCOM, the sources of data are the Atmospheric Sciences Laboratory (ASL) and the Night Vision and Electro-Optics Laboratory (NVEOL) with HDL serving as the lead agency for applying these data to the standards. The organizational responsibilities for collecting data were assigned as follows:

Climatology (frequency of occurrence and visibility impairment): ASL

Target signature data base: NVEOL

Enemy capability (induced smoke): HDL

Battlefield dust and incidental smoke: ASL and NVEOL

Composite complex battlefield: ASL and NVEOL

ASL agreed to provide climatology data extracted from the data base of tapes obtained from the Environmental Technical Applications Center (ETAC). These tapes contain weather records of German- and U.S. Air Force-operated weather stations in the Federal Republic of Germany. NVEOL agreed to supply target signature data as needed from its signature measurement program. Such data would include photopic and thermal contrast and reflectivity with sensitivity to environmental conditions. HDL agreed to investigate smoke obscuration from an earlier study on limited visibility. Completion of the two other

responsibilities was less definite: NVEOL would provide some obscuration statistics on battlefield dust and smoke based on GRAF II tests¹⁰ and some material on the effects of combined obscurants for the composite complex battlefield.

2. ENVIRONMENTAL EFFECTS ON SIGNAL LINKS

The major applications of EO signal links in weapon systems are for battlefield surveillance, target acquisition (includes weapon sights), and guidance. Battlefield surveillance and target acquisition involve target detection, recognition, and identification--usually in a viewing system. The guidance system of currently fielded or developmental antitank weapons, and the associated surveillance equipment, may operate in the visible, near-IR, and far-IR regions of the electromagnetic spectrum. For future systems, extensions to the near millimeter wave (NMMW) spectrum is likely.

For each of these categories, generic systems elements can be identified, and for each of these elements parameters can be identified that affect EO performance on the battlefield.

2.1 Weapon Systems with Signal Links

For battlefield surveillance and target acquisition, the EO system parameters which can be affected by battlefield conditions include

Target contrast with respect to background (for passive viewing systems),

Signal transmission through the medium, and

Signal scattering by the medium and spurious sources.

For weapon guidance concepts, EO system parameters which can be affected by battlefield conditions include

Signal transmission through the medium (all systems),

Target reflectance (for laser terminal homing systems),

Signal scattering by the medium (false targets for laser terminal homing systems),

Signal scattering and spreading (for beam rider systems), and

Target contrast with respect to background (for passive guidance systems).

¹⁰Realistic Battlefield Sensor Trials, GRAF II Test Plan, J. R. Moulton, Test Director, Night Vision and Electro-Optics Laboratory (1 June 1979). ADA 075683

Several weapon guidance concepts in the IR region are in use or have been proposed. The generic guidance concepts listed all use guidance signal links. In addition, most use target acquisition devices (sights) which also use signal links. Examples of system concepts follow.

<u>Guidance concept</u>	<u>Weapon system</u>
Command to line of sight (CLCS)	TOW Dragon Shillelagh
Laser terminal homing (LTH)	Copperhead HELLFIRE
Passive homing (home on emission) air target	Chaparral Redeye Stinger
Passive homing (home on contrast) ground target	STAFF SADARM
Beam-rider	AHAWS AMAWS

The weapon systems concepts use these imaging sights:

- Telescope
- Image intensifier
- Thermal sight

2.2 EO Parameters

Physical parameters (primarily EO parameters) are necessary to characterize signal link performance on the realistic battlefield for each guidance or surveillance concept used in weapon systems. EO parameters are those environmental quantities on which system performance depends and are used in analysis to evaluate system performance. We are concerned with changes in the EO parameters caused by battlefield conditions. These include not only changes in the transmitting mediums but also changes in target characteristics such as altered reflectivity or altered target to background contrast.

EO parameters of the greatest concern are the following:

- Path transmission
- Scattering
- Turbulence
- Thermal emission
- Reflectance
- Illumination
- Target-to-background contrast

CLOS systems such as TOW, Dragon, and Shillelagh all operate in the 0.9- μm spectral region. Usually, path transmission is the only EO parameter that must be considered for these systems.

LTH systems include the developmental weapons Copperhead and Hellfire, both of which use Nd:YAG laser designators. In addition to path transmission, scattering from both aerosols and terrain and target reflectivity are important for system performance.

For passive homing systems such as Chaparral, Redeye, and Stinger operating against air targets, an important parameter is total emission in the direction of the sensor, as modified by transmission losses. These systems all operate in the mid-IR portion of the spectrum since the target temperature is high enough for thermal emission in that region.

For passive homing systems such as the proposed STAFF and SADARM rounds operating against surface targets, the system concepts use the fact that portions of tank targets, when viewed from overhead, reflect incident radiation from the sky. Thus, millimeter wave radiometric sensors looking at the tank target see approximately the low temperature of the sky. If the sensor compares the reflected sky temperature and the nonreflecting ground, a large temperature difference is measured. The processor logic uses this difference to determine the presence of a manmade target. These systems are affected by path transmissions and target surface conditions as well as by high cloud cover.

Beam-rider systems are in an early stage of development. With some beam coding systems, beam broadening due to scattering can occur under some atmospheric conditions.

For the laser rangefinder, the important parameters are similar to those for LTH.

For surveillance, it is assumed that a telescope sight is used in daylight. An image intensifier sight is used at night or under poor visibility conditions such as artificial illumination. The level of illumination is most important for an image intensifier sight since there is a great difference in weapon performance when, for example, there is a full moon and when there is no moon.

Although thermal night sight is, of course, used mainly at night, it is used also for daylight conditions of haze and smoke. For a thermal sight, thermal contrast or signature of the target with respect to its immediate background is an important EO parameter. The background effect of a heat source such as fire in the field of view (FOV) can degrade sight performance.

2.3 Battlefield Conditions

Battlefield environmental conditions that can affect the EO parameters and signal link performance are of three origins: natural, battlefield induced, and enemy induced. Natural phenomena which can occur on the battlefield and can adversely affect signal link performance include the following:

"Wet" aerosols: cloud, fog

"Dry" aerosols: haze, dust, nonmilitary smoke

Precipitation: rain, snow, other hydrometeors

Atmospheric stratification and turbulence

Humidity variation

Ground conditions: mud, snow, ice

Variable atmospheric constituents: gaseous pollution from industrial activity, nonmilitary atmospheric contaminants

The EO parameter, transmission, can be degraded by any of the preceding conditions (except ground). Reflectance can be degraded (or enhanced) by dust, rain, snow, mud, or ice. Atmospheric turbulence is primarily a clear day effect resulting from the instability of the lower atmosphere due to solar heating of the ground surface, but also is due to wind, atmospheric instability, and other factors. Wind is not listed since it does not directly affect EO system performance. Indirect effects of wind are blowing dust, blowing snow, and smoke persistence. Natural dust is a minor factor due to the high relative humidity and the general prevalence of vegetative cover in Central Europe, the area of greatest concern in this study. Temperature is not listed either under natural conditions or EO parameters (although it is both) because that quantity is already routinely considered in the design and performance of military equipment.

Battlefield-induced phenomena which can obscure the LOS to the target or otherwise degrade signal link performance include the following:

Dust from vehicles

Smoke, dirt, debris from high explosives and muzzle blast

Fires from burning vehicles and ground debris

Dirt, smoke, oil affecting target reflectivity and contrast

Enemy-induced phenomena are conditions deliberately produced by the enemy to degrade the performance of signal links. This category might include countermeasures and camouflage, but for the purposes of this report will be limited to the consideration of tactical smoke.

The battlefield environmental conditions are the quantities that must be specified in weapons system performance requirements. These requirements should be based on the likelihood of signal link failure under extreme conditions. This matter is considered in detail in the next section.

3. DEFINITION OF STANDARDS

The objective of this portion of the effort initiated by the VCSA request is to develop a realistic set of battlefield environmental conditions and apply these data to the entire spectrum of materiel acquisition activities, training, and operations of the Army. This information has been requested in the form of a set of standard environmental conditions. Thus, a definition of "standard" is required which is in consonance with existing usage of the word, and yet can satisfy the objectives posed by the VCSA message and tasking documents.

3.1 Mathematical Bases for Standards

The chief objective of having a standard is to be able to determine a probability of successful performance of a system designed to just meet that standard, or to be able to estimate the probability of successful system performance in a standard environment. Conversely, given a required performance capability for a system, the design criteria can be set. One procedure for doing this is to assume that a probability distribution function of occurrence for a given parameter is known, and that system performance is yes-no with respect to a given threshold level of that parameter. Assume that any value of that parameter which is more severe than that threshold will result in system failure and any value of that parameter which is less severe than that threshold will not cause a system failure, all other factors being invariant. Given these assumptions, the probability of system failure can be determined if the system is designed to a certain parameter threshold level, given the defined probability density function of occurrence of that parameter. This design criterion can be defined as a "risk policy." Thus, a system requirement for a one-percent risk implies successful operation with respect to that parameter for 99 percent of the trials.

One of the major problems in defining the parameter probability distribution function, which ideally should be done in terms of the total of expected trials, is that such data cannot generally be obtained. However, there may well be data available or measurable which can be interpreted in terms of, or are equivalent to, the total number of trials. The data requirements for such equivalence will be different for natural environments, for battlefield-induced environments, and for enemy-induced environments. However, since for most systems the requirement will be for a high probability of success (i.e., low risk), the probability density function of occurrence need only be acceptable for the extreme region. This is discussed in the following section for each class of battlefield phenomena that affects the signal link performance of EO weapon systems.

3.2 Existing Standards for Natural Phenomena

Military operations must be carried out throughout the world under a wide variety of climatic conditions and materiel must perform satisfactorily under a wide range of natural conditions. Therefore, all materiel requirements documents contain temperature and other climatic specifications. These are normally drawn from standard's documents. The following are standards documents which will be frequently referenced.

AR-70-38 (1969), Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions²

AR-70-38 (1978), Draft Revision, Research, Development, Test, and Evaluation of Materiel for Extreme Climatic Conditions³

MIL-STD-210B (1973), Military Standard--Climatic Extremes for Military Equipment¹

AFCRL-TR-74-0052 (1974), Synopsis of Background Material for MIL-STD-210B, Climatic Extremes for Military Equipment¹¹

In AR-70-38 eight climatic categories are defined, ranging from hot, or hot and humid, to extreme cold and other extreme conditions which military equipment must withstand. Temperature, relative humidity, and solar load are specified for operation, storage, or transit conditions. In the draft revision, the climatic categories are reduced to four basic categories, with a special hot category and two special extreme cold categories.

MIL-STD-210B is a Department of Defense (DoD) document and identifies extreme conditions not only of temperature and humidity, but also of wind speed, rainfall rate, blowing snow, snow load, sand and dust, and others.

Normally, it is intended that Army materiel will not be designed, developed, and tested to operate or withstand the absolute extreme climatic conditions which occur in an area. Rather, it is desired that materiel be designed, developed, and tested to operate during or to withstand extreme climatic conditions, given that more severe climatic extremes are expected to occur only rarely. To define the accepted risk associated with rare occasions where climatic conditions exceed the conditions for which the materiel was designed, the concepts of extreme, or extreme risk, or, especially, the one-percent extreme policy as defined in section 4.1 of MIL-STD-210B have been used. The one percent extreme policy is defined in this document as follows:

Materiel will be designed, developed, and tested to operate [during] or to withstand extreme climatic conditions such that more severe climatic extremes are expected to occur only one percent of the time (hours) in the most extreme month in the most extreme parts of the appropriate area.¹

¹Military Standard, MIL-STD-210B, Climatic Extremes for Military Equipment, Department of Defense (15 December 1973).

²AR-70-38, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

¹¹Norman Sissenwine and Rene V. Cormier, Synopsis of Background Material for MIL-STD-210B, Climatic Extremes for Military Equipment, Air Force Cambridge Research Laboratories AFCRL-TR-74-0052 (24 January 1974).

For example, the one percent extreme of a meteorological parameter, such as temperature, would be the value of that parameter that was exceeded on only 7 hourly observations of the 744 hourly observations that could be made during a 31-day month. The accepted exceptions to the one percent extreme policy as given in these documents are surface low temperature, where a 20 percent extreme is proposed for use, and surface high rainfall rate, where a 1/2 percent extreme is usually the required specification.

The one percent extreme policy is largely the rule for environmental conditions given in AR-70-38² and in MIL-STD-210B.¹ In the draft revision of AR-70-38³ an attempt has been made to downplay the one percent extreme policy, and propose a more flexible rule. This is largely because of recognition that the statistical quality of the world-wide data does not support such a precise statement as the one percent extreme. Other objections are that, even if accurate, the extremes apply to world-wide (except Antarctica) conditions. Great areas of the world are included in which military activity in the next few decades is highly unlikely; a time period of decades exceeds the expected useful life of much of the material now in development. By using world-wide statistical data, too little emphasis is given to the special problems of areas of the world where military activity in the next decade or so seems rather likely. Even with these limitations, the concept of climatic extremes is very useful, and will be adapted for use in this study.

Actually, in the standards documents^{2,3} the one percent risk policy is applied only to temperature and humidity conditions. It is not applied to other climatic parameters (precipitation, wind, solar radiation, etc) because the necessary data for these applications are not available. Nevertheless, the values given for these other parameters are appropriate for research, development, and testing of material until more complete data are available and the one percent policy can be applied. The one percent temperature and humidity values were determined from records of hourly observations taken over a number of years. Thus, they should not be construed to be values which will occur in any given year.

Temperature can be measured with ease to a precision of one or a few tenths of a degree and it changes slowly, usually only a few degrees per hour. Even the older records are reliable to a precision of a degree. Humidity involves only a second temperature measurement (dewpoint, frost-point, or wet bulb) and can also be made easily with one degree precision. In contrast, other parameters (precipitation, wind, etc) are quite variable, with significant possible variations in a period of a few seconds, and their measurement and tabulation presents many problems.

¹Military Standard, MIL-STD-210B, Climatic Extremes for Military Equipment, Department of Defense (15 December 1973).

²AR-70-38, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

Precipitation is usually measured as accumulation over a period of time, such as six hours or a day. Equipment performance in rain, however, depends on the instantaneous rate. Measurement of instantaneous rain rate is a recent innovation, and little data exist.

The present standards documents have evolved largely due to experiences with equipment failure in World War II. In that war military operations were carried out under a wide variety of climatic conditions. This situation may have led to an over concern with world extremes, and even to the somewhat grandiose idea that equipment will be designed to sustain the worst the world has to offer. Such an attitude can lead to over-specification of materiel requirements, resulting in high development and testing costs. The present trend is to tone down the requirements to what is essential, and this is evident in the draft revision of AR-70-38^{2,3} in separation of the basic and the more severe climatic categories. Perhaps the next logical step is to specialize the standards to localities of high military concern. With today's modeling and wargaming capabilities, localized climatic extremes can be weighted by importance to military concern. Such a procedure could both improve the Army preparedness and reduce the over-specification and over-design of equipment.

3.3 Application to Sensor Standards

The current standards documents are primarily (or exclusively) concerned with specification of conditions that apply to the mechanical function or physical survival of equipment (trucks, guns, engines) here termed withstanding, with little or no attention given to the operational problem (such as of EO signal links). These sensor performance problems are largely concerned with the optical properties of the atmosphere and the correlation of these properties with climatic conditions, or with conditions resulting from tactical military operation. It is proposed here that the concepts that have been developed for mechanical withstanding standards be extended to the operational aspects of military equipment, with first emphasis on EO signal links.

The defining criteria for a standard for mechanical function given in AR-70-38, with modifications as justified in the following, are felt to be potentially applicable to sensor performance based on natural environmental conditions. The quotations given below are all taken from the draft revision of this AR, dated January 1978.³

The stated purpose of AR 70-38 is that it "is concerned primarily with the mechanical operation or functioning of materiel under the extremes of climate to which it is likely to be exposed. It is recognized that there are several common environmental elements (smoke, haze, fog, shimmer, and cloud

²AR-70-38, *Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions*, Headquarters, Department of the Army (5 May 1969).

³AR-70-38, *Draft Revision, Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions*, H. S. McPhilimy, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (January 1978).

cover, for example) that may have a profound effect on the ability of some materiel to perform its intended mission. These factors, mostly related to visibility and target acquisition, are commonplace, and the desired performance of equipment in relation to them must be spelled out individually in requirement documents."

The performance of equipment in relation to visibility and target acquisition is the responsibility of the Commanding General, TRADOC and the Commanding General, U.S. Army Communications Command. No guidelines are given so that the desired sensor performance can be assessed in terms of the probability of failure, as is the case for mechanical operation. Given the requirement that a set of standard environmental conditions be developed for training, R&D, and analysis, however, it would seem to be reasonable to apply the existing methodology for defining criteria for mechanical performance to sensor performance also, for such phenomena.

However, two changes are considered to be desirable. The first change takes into account the fact that the diurnal variation of some of the more important parameters, as, for example, fog, is on the average quite predictable, and can be used by an enemy to plan the attack. The second change recognizes that it is a user responsibility to set specific standards for the tactical operational purpose of the materiel.

It is suggested that the design value will be defined, in terms of risk that a particular extreme will be exceeded, as the value not exceeded for a specified percent of the hours at the most extreme time of day and month in an average year at the most severe location for that element.

In the context of each individual factor, the word "exceeded" implies in the direction of poorer link performance. Thus, for visibility, a percentage risk defined for a given range means, under the conditions specified, for the cited percentage of the time, that the visible range will be at that level or less. For rain, the risk defined for a given rate means, under the conditions specified, that for the cited percentage of the time the rainfall rate will be at that rate or more. For target reflectivity, a percentage risk means, for the specified percentage of measurements taken on a given vehicle or vehicle type, that the target reflectivity will be at that level or lower. In all instances, unless cited, the criterion for performance degradation will be self-evident.

The risk definition permits the user to specify an operational performance requirement, based on the specific application of the equipment, in terms of a standard set of natural environmental conditions. Thus, equipment satisfying a specific risk factor will have a predictable probability of failure at the location exhibiting the most severe conditions for that factor. This assumes that conversion data to a required format, where necessary, is available. Basically, the majority of available statistical data on natural environmental conditions is not in a format from which required attenuation data can be derived with confidence. For visible range, the available data is in the visual. The signal attenuation in the various IR bands of interest can be determined from this only on an average basis with available models. For

rainfall, the available data are in terms of total fall in a given time interval or intensity on a rate-of-fall basis. Since attenuation at a given frequency is to some extent a function of drop size, the attenuation again can only be determined for some average drop size distribution, since drop size data are normally not recorded. Using available statistical data, the failure probability can be determined for specific operating conditions at other locations and times, or combinations thereof, than those on which the standard is based.

The above discussion of risk applies directly to natural phenomena which can affect the performance of electro-optical links of weapon systems. For battlefield phenomena and deliberate phenomena, however, this will not be satisfactory by itself. For these cases, the definitions must be given in terms of a specific battlefield scenario. For battlefield phenomena, and for target signature data, it is suggested that the standard conditions be described in terms of the battle scenario, using statistical concepts similar to those applicable to the data on natural phenomena. For enemy-induced phenomena, an additional factor must be added--that of enemy intent.

3.4 Definitions of Risk

The use of risk based on a time distribution of occurrence applies only to the natural environment. For battlefield- and enemy-induced environments, some measure of probability of occurrence will be necessary other than elapsed time. It is proposed that the criteria for performance be defined as follows:

Natural environment.--The design value will be defined, in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the hours at the most extreme time of day and month in an average year at the most severe location for that element.

Battlefield-induced environment.--The design value will be defined, for a specified scenario, in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the events affecting a weapon element.

Enemy-induced environment.--The design value will be defined, for a specified threat in terms of risk that the extreme will be exceeded, as the value not exceeded for a specified percentage of the events affecting a weapon element.

3.5 Data Requirements

In order to determine the probability of successful performance of the EO links of weapon systems, probability of occurrence data are required on each of the factors which affect the signals. For target recognition, the factors include those which can degrade the signal as it passes through the environment, such as attenuation and scattering, and those which can change the target signature. For passive systems, in which the target emission or

target contrast with respect to the background defines the signature, any environmental condition which can affect the target or the background should be defined and data collected.

Probability of occurrence data can frequently be derived from existing data bases. In many cases, the existing data base is not in the form, or at the wavelength, of interest. In these cases, the desired data must be derived from the existing data base by conversion models.

The problem of converting visible attenuation coefficients to IR attenuation coefficients is discussed in appendix A. Problems associated with deriving visible attenuation coefficients from visibility observations are discussed in appendix B.

The existing statistical base includes climatology information from Air Force (ETAC*) data for visibility, ceiling, cloud cover, rain intensity, snow intensity, and absolute humidity. Smoke obscuration data are available from Smoke Week tests managed by the Project Manager (PM) Smoke/Obscurants. Target reflectivity data for tanks, at 1.06 μm , are available from the U.S. Army Missile Command (MIRADCOM) and ASL. Target signatures for selected tanks are available from an NVEOL data base. A discussion of some of the data available, its quality, and reduced probability distribution functions is given in section 4.

4. NATURAL ENVIRONMENTAL CONDITIONS

The present status of data and analysis in atmospheric conditions is sufficient only to address standard conditions in the natural area. For evaluation of natural conditions, we wished to study weather data and data problems for selected localized areas of Germany rather than compiled data based on wide area averages. Details of weather data are available as daily reports recorded on tape. Arrangements were made with ASL to supply selected data in partially processed form. The area selected for an initial detailed look was the Fulda corridor.

Another environmental effect considered is target signature alteration, in this case the reflectance difference of a tank when wet and dry. Data available were very preliminary; however, the use of that data illustrates how such data can be used.

4.1 Data Package

ASL supplied climatology data of the types listed in table 1.* These data were taken from ETAC data tapes for the nine stations listed in table 2 and shown in figure 1.

*Data package, H. H. Monahan and E. P. Avara, U. S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico.

TABLE 1. NATURAL ENVIRONMENTS

Factors	Climatological information
Visibility	Percentage of frequency of occurrence by month, morning hours, all hours, nine intervals Temperature Relative humidity Absolute humidity reported by visibility interval
Ceiling	Percentage of frequency of occurrence by month, all hours, 11 intervals Temperature Relative humidity Visibility Cloud type reported by ceiling interval
Cloud cover	Percentage of frequency of occurrence by month, all hours, eight intervals Temperature Relative humidity Visibility Cloud type reported by cloud cover interval
Rain intensity	Average hours of occurrence by month Light, moderate, and heavy categories Temperature Visibility reported by rain intensity interval
Snow intensity	Average hours of occurrence by month Light, moderate, and heavy categories Temperature Visibility reported by snow intensity interval
Absolute humidity	Percentage of frequency of occurrence by month, morning hours, all hours, nine intervals Temperature Visibility reported by absolute humidity interval

TABLE 2. WEATHER STATIONS AROUND FULDA

Station	Evaluation (m)
Fulda	305
Bad Hersfeld	212
Wasserkuppe	921
	} Within 25 nm ^a radius of Fulda
Geissen	186
Hanau	112
Kassel	158
Wertheim	338
Wurzburg	259
	} Within 50 nm radius of Fulda

^aNautical miles

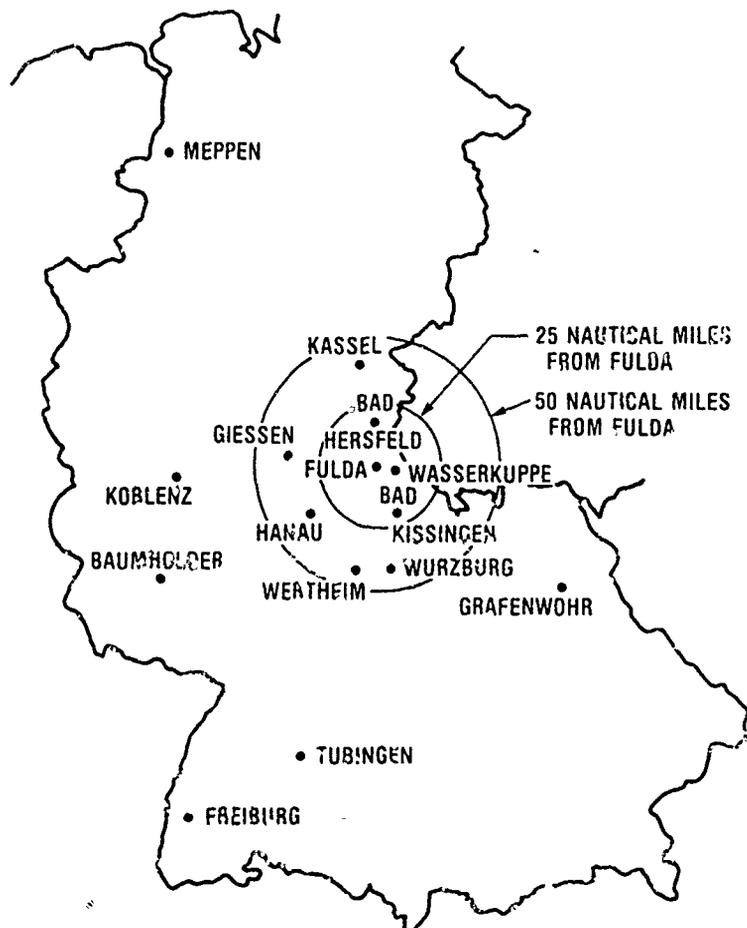


Figure 1. Locations of selected weather stations, Federal Republic of Germany.

Originally, printouts were provided for the Fulda station, for the summation of three stations within 25 nautical miles of Fulda, and for the summation of eight stations within 50 nautical miles of Fulda. These summations were badly distorted by the data from the Wasserkuppe station, which is on a hilltop. This region of Germany has hills and ranges of hills and several weather stations have been built on hilltops. Their climates differ from those of valleys, where weather stations for cities and airports are located. Therefore, additional printouts were provided for Bad Hersfeld, for Wasserkuppe, and for the summation of the seven stations in table 2 less Wasserkuppe.

Regarding other stations in figure 1, Grafenwohr and Baumholder are sites of NVEOL transmission and signature measurements and the GRAF II test. Important rain intensity data have been obtained from the Koblenz and Freiburg stations. The North Atlantic Treaty Organization (NATO) transmission measurement program OPAQUE* stations are at Meppen and Tubingen.

*OPAQUE: Optical Atmospheric Quantities in Europe.

4.2 Visibility Data Collection

In the Federal Republic of Germany, visibility is the most significant natural environmental factor because fog is common and severe enough to seriously degrade the performance of EO links in weapon systems operating in the IR. The problem of scaling visibility data to IR attenuation is discussed in appendix A. Visibility is observed hourly at weather stations, and many data have been collected. Visibility is defined as the range for which the apparent contrast of a high-contrast target is reduced to 2 percent. In this common definition 2 percent is assumed to be the threshold contrast of the human eye. To observe visibility ideally, an experienced observer looks for landmarks that are at known ranges and have sky background; he looks in directions representing his entire circle of observation. The prevailing visibility at German-operated stations is reported as the minimum visibility observed. The prevailing visibility at stations operated by the U.S. Air Force is reported as the greatest visibility that is attained or surpassed throughout half of the horizon circle, not necessarily continuous. The difference between the German and U.S. Air Force observation methods is insignificant for uniform adverse weather conditions. In a uniform fog, all observers would report the same visibility. Our concern here is with the more widespread conditions that would tend toward uniformity locally. However, considerable variability does occur and recent studies are reviewed in appendix B.

Unfortunately, for visibility observations, the ideal situation seldom exists. At a given weather station, it is essentially impossible to have enough targets at enough ranges and directions, all with sky background, in addition to lights for night observations. There are several problems with visibility data collection that must be taken into account to estimate the quality of the data and the probable errors in them.

Visibility is usually measured in a forced-choice situation. That is, the meteorological observer knows where the target is and asks himself the subjective question, "Can I or can I not see it?" But the military observer searching for a target of opportunity asks himself two subjective questions, "Is there a target? If so, where is it?" It is apparent that marginal visibility as reported by meteorologists is not sufficient for target acquisition.

4.2.1 Threshold of Contrast

The physiological basis of the threshold of contrast has received considerable attention. The classic Koshmeider value is 2 percent, although more recent studies indicate that the threshold of contrast can vary from 1 to 5 percent or more.¹² The Koshmeider theory is characterized by a uniform scattering medium, uniform lighting, negligible absorption, exponential decay of transmitted radiation flux, and exponential growth of scattered flux in the path of observation. Under these conditions, flux transmissivity is the same as contrast transmissivity.

¹²W. E. K. Middleton, *University of Toronto Press* (1952).

In a landmark study during World War II, Blackwell¹³ measured the threshold of contrast in a specially constructed laboratory under many different conditions. He established a value for the threshold of contrast as 1 percent for high illumination, well-resolved target, and 50-percent probability of detection. He verified the 2-percent threshold of contrast for high illumination, target well-resolved, and >90-percent probability of detection. In a later outdoor study better representing field conditions, the data scattered considerably, but Blackwell believed that the results of his laboratory study were valid for the field within an error of ± 25 percent.

In contrast, Douglass suggests that 5 percent is better than 2 percent for a threshold of contrast for field conditions.¹⁴ (However, Douglass is concerned mainly with airport runway visibility and is a proponent of transmissometers for instrument measurement rather than visual observation of visibility.)

As an example of the problem, suppose two observers look at the same fog. One observer picks a target at a known range with an apparent threshold of contrast of 2 percent and says that the target is barely visible. The other observer picks another target at a known range with an apparent threshold of contrast of 5 percent and says that the target is barely visible. The difference in the reported visibilities is almost 24 percent.

4.2.2 The Data Package

There is an additional problem with the data as reported in the visibility bins. The minimum increment reported is 0.1 km. The visibility bins as reported include data from the lower limit up to but not including the upper limit. Thus, the 0- to 0.1-km visibility bin contains all "zero" visibility cases. Another problem is that a "no data" observation and a "visibility of less than 0.1 km" are both reported as "0-km visibility." Significant percentages of the data in many cases are in the 0- to 0.1-km bin. These parts of the data must be used with care and with a full appreciation of the limitations caused by including "no data" reports in this bin.

There are insufficient night data. In the seven-station summation for the hours from 2400 to 0500, there are 250 to 1200 observations per month (the number varying from month to month). For the hours 0600 to 1200, there are 1200 to 1900 observations per month. Only morning hours are summarized for analysis. Thus, the overall average for the seven-station summation is 1180 observations per month for each hour out of a possible 2100 observations for a 30-day month over the 10-year period of summation.

Considering the problems with visibility observation, little better can be done than to consider Blackwell's suggestion for a ± 25 percent probable error. To this must be added an allowance for the minimum increment reported, which is 0.1 km. Therefore, it is suggested that the estimated error on the visibility data may be regarded to be ± 25 percent ± 0.1 km.

¹³H. R. Blackwell, *Contrast Thresholds of the Human Eye*, *J. Opt. Soc. of America*, 36, 11 (November 1946).

¹⁴C. A. Douglass, *Visual Range*, National Bureau of Standards Monograph 159, Government Printing Office (1977).

4.3 Fulda Area Natural Environment

4.3.1 Visibility

Samples of the data for seven stations averaged and for Wasserkuppe are discussed here from the standpoint of standard conditions, including sun, cloud, haze, fog, rain, and snow. The visibility data were taken from the ETAC data tapes and arranged in bins of 0 to <0.1 km, 0.1 to <0.2 km, 0.2 to <0.5 km, and so on as indicated on the abscissas of the figures. The numbers reported are the percentages of the total number of observations for the conditions stated. These are plotted as the cumulative frequency of occurrence to the upper bin boundary.

In figure 2, visibility for all hours is shown for the worst and best months. October is the worst month, with low visibility (<2 km), and January is the worst month for visibility of >2 km. July is the best month. (For most stations, the June and July visibility curves are almost identical.)

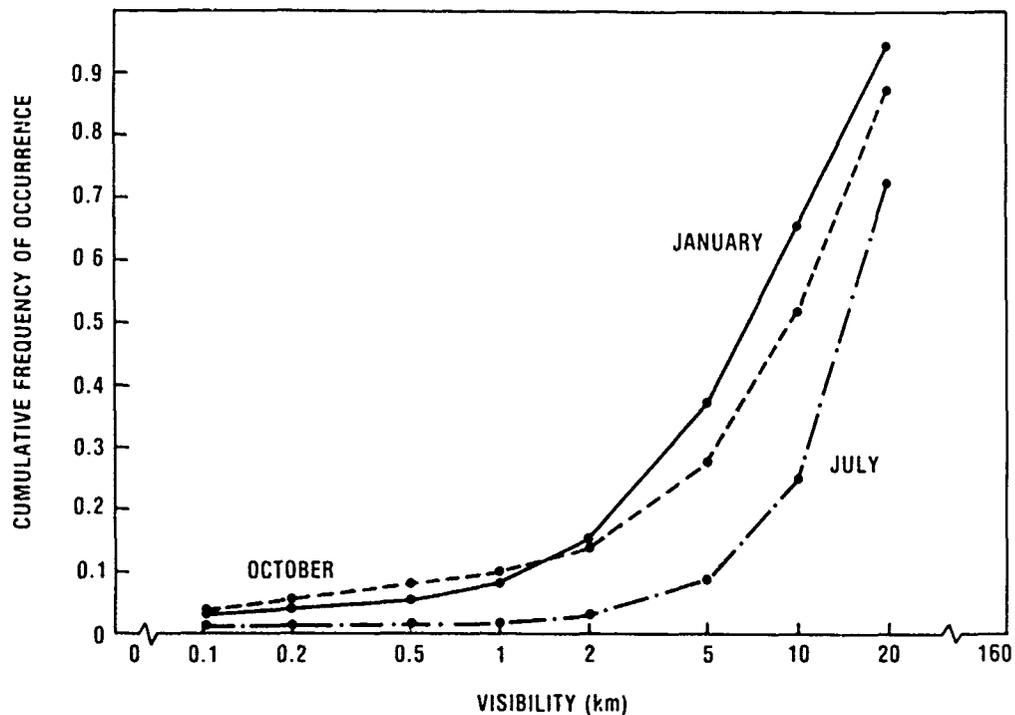


Figure 2. Visibility versus frequency of occurrence, by month, seven-station average, all hours.

Figure 3 shows the same type of data for the hours 0600 to 0800. For these morning hours, September is the worst month. In January, the increase in frequency of occurrence is small, but January still is the worst month for visibility of ≥ 10 km. July is the best month, but for morning hours there is a substantial increase in the frequency of occurrence in all the bins.

In figures 4 and 5, the same data as in figures 2 and 3 are shown for the lower end of the curves on an expanded scale. Error bars based on the estimated error (± 25 percent, ± 0.1 km) are shown for the worst month curves. These error bars apply to all the visibility curves and indicate that the errors are too large to estimate risk for visibilities of < 0.5 km. Therefore, the risk factors based on these data are stated for a visibility of only 0.5 km.

From figure 4, the risk of encountering visibility of ≤ 0.5 km for the seven-station average during the worst month (October) for all hours is 8 percent, with a spread of 7 to 10 percent. From figure 5, the risk of encountering visibility of ≤ 0.5 km for the seven-station average during the worst month (September) for morning hours is 20 percent, with a spread of 18 to 22 percent.

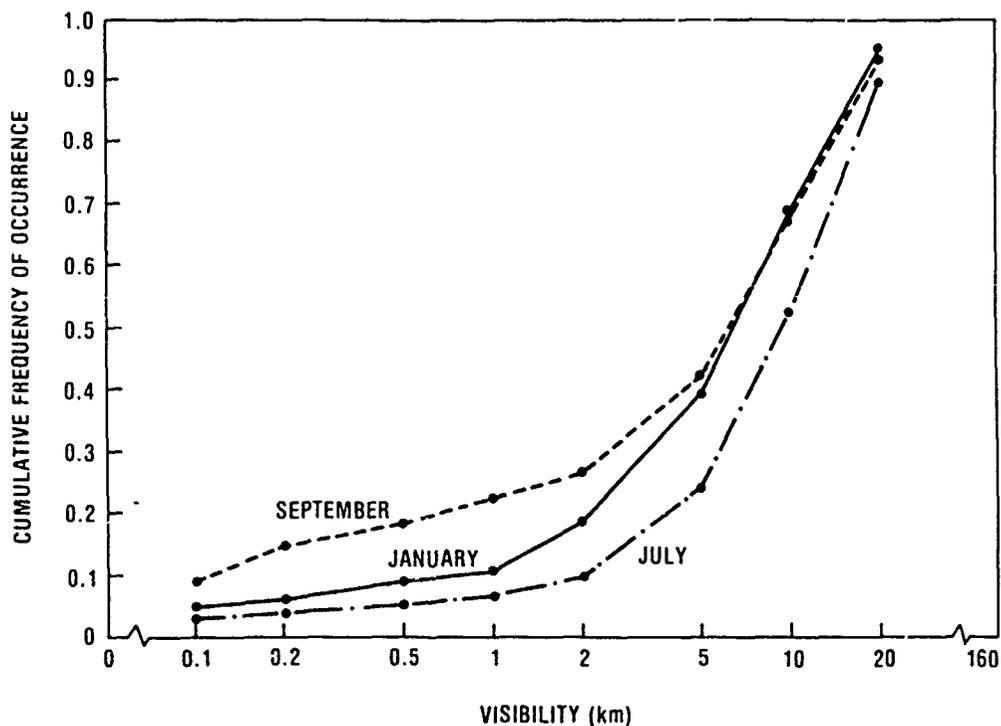


Figure 3. Visibility versus frequency of occurrence, by month, seven-station average, morning hours (0600, 0700, 0800).

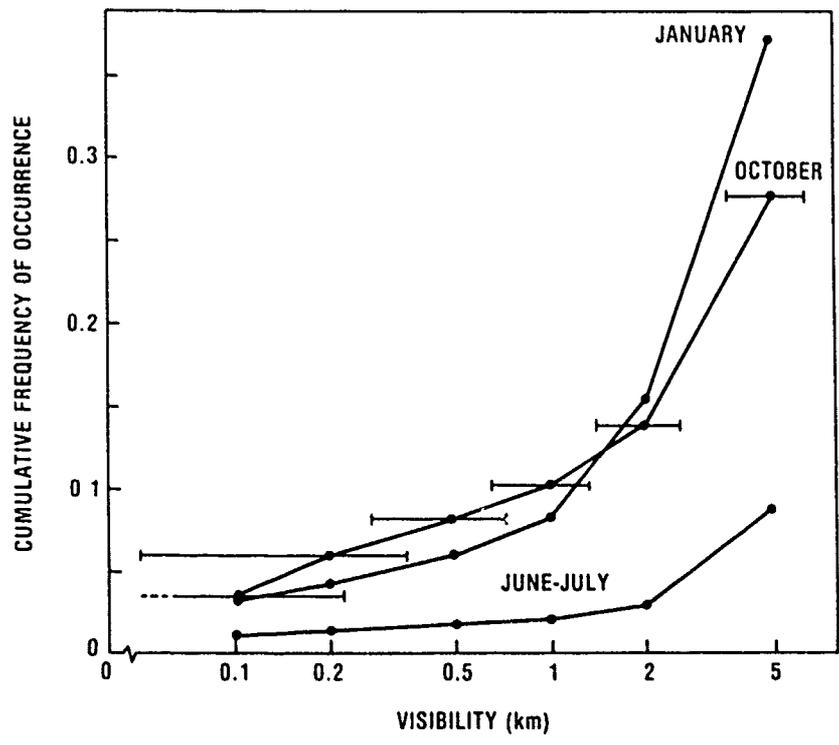


Figure 4. Visibility versus frequency of occurrence, worst months, best months; seven stations, all hours.

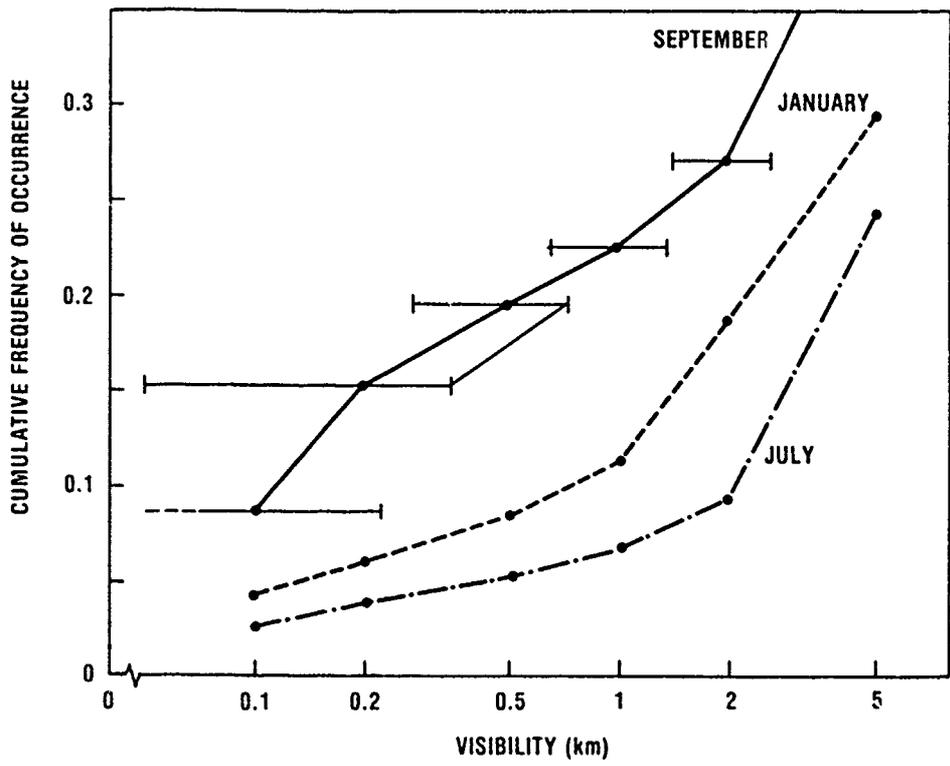


Figure 5. Visibility versus frequency of occurrence, worst months, best months, seven stations, morning hours (0600, 0700, 0800).

In figure 6, visibility data are shown for Wasserkuppe, the hilltop station that is 600 to 800 m higher than the other seven stations. The pattern is quite different, with nearly 50 percent of the December data in the first bin. The same estimated errors apply. Although error bars are not shown, the risk of encountering visibility of ≤ 0.5 km for Wasserkuppe during the worst month (December) for all hours is 60 percent, with a spread from about 57 to 61 percent. There is little difference for the morning hours, not more than an additional 1 percent. July is the best month: the risk of visibility of ≤ 0.5 km for all hours is 19 percent. July morning hours are substantially worse: the risk of visibility of ≤ 0.5 km is 33 percent.

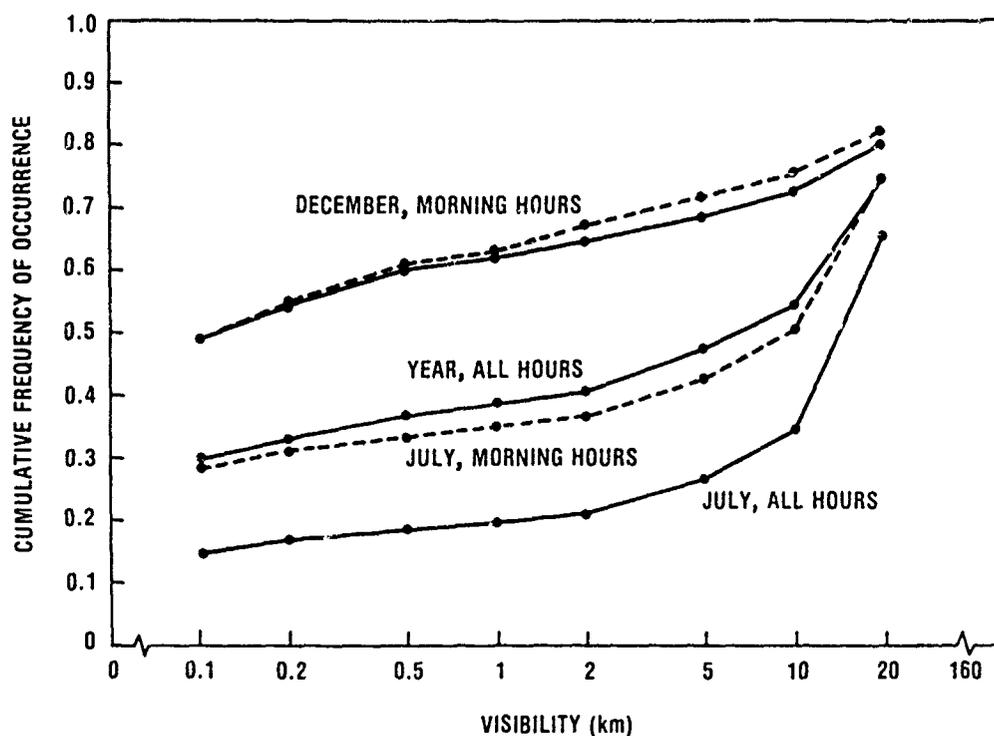


Figure 6. Visibility versus frequency of occurrence, Wasserkuppe. Data are for worst month and best month, all hours and morning hours (0600, 0700, 0800). Also, the yearly average, all hours, is given.

In figure 7, several possible criteria for selecting standard conditions can be compared. The worst location for the worst month is hill-top-site Wasserkuppe in December with a 60-percent risk of visibility of ≤ 0.5 km. For the lowland seven-station average for the worst month and worst hours, the risk is 19 percent. For the seven-station average for the worst month and all hours, the risk is 8 percent.

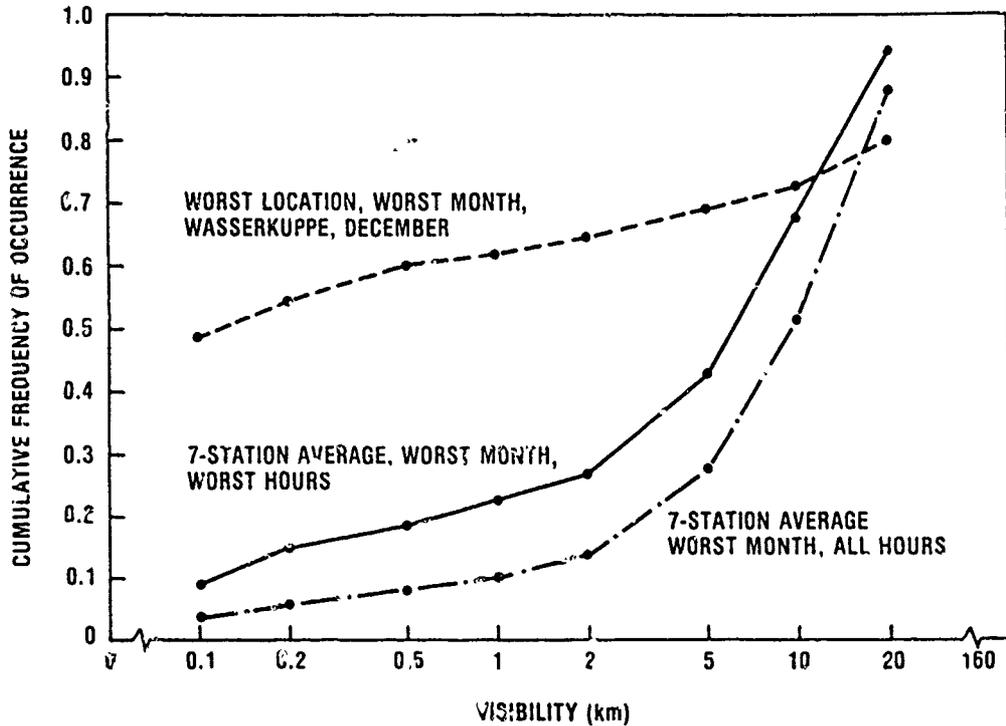


Figure 7. Visibility versus frequency of occurrence, comparison of extreme cases.

4.3.2 Ceiling and Cloud Cover

Data are shown in figure 8 for a low ceiling, the lowest height above the ground at which all cloud layers at or below that level cover more than half the sky. No estimate has been made of errors, so the data are used in raw form. The hilltop station has a different pattern from the lowland stations. The worst location for the worst month is Wasserkuppe in December with, for example, a risk of 53 percent of ceiling of ≤ 0.3 km. For the seven-station average, the worst month is December, with a risk of 16 percent of ceiling of ≤ 0.3 km. For the yearly seven-station average, the risk is about 7 percent.

A problem with ceiling data is their relationship to low surface visibility data. Ceiling is obscured by surface conditions such as fog. However, surface fog can grade into cloud as is the case with vertical profile conditions such as measured by Pinnick.¹⁵ The ceiling observations as reported by RTAC provide no insight into the vertical profile problem.

¹⁵R. G. Pinnick, J. D. Lindberg, and E. B. Stenmark, *Vertical Inhomogeneity in Wintertime Atmospheric Fog and Haze in West Germany and the Effects on IR Transmission*, IRIS, 21, Atmospheric Sciences Laboratory, White Sands Missile Range, NM (August 1977).

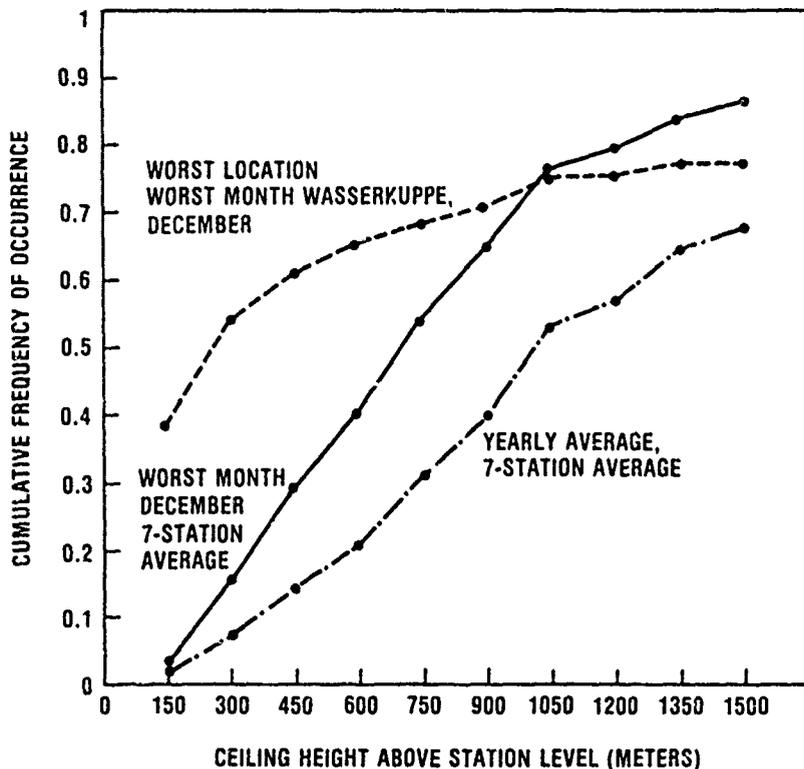


Figure 8. Frequency of occurrence versus ceiling height.

4.3.3 Rain Intensity

In the ETAC data, rain rate has been interpreted according to reported rain intensity, that is, light (from a trace to 3.5 mm/hr), medium (3.5 to 7.5 mm/hr), and heavy (>7.5 mm/hr). For rain rate, the 0.5-percent extreme is the suggested risk factor in MIL-STD-210B. Wasserkuppe in May is the worst location for the worst month with 7 mm/hr representing the 0.5-percent extreme (fig. 9). For the yearly seven-station average, 5 mm/hr represents the 0.5 percent extreme. The Koblenz data¹⁶ were a continuous record (equipment was not described) with time resolution sufficient to measure a 4-min average. These data indicate that 3 mm/hr represents the 0.5-percent extreme.

Rain intensity extremes reported by Niedringhaus¹⁷ match ETAC extremes fairly well. Reading from Niedringhaus's charts for central Germany in July, the 1-percent extreme is 3 mm/hr, the 0.5-percent extreme also is 3 mm/hr, and the 0.1-percent extreme is 18 mm/hr.

¹⁶A. L. Sims et al, *Climatology of Instantaneous Precipitation Rates*, Illinois State Water Survey, Air Force Cambridge Research Laboratories AFCRL-TR-73-0171 (1973). AD760785

¹⁷T. E. Niedringhaus, *Distribution of Mean Monthly Precipitation and Rainfall Intensities*, U. S. Army Engineer Topographic Laboratories, FT Belvoir, VA (November 1972).

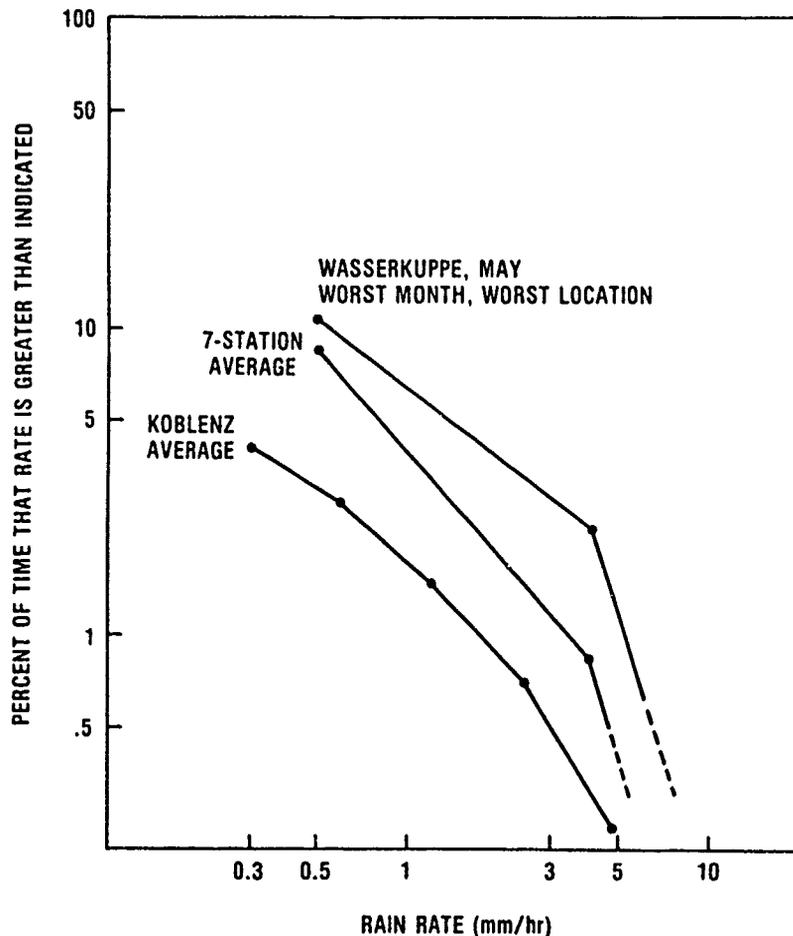


Figure 9. Frequency of occurrence versus rain rate.

4.3.4 Snow Intensity

Snow rates are reported as the percentage of 1-hr or 3-hr observations with light, moderate, or heavy snow. These rates have been interpreted as equivalent to rain rates. Wasserkuppe in December is the worst location for the worst month with a 0.5-percent extreme of about 4.5 mm/hr (fig. 10). For the seven-station average, December is the worst month with a 0.5-percent extreme of about 3.5 mm/hr. The five-month average is slightly lower.

4.3.5 Absolute Humidity

Absolute humidity is an important factor for evaluating how thermal imaging devices and NMMW systems will perform in clear weather. Absolute humidity data are shown in figure 11 for the seven-station average. January has the lowest and February and December are almost identical to it in absolute humidity. July has the highest absolute humidity and August is

almost identical to it. The 10-percent low humidity extreme occurs in January and is equivalent to about 2.5 g/m^3 . The 10-percent high humidity extreme occurs in July and is equivalent to about 13.5 g/m^3 . An average for summer is 10 g/m^3 .

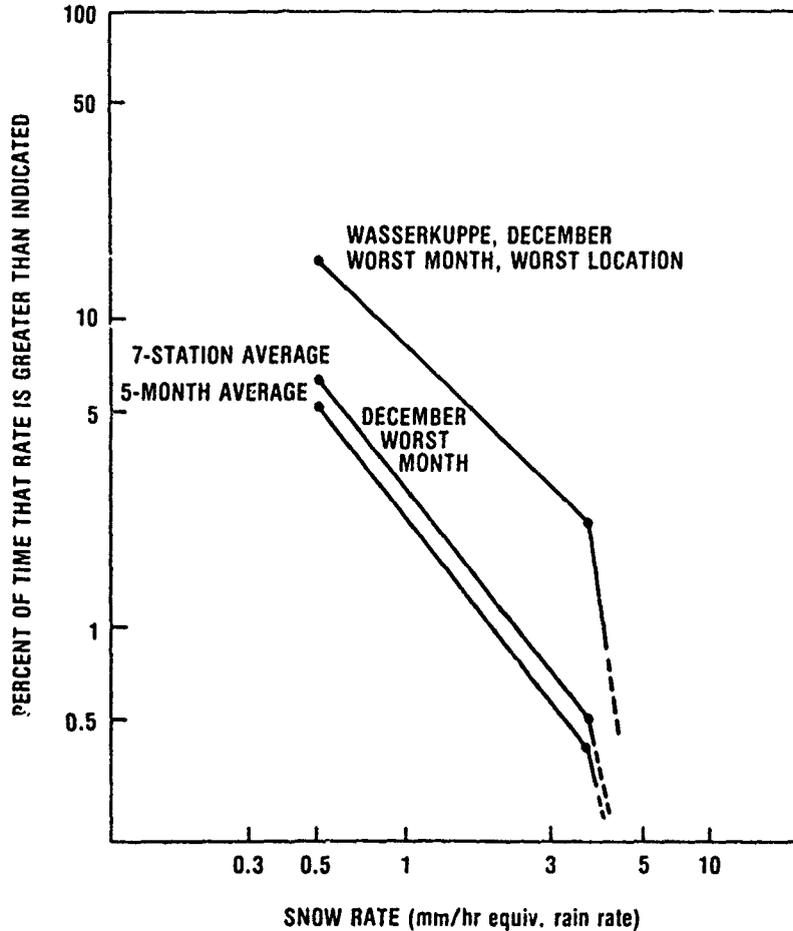


Figure 10. Frequency of occurrence versus snow rate.

4.4 Composite Effects

Figures 12 and 13 are samples of data on other parameters correlated with the visibility data for selected months. For each visibility bin, the data on the other parameters were grouped.

The temperature increases gradually with increasing visibility, as expected. No correlation between absolute humidity and visibility is apparent. Relative humidity, however, increases to essentially 100 percent with very little spread for low visibility. The exception is the lowest bin,

which contains all 0's. These 0's are assumed to indicate visibility of <0.1 km, but some 0's indicate "no data" due to incapacity of the computer used in decoding the applicable format established in the original data base. These "no data" observations cause random data on the correlated parameters to fall into the lowest bin. Therefore, the departure of the relative humidity from 100 percent and the spread of the data indicate the number of "no data" points that are mixed with valid data.

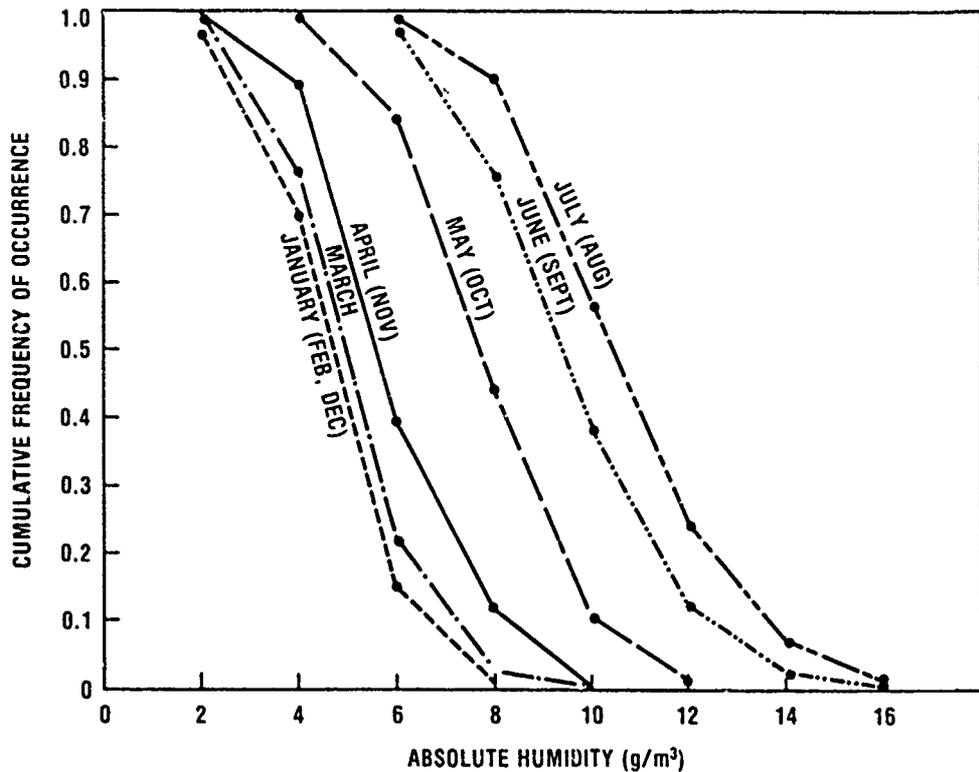


Figure 11. Frequency of occurrence of absolute humidity greater than that indicated, by month, all hours, seven-station average.

Because of the problems with collecting visibility data and therefore the difficulty of relating them to data for ceiling, cloud cover, rain and snow intensity, and absolute humidity, we recommend giving up and going home.

4.5 Target Signatures

Battlefield conditions affect target signatures, not only because of reduced atmospheric transmission, but also by changes in the signatures themselves. Armored vehicles are usually painted with low reflectance paint and their reflectance is frequently changed due to dust or mud coating. The angular scattering characteristic of energy reflected from a target (important to the operation of LTH weapons) is greatly affected by wet surface conditions, with wet surfaces having a larger specular component of reflectance.

Snow, ice, dust, mud, soot, spilled oil, etc., are other battlefield conditions that can affect reflectance. For night sights, the thermal contrast is affected by all types of precipitation. Ground moisture has an effect on operations since heated tracks are a major part of the thermal signature. Surface effects, such as mud and dirt, can be expected to have relatively little effect on thermal signatures. However, visual or near IR contrast (for TV or image intensifier devices) are greatly affected by mud, dust, dirt, or anything that can change surface color or contrast. Visual and near IR contrast are affected by wet-dry conditions. Snow, either on the ground or on the target, will greatly affect tank vehicle visual contrast.

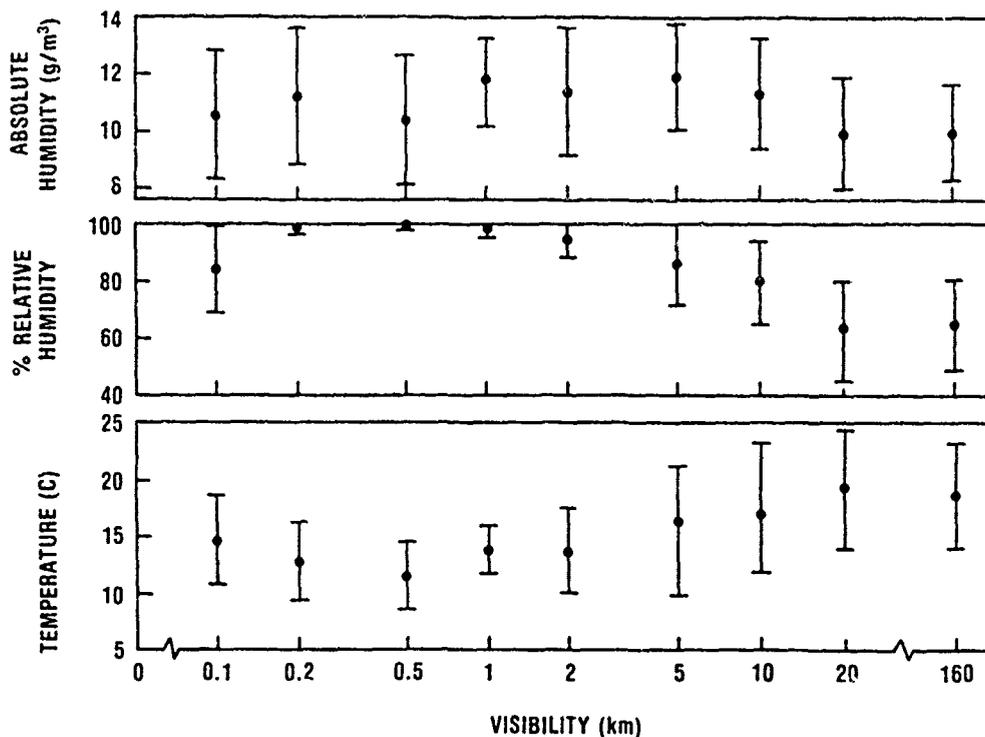


Figure 12. Visibility versus meteorological parameters, Fulda, July, all hours (● = average value and | - | = standard deviation).

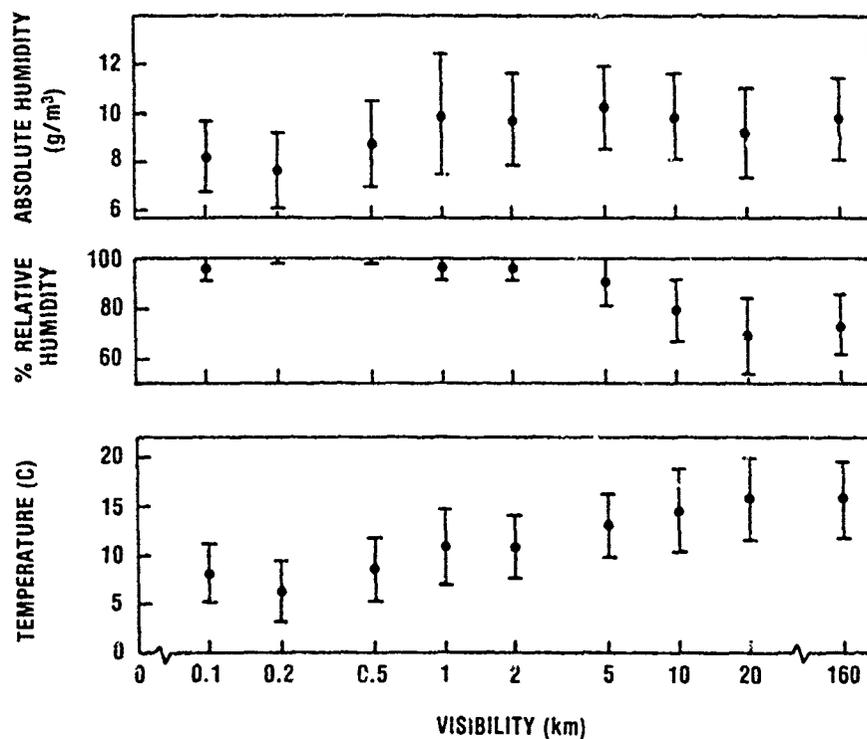


Figure 13. Visibility versus meteorological parameters, Fulda, September, all hours (● = average value and |—| = standard deviation).

4.6 Target Reflectance

A series of measurements of reflectance were made by MIRADCOM to evaluate the angular reflectance effects (or specular reflectance) of an LTH weapon engaging an armored target (an M48 tank) under clean dry and wet conditions.* The test geometry was designed such that the Ground-Located Laser Designator (GLLD) would be at a realistic battlefield distance of 2.277 km from the target. Radiometers were positioned on each side of the range center line from minus 30 deg, through zero, to plus 60 deg. The M48 tank was located approximately 200 m from trees, bushes, or other obstructions above the ground plane. Thus, the scattering from any foreign objects could be held to a minimum. The radiometers were positioned approximately four feet above the ground plane. Reflectance values were determined by direct comparison with a 4 x 8 ft target board painted with 12-percent reflectance paint. A discussion of reflectance conventions can be found in appendix C.

Twelve data points for dry and 12 for wet were grouped together (although various angles are represented) and are plotted in figure 14 as cumulative frequency of occurrence of bidirectional reflectance. The dry tank exhibited lower reflectance than the wet tank, but the difference is small.

*Private communication from G. Widenhofer, H. Anderson, Advanced Sensor Directorate, MIRADCOM.

The traditional value used for bidirectional reflectance is 5 percent, and it is used as is done here, with no angular adjustments. Three of the data points (two dry and one wet) lie below that value. Thus, a 5-percent reflectance represents, judging from these limited data, approximately a 20-percent risk factor for the dry tank and 15-percent risk factor for the wet tank.

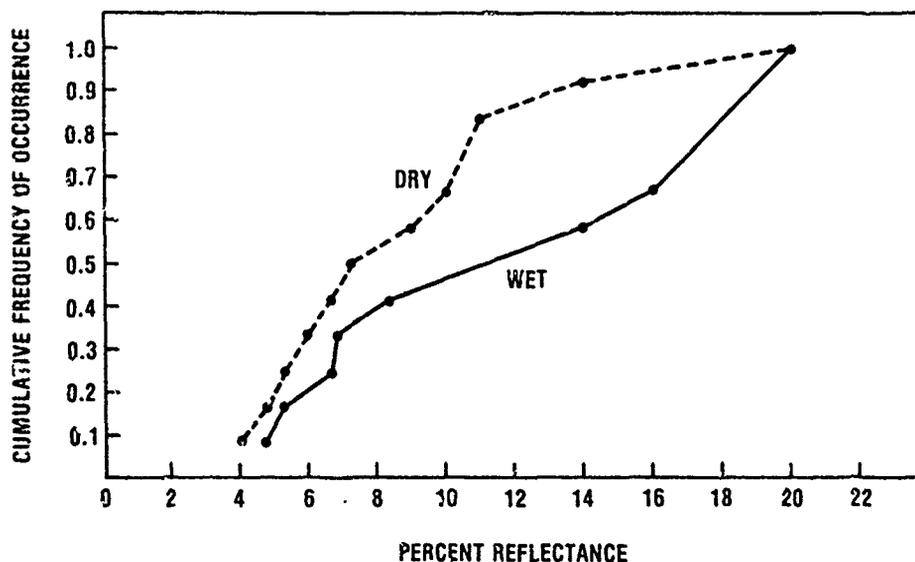


Figure 14. Bidirectional reflectance, M48 tank; reflectance angular range: 0 to 60 deg.

5. STATUS OF CURRENT EFFORTS

The earlier sections of this report review criteria for establishing standards for environmental conditions for training, R&D, and analysis. The proposed standards are based on risk of occurrence of an extreme condition and are similar to methodology used in other standardization efforts. The criteria selected can be extended to natural, battlefield-induced, and enemy-induced factors that degrade the performance of EO links in weapon systems.

5.1 Natural Environment

For the natural environment, climatology data for central Germany have been evaluated. Data have also been received for the northern German plains and have many similarities. Needed interfaces with other activities have been identified: the Electro-Optical Systems Atmospheric Effects Library (EO SAEL), the Optical Atmospheric Quantities in Europe (OPAQUE) program,^{18,19} and the Regional Environments Branch of Engineer Topographic Laboratories (ETL).

¹⁸R. W. Fenn, *OPAQUE, A Measurement Program on Optical Atmospheric Quantities in Europe, Vol I, The NATO OPAQUE Program, Air Force Geophysical Laboratories AFGL-TR-78-0011 (January 1978).*

¹⁹T. S. Cress and R. W. Fenn, *Climatology of Atmospheric Aerosols in Europe, Project OPAQUE, Proceedings of the SPIE, 142, Optical Properties of the Atmosphere, 30-31 March 1978, Washington, D.C.*

The Atmospheric Sciences Laboratory EO SAEL program holds validated user models and computer codes that can be used with confidence to determine the effects of the battlefield-induced environment on EO and NMMW weapon systems or sensors. Environments include natural weather (clear air, cloud, fog, haze, rain, and snow) and battlefield- and enemy-induced contamination (dust and smoke). The interim version of EO SAEL is oriented for the user, works with analytical fits and simplified algorithms, and will be backed up by more complete, first-principle-oriented computer simulations of battlefield-induced environments. It will provide for the use of processed ETAC data tapes of meteorological conditions at selected reporting sites.

The OPAQUE program is the North Atlantic Treaty Organization program of atmospheric measurements at 12 European stations. The two German stations and the Netherlands station represent stations of central and northern Germany. Only a small amount of data from the Netherlands station had been available by early 1979; however, additional data have been passed to an ASL contractor, Science Applications, Inc., for analysis. In the OPAQUE program, extinction coefficients are measured regularly in the visible and in several IR bands, as well as with standard meteorological observations. These data will provide independent statistics on occurrence of low visibility and long-wave IR transmission. The availability of such data will help resolve the wavelength scaling problem.

ETL is the Army agency charged with writing standards documents including AR-70-38. Also it is the Army liaison with the standards effort at the Air Force Geophysical Laboratory, MIL-STD-210B. This report will be transmitted to ETL for possible incorporation of proposals into the standards documents.

An additional interface is the Battlefield Environment Obscuration Handbook. This handbook is being compiled by AMSAA and TRASANA and will provide obscurants information.

For signatures, NVEOL's program primarily measures thermal contrast of targets. Signature data indicating environmental sensitivity are limited. Reflectivity data indicating environmental sensitivity also are limited from NVEOL and also from MIRADCOM measurements. Some of these data are in raw form. Analysis is necessary to evaluate the data and to express them in a common format.

5.2 Battlefield- and Enemy-Induced Environments

In the battlefield- and enemy-induced environments, the characteristics of tactical smoke have been measured. Several models are in development or use. Validation of models is a much discussed subject. In general, the status of validation is unsatisfactory. One difficulty is the use of a normal distribution model of diffusional cloud growth. In reality, turbulence due to thermal pluming and to wind eddies affects cloud growth by producing highly nonuniform distributions and holes, which the models do not indicate. Important data are available from the Smoke Week test conducted by PM Smoke/Obscurants. Much analysis is needed to reduce these and other data and to compare them with modeling efforts.

For incidental smoke and dust, important data have been generated thought the Smoke Week test, GRAF II, and other tests. A great analysis effort is needed to evaluate the environment and EO weapon performance.

5.3 Comparisons with Other Efforts

A comparison can be made between values for natural factors selected by Hock²⁰ from literature sources for his Carmonette study and values taken from the present study. In table 3, selected data of natural factors can be compared. Typical visibility has 20-, 50-, and 80-percent cumulative frequencies of occurrence. The two sources of data agree reasonably well for lower visibilities, but differ greatly for high visibility. Hock reports few observations of >10 km for good visibility. The ETAC data, however, report many visibilities of >10 km. For example, 30 to 80 percent of the data in figure 2 is reported as ≥ 10 km and 5 to 30 percent is reported as ≥ 20 km.

A visibility of 0.5 km was suggested by Hock as a low-visibility standard condition for modeling. Because of problems with the data, 0.5 km is the lowest visibility for which extremes can be evaluated with the ETAC data base. The extreme risk factors are listed in table 3 for several situations.

Hock suggests values for mid-latitude absolute humidity. The winter value of 3.6 g/m^3 represents a 23-percent low humidity extreme. Perhaps more significant is the summer value of 14 g/m^3 , which represents a cumulative frequency of occurrence of 95 percent in July or a high humidity extreme of 7 percent. That is, in the worst location and month, humidity exceeds the stated value 7 percent of the time.

For rain rate, Hock's suggested value is 4 mm/hr, which represents an 0.8-percent high extreme based on the seven-station average (fig. 9). This extreme is close to 0.5 percent, which is the basis for existing standards. For snow rate, Hock's suggested value of 2 mm/hr (rain equivalent) represents a 1-percent extreme. However, at Wasserkuppe in December, that rate is exceeded 5 percent of the time. Snow rate and snow accumulation are both much greater at the hilltop station than in the seven valley stations.

5.4 Status Summary

The principal result of this study for setting standards for environmental conditions has been to clarify the methodology and the interfacing requirements for the tasking. The effort was more complex than realized at the time of the tasking. The present status of data and analysis at atmospheric is sufficient only to address standard conditions in the natural environment, with some additional capability in tactical smoke for the battle-field- and enemy-induced environments. This report largely verifies Hock's recommended values for natural parameters. Development of the backup data base for a larger set of standard conditions depends on coordination of the

²⁰H. E. Hock, *Degraded Environment Modeling in High Resolution Ground Combat Simulations (U)*, U.S. Army Concepts Analysis Agency CAA-TP-78-2 (May 1978). (SECRET)

Army's atmospheric community. Earlier, this development was carried out by working groups such as the Smoke/Aerosol Working Group and the EO Sensors Atmospheric Optics Working Group. Recently, meetings on the obscurants tasks and the DoD Atmospheric Transmission Plan have served as working groups and have included ERADCOM agencies, AMSAA, TRASANA, Headquarters TECOM, PM Smoke/Obscurants, the Corps of Engineers, and others. The current effort is adding the user and the testing agencies: TRADOC, Combat Developments Experimental Center, FT Ord, CA (CDEC); CACDA; and Test and Evaluation Command (TECOM). The good working relationship and dialogue should develop final standards for environments in which EO links in weapon systems perform.

TABLE 3. ENVIRONMENTAL DATA FOR NATURAL FACTORS

Factor	Data		
	Hock ^a	ETAC ^b	
		Wasserkuppe	Seven-station average
Visibility			
Typical			
Cumulative frequency of occurrence			
20%			
January	2.3	--	2.5
Spread	1.9 to 2.8	--	1.8 to 3.2
50%			
January	5.2	--	6.0
Spread	4.0 to 6.4	--	4.4 to 7.6
80%			
January	7.0	--	14
Spread	6.3 to 7.7	--	10.4 to 17.6
0.5 km			
October, all hours	--	--	8% (risk factor)
September, morning hours	--	--	20%
December, all hours	--	60%	
Absolute humidity			
Winter	3.6 g/m ³	--	23% (January)
Summer	14 g/m ³	--	93% (July) or 7% high extreme
Precipitation			
Rain rate	4 mm/hr	--	0.8%
Snow rate (equivalent rain)	2 mm/hr	5% (December)	1%

^aH. E. Hock, U.S. Army Concepts Analysis Agency CAA-TP-78-2 (May 1978). (SECRET)

^bEnvironmental Technical Applications Center, Scott AFB, IL.

~~CONFIDENTIAL~~

ACKNOWLEDGEMENTS

The authors wish to thank Robert W. Tucker for preparation of Appendix B, and also Dominick A. Giglio and Zoltan G. Sztankay for technical review and many helpful suggestions.

ACRONYMS

AR	Department of the Army regulation
AMSAA	U.S. Army Materiel Systems Analysis Activity
ASL	U.S. Army Electronics Research and Development Command, Atmospheric Sciences Laboratories
APC	Armored personnel carrier
AFGL	Air Force Geophysical Laboratory
BR	Beam-rider
CLOS	Command to line of sight
CDEC	U.S. Army Combat Development Evaluation Command
CAC	U.S. Army Combined Arms Center
CACDA	U.S. Army Combined Arms Center, Combat Development Activity
DARCOM	U.S. Army Materiel Development and Readiness Command
DRCBSI	U.S. Army DARCOM Battlefield Systems Integration Directorate
EO SAEL	Electro-Optical Systems Atmospheric Effects Library
ETL	U.S. Army Engineer Topographic Laboratories
ETAC	U.S. Air Force Environmental Technical Applications Center
ERADCOM	U.S. Army Electronics Research and Development Command
EO	Electro-optics or electro-optical
FOV	Field of view
GLLD	Ground laser locator designator
HE	High explosive
INSCOM	U.S. Army Intelligence and Security Command
IR	Infrared
LOS	Line of sight
LTH	Laser terminal homing
MIRADCOM	U.S. Army Missile Command

ACRONYMS (Cont'd)

NATO	North Atlantic Treaty Organization
NIR	Near infrared
NMMW	Near millimeter wave
NVEOL	U.S. Army ERADCOM Night Vision and Electro-Optics Laboratory
OPAQUE	Optical Atmospheric Quantities in Europe
PM	Project manager
TECOM	U.S. Army Test and Evaluation Command
TRADOC	U.S. Army Training and Doctrine Command
TRASANA	U.S. Army TRADOC Systems Analysis Activity
WWII	World War II

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APPENDIX A.--EXTINCTION COEFFICIENT MODELS

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CONTENTS

	<u>Page</u>
A-1. INTRODUCTION	55
A-2. HAZE, FOG, AND CLOUD MODELS	55
A-3. RELATIONSHIP OF EXTINCTION COEFFICIENTS FOR VISIBLE AND 8- TO 12- μ m REGIONS	59
LITERATURE CITED	64

FIGURES

A-1. Extinction coefficients for cloud, haze, and fog: models (X) and data	61
A-2. Extinction coefficients for cloud, haze, and fog: additional models and data	62
A-3. Extinction coefficients for cloud, haze, and fog: additional models and expanded distribution of data	63

TABLES

A-1. Haze, Fog, and Cloud Models	56
A-2. Extinction Coefficients of Haze and Smoke	58
A-3. Extinction Coefficient Cloud Models	59
A-4. Extinction Coefficients of Cloud and Haze	60

A-1. INTRODUCTION

A fundamental problem area in defining standard environmental conditions is in the wavelength variation of the extinction coefficient and other optical parameters of aerosols. In natural haze and fog, the only parameter regularly included in meteorological reports is visibility. Electro-optical (EO) devices and weapon systems can use visible sights in addition to sights and guidance links operating at a variety of infrared (IR) wavelengths. The fraction of time such EO links are operable depends on the probability of occurrence of aerosol environments that affect them. An objective of atmospheric studies is to relate the probability of occurrence of such aerosol environments to the available data on visibility. The present status of these efforts is reviewed in this appendix.

The problem considered here is prediction of optical parameters at longer wavelengths when the visibility, or rather the photopic extinction coefficient (σ_{phot}), is known. Special problems with visibility observations as they are made in the field are discussed elsewhere. Several well-known models for haze, fog, and cloud are examined. These range from purely theoretical estimates of drop size distribution and calculation of the corresponding optical parameters to empirical distributions and attempts to hypothesize wavelength scaling laws. A comparison is made with some existing measurements. Only the variation of extinction coefficients in the visible and 8- to 12- μm regions is considered.

A-2. HAZE, FOG, AND CLOUD MODELS

In table A-1, selected properties of haze, fog, and cloud models are listed. Hazes M and L and clouds C.1, C.2, and C.3 are Deirmendjian¹ models and have distributions of the general form

$$n(r) = ar^{\alpha}e^{-br^{\gamma}} ,$$

where $n(r)$ is the number density of particles of radius r . The constants a , α , b , and γ determine the particle density, N ; the mode radius, r_c (which may be expressed as number mode radius or as mass mode radius); and other features of the distribution. Deirmendjian has tabulated extinction coefficients, σ , and normalized phase functions that determine the volume scattering function, $\beta(\theta)$, for numerous wavelengths using complex indices of refraction for liquid water found in the literature.

The calculated extinction coefficients apply only to the aerosol. The absorption considered is liquid water or solution absorption. No water vapor absorption or absorption by other atmospheric gases is considered here.

¹D. Deirmendjian, *Electromagnetic Scattering on Spherical Polydispersions*, American Elsevier Publishing Co, Inc., New York (1969).

APPENDIX A

TABLE A-1. HAZE, FOG, AND CLOUD MODELS

Distribution	Density (particles/cm ³)	Visual range (km)	Mode radius (μ m)	Concentration (g/m ³)	Remarks
Haze M	100	37	0.05	4.95×10^{-5}	Has marine or coastal distribution
	369	10	0.05	1.8×10^{-4}	Has marine or coastal distribution
	10,000	--	0.05	0.05	Resembles white phosphorous smoke
Haze L	100	89	0.07	1.17×10^{-5}	Has continental distribution
	10,000	--	0.07	0.012	Resembles hexachloroethane smoke
Cloud C.1	100	0.240	4.0	0.0626	--
	606	0.040	4.0	0.38	Resembles stratus II and dense fog
Cloud C.2	100	0.346	4.0	0.0302	--
Cloud C.3	100	1.32	2.0	0.00377	--
Nimbostratus	330	0.030	3.5	1.34	--
Fair weather cumulus	300	0.186	3.5	0.072	Standard weather code, low cloud type 2
Stratus II	260	0.039	4.5	0.71	Representative of stratus deck over land; resembles dense fog
Cumulus congestus	207	0.057	3.5	--	--

The particle density used in these calculations was arbitrarily chosen to be 100 particles/cm³. This number may be adjusted as needed with the extinction coefficients, the concentration (C), and the volume scattering function being proportional. The normalized phase functions are not affected by adjustment of N.

The haze M, representative of marine or coastal haze, with N of 100 particles/cm³, represents a clear condition and is of little concern in regard to degraded performance of EO equipment. With N increased to 369 particles/cm³, the visual range is 10 km, and N represents a small particle selective haze, selective in the sense that long wavelength attenuation is much less than visible attenuation.

The haze M, with greatly increased particle density (10⁵ particles/cm³), resembles the distribution typical of white phosphorous (WP) smoke.^{2,3} Haze L represents a continental distribution with fewer large particles than haze M. With greatly increased particle density, haze L resembles the distribution more typical of hexachloroethane (HC) smoke.

²Z. G. Sztankay, R. Humphrey, and H. Smalley, *Backscatter Measurements at November 77 Smoke Week Test (U)*, in *Project Manager Smoke and Obscurants DRCPM-SMK-T 002 78*, Aberdeen Proving Ground, MD (April 1978). (CONFIDENTIAL)

³E. Bowman and J. Steedman, *Smoke Week-1 EO Systems Performance in Characterized Smoke Environments at Dugway Proving Ground, UT, November 77 (U)*, in *Project Manager Smoke and Obscurants DRCPM-SMK-T 002 78*, Aberdeen Proving Ground, MD (April 1978). (CONFIDENTIAL)

Cloud C.1 is of greater interest with N increased to 606 particles/cm³ for visible range of 40 m. This adjusted model resembles stratus cloud and dense fog. Clouds C.2 and C.3 represent progressively narrower distributions with fewer large particles. Their properties grade toward the hazes.

The next series of cloud models is of empirical origin resulting from the survey by Carrier et al⁴ of *in situ* distribution measurements. The models listed represent clouds that may interfere with EO weapon systems that are air launched, have high trajectories, or are launched against airborne targets. All the cloud models listed, except fair weather cumulus, can occur at altitudes as low as a few hundred meters. Stratus II represents stratus deck over land and can occur also as upland fog. Such occurrence is common in the Appalachian ridges of the eastern United States, where it is usually identified as frontal fog. The same effect is common on hills and ridges of central and southern Germany.

In table A-2, extinction coefficients are listed for hazes M and L, and these can be compared with the properties of WP and HC smoke.⁵ For haze M, extinction coefficients are listed for N = 100 and for the concentrations increased 1000 times. The values of the extinction coefficient are simply reproduced with the units changed from inverse kilometers to inverse meters. For comparison of haze and smoke, the form of the extinction coefficient customarily used with smoke is computed. It is usually called the mass extinction coefficient, α , and is defined as

$$\alpha = \sigma/C .$$

The higher particle density and the corresponding concentration of 0.05 g/cm³ is typical of WP smoke. In calculating the mass extinction coefficient, the concentration drops out, and the values listed are controlled by particle size distribution and particle composition. In comparing values for the mass extinction coefficient for haze with those for WP smoke, it is seen that α_{WP} is somewhat higher in the visible and somewhat lower in the 3- to 4- μ m region. In the 8- to 12- μ m region, α_{WP} is larger than the haze value due to absorption properties of the phosphoric acid.

⁴L. W. Carrier, G. A. Cato, and K. J. Von Essen, *The Backscattering and Extinction of Visible and Infrared Radiation by Selected Major Cloud Modules*, *Appl. Opt.*, 6 (July 1967).

⁵J. J. Vervier, *Properties of Aerosols Generated by Inventory Smoke Compositions (U)*, *Proceedings of 1977 Smoke Symposium*, Office of Project Manager for Smoke/Obscurants, Aberdeen Proving Ground, MD (1977). (CONFIDENTIAL)

APPENDIX A

TABLE A-2. EXTINCTION COEFFICIENTS OF HAZE AND SMOKE

Wavelength (μm)	Haze M			White phosphorous (WP) smoke, α_{WP}	Haze L			Hexachloro- ethane (HC) smoke, α_{HC} (m^2/g)
	$N = 100,$ σ (km^{-1})	$N = 10^5$ particles/ cm^3 $C = 0.05$ g/ m^3			$N = 100,$ σ (km^{-1})	$N = 10^5$ particles/ cm^3 , $C = 0.012$ g/ m^3		
		σ (m^{-1})	$\alpha_{\text{H}_2\text{O}}$ (m^2/g)			σ (m^{-1})	$\alpha_{\text{H}_2\text{O}}$ (m^2/g)	
0.45	0.106	0.106	2.11	3.7	0.0480	0.048	4.0	4.8
0.488	--	--	--	3.7	--	--	--	4.8
0.694	--	--	--	3.0	--	--	--	4.0
0.70	0.106	0.106	2.11	3.0	0.0395	0.040	3.3	4.0
1.06	--	--	--	1.0	--	--	--	2.4
1.19	0.0882	0.088	1.76	0.60	0.0222	0.022	1.8	1.8
1.45	0.0763	0.076	1.52	--	--	--	--	--
1.61	0.0691	0.069	1.38	--	--	--	--	--
1.94	0.0555	0.055	1.10	0.20	0.00895	0.0089	0.74	0.20
2.25	0.0424	0.042	0.84	--	--	--	--	--
3.0	0.0593	0.059	1.18	0.3	0.0159	0.015	1.3	0.72
3.90	0.0236	0.024	0.48	0.37	0.00222	0.0022	0.18	0.27
4.0	--	--	--	0.35	--	--	--	0.20
5.30	0.0112	0.011	0.22	--	0.00109	0.0011	0.09	--
6.05	0.0189	0.018	0.38	--	0.00357	0.0036	0.03	--
8.15	0.00624	0.0062	0.124	0.45	0.00094* 0.00055 [†]	0.007	0.06	0.1
10.0	0.00449	0.0045	0.090	0.40	--	--	--	0.10
10.6	--	--	--	0.38	--	--	--	0.15
11.5	0.00973	0.0097	0.194	0.2	--	--	--	0.2
16.6	0.0135	0.013	0.27	--	--	0.0029	0.24	--

*Index of refraction used in calculation was $1.290 + i0.04720$.

†Index of refraction used in calculation was $1.290 + i0.02360$.

Notes: N is particle density, C is concentration, σ is extinction coefficient, and $\alpha = \sigma/C$ is mass extinction coefficient.

For haze L, the particle density was increased 1000 times. The resulting concentration is somewhat lower than is typical of HC smoke, but serves for illustration. The values for the mass extinction coefficient are compared with those for HC smoke. Correspondence is better in all wavelength regions than for WP smoke, indicating little absorption in the regions of comparison for the principal solute of HC smoke, which is zinc chloride.

In table A-3, extinction coefficients for the low-altitude cloud models are listed. For cloud C.1 and for fair weather cumulus, the extinction coefficient in the 10- μm region is only half that in the visible region, indicating relatively few large particles. The other empirical models have relatively greater concentration of larger particles, and their extinction coefficients hold undiminished through the 10- μm region.

In table A-4, extinction coefficients of clouds and haze can be compared. Clouds C.2 and C.3 are representative of higher-altitude clouds, but also grade toward haze. As the distributions go to smaller particle size, they become more selective; the long wavelength IR attenuation becomes much less than the visible attenuation. Cloud C.2 is a much narrower distribution than cloud C.1 and contains fewer large particles. However, the number mode radii for the two models is the same. Mass mode radii were calculated for clouds C.1, C.2, and C.3 from the distributions, and these values clearly indicate the shift to smaller particles.

TABLE A-3. EXTINCTION COEFFICIENT CLOUD MODELS

Wavelength (μm)	Extinction coefficient (m^{-1})					
	Cloud C.1		Nimbo- stratus, N = 303, R = 30	Fair weather cumulus, N = 300, R = 186	Stratus II N = 260, R = 39	Cumulus congestus, N = 207 R = 57
	N = 100 R = 240	N = 506, R = 40				
0.45	0.0163	0.039	--	--	--	--
0.488	--	--	0.128	0.0210	0.100	0.0692
0.694	--	--	0.130	0.0213	0.101	0.0698
0.70	0.167	0.101	--	--	--	--
1.06	--	--	0.132	0.0219	0.013	0.0713
1.19	0.0173	0.105	--	--	--	--
1.45	0.0176	0.107	--	--	--	--
1.61	0.0176	0.107	--	--	--	--
1.94	0.0181	0.109	--	--	--	--
2.25	0.0184	0.111	--	--	--	--
3.0	0.0180	0.109	--	--	--	--
3.9	0.0206	0.125	--	--	--	--
4.0	--	--	0.147	0.0276	0.114	0.0810
5.3	0.0239	0.145	--	--	--	--
6.05	0.0199	0.120	--	--	--	--
8.15	0.0188*	0.144*	--	--	--	--
	0.0193 [†]	0.177 [†]	--	--	--	--
10.0	0.0112	0.068	--	--	--	--
10.6	--	--	0.136	0.0117	0.104	0.0676
11.5	0.0101	0.061	--	--	--	--
16.6	0.0170	0.103	--	--	--	--

*Index of refraction used in calculation was $1.290 + i0.04720$.

[†]Index of refraction used in calculation was $1.290 + i0.02360$.

Note: N is particle density (particles/cm³) and R is visual range (m).

A-3. RELATIONSHIP OF EXTINCTION COEFFICIENTS FOR VISIBLE AND 8- TO 12- μm REGIONS

An empirical scaling law identified as the G/AP aerosol model* has been devised (fig. A-1). It is based on measurements by the U.S. Army Night Vision and Electro-Optics Laboratory (NVEOL) at Grafenwohr, Federal Republic of Germany, and at Fort A. P. Hill, VA. The purpose of a scaling law is to permit estimation of the long-wavelength extinction coefficients of natural haze and fog based on observations in the visible region.

Figure A-1 illustrates the relationship between the extinction coefficient for the visible, or photopic, region and that for the 8- to 12- μm region as predicted by models. The widely spaced dashed diagonal line indicates no

*F. J. Shields, NVEOL G/AP Aerosol Atmospheric Models, U.S. Army Night Vision and Electro-Optics Laboratory, Fort Belvoir, VA (6 June 1978).

APPENDIX A

selectivity with σ_{8-12} equal to σ_{phot} . Cloud model C.1 lies close to the diagonal. The empirical low cloud models would lie nearly on the diagonal and off the chart to the upper right. In contrast, haze M is highly selective and lies below the diagonal by a factor of almost 20. Adjustment of concentration shifts a given distribution along a diagonal (as indicated for haze M), with its selectivity remaining the same.

In the G/AP model, two types of fog are recognized, wet and dry. The observed difference is that the wet fog wets exposed surfaces, whereas the dry fog does not. As is evident, the dry fog is much more selective. The line labeled "LINEAR FIT" represents essentially the same dry fog data as the curve.

TABLE A-4. EXTINCTION COEFFICIENTS OF CLOUD AND HAZE

Wavelength (μm)	Extinction coefficient (km^{-1})			
	Cloud C.1, R = 0.237, $r_n = 4$, $r_m = 6.1$, C = 0.0626	Cloud C.2, R = 0.346, $r_n = 4$, $r_m = 4.2$, C = 0.0302	Cloud C.3, R = 1.32, $r_n = 2$, $r_m = 2.2$, C = 0.00377	Haze M ($\times 3.689$), R = 10, $r_n = 0.05$, C = 0.00018
0.45	16.3	11.2	2.91	0.391
0.70	16.7	11.4	3.02	0.391
1.61	17.6	12.6	4.13	0.255
2.25	18.4	--	4.55	0.156
3.0	18.0	12.4	3.25	0.219
3.9	20.6	17.7	3.24	0.0869
5.3	23.9	--	1.62	0.0414
6.05	19.9	13.1	1.84	0.0698
8.15*	18.8	--	0.729	0.0230
8.15†	19.3	--	--	--
10	11.2	4.94	0.430	0.0166
11.5	10.1	--	--	0.0359
16.6	17.0	9.75	1.18	0.0496

*Index of refraction used in calculation was $1.290 + i0.04720$.

†Index of refraction used in calculation was $1.290 + i0.02360$.

Note: R is visual range (km), r_n is number mode radius (μm), r_m is mass mode radius (μm), and C is concentration (g/m^3).

In figure A-2, the previous figure is overlaid with additional material. The curves labeled "NVEOL WORST" represent some worst case data acquired in the NVEOL program. An 8- to 23- μm ED device evaluated against such a severe model would get a poor score. The LOTRAN continental aerosol model^{6,†} is a haze model in common use.

⁶J. E. A. Selby, E. P. Shettle, and R. A. McClatchey, *Atmospheric Transmittance from 0.25 to 28.5 μm : Supplement LOTRAN 3B (1976), Air Force Geophysical Laboratory AFGL-TR-76-0258 (1 November 1977)*.

[†]R. B. Gomez, *Approach to Natural Environmental Aerosol Modeling, Atmospheric Sciences Laboratory, White Sands Missile Range, NM (16 August 1978)*.

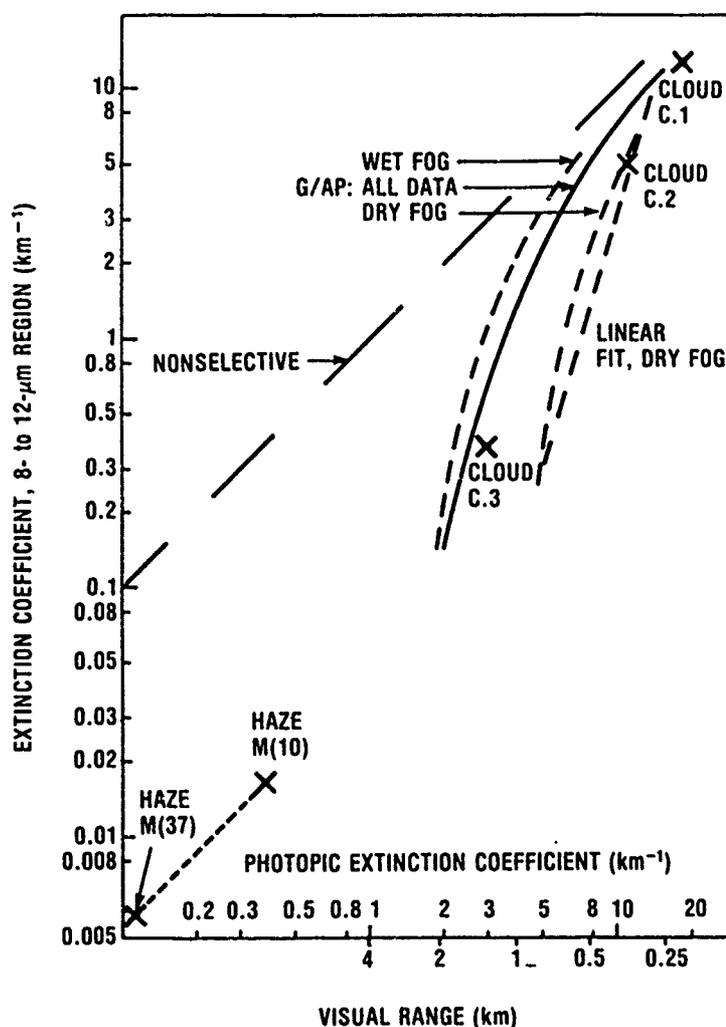


Figure A-1. Extinction coefficients for cloud, haze, and fog: models (X) and data.

The remaining curve is a linear fit to data taken in the Optical Atmospheric Quantities in Europe (OPAQUE) program, run by the North Atlantic Treaty Organization (NATO), of meteorological observations at 12 European stations. The program is intended to extend over several years. Not only meteorological observations, but also transmission measurements in several wavelength regions are emphasized. In this program, σ_{8-12} and σ_{phot} are measured independently and over a span of time, permitting the frequency of occurrence of the parameters to be determined independently. Such data, when they become sufficiently general, will remove the need for a scaling law and provide accurate data on environmental conditions in long wavelength regions. The curve shown in figure A-3 represents data from the Netherlands station for March to May 1977.*

*R. B. Gomez, Approach to Natural Environmental Aerosol Modeling, Atmospheric Sciences Laboratory, White Sands Missile Range, NM (16 August 1978).

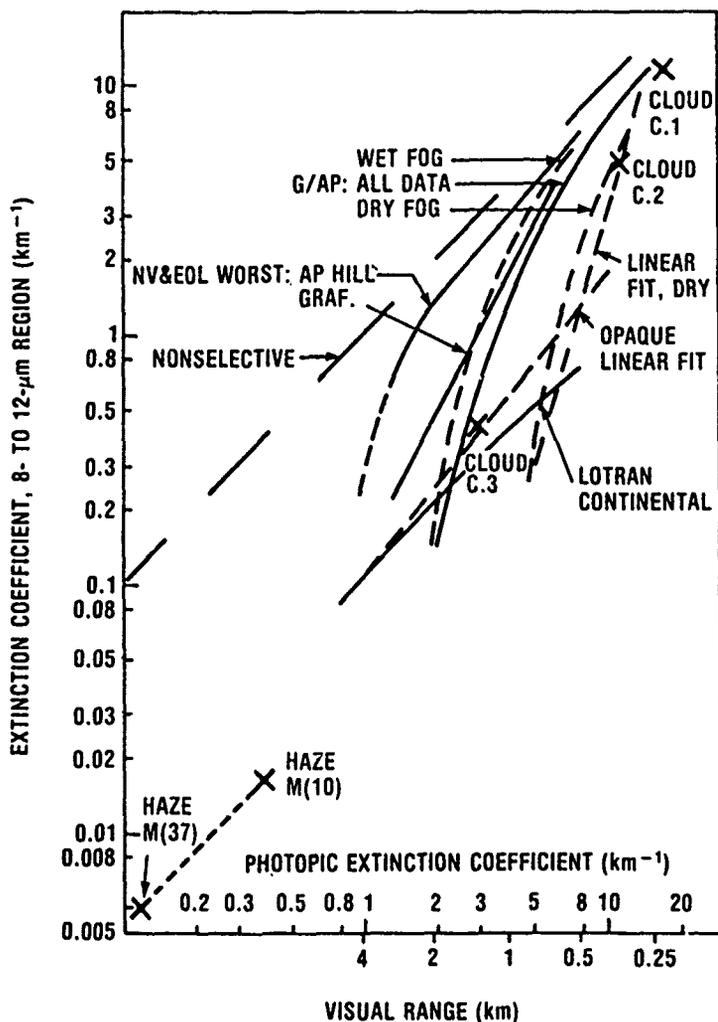


Figure A-2. Extinction coefficients for cloud, haze, and fog: additional models and data.

In figure A-3, a second overlay shows the distribution of the OPAQUE data. Typical of this type of data, the distribution illustrates the fundamental nature of the scaling problem. The data spread from nonselective to highly selective haze and fog. All the models lie well within the spread of the data except "NVEOL WORST," which really is a worst-case model.

In summary, the photopic spectral region is affected. The long wavelengths are affected only by the large particles (radius $\sim 10 \mu\text{m}$). For low cloud and dense fog (visual range $< 0.25 \text{ km}$), there are enough large particles to obscure the long wavelengths. However, for visual ranges of 0.5 to 4 km, which are of great military significance, the presence of small particles implies almost nothing about the presence of large particles. Resolution of this problem must await the independent determination of the short and long wavelength parameters.

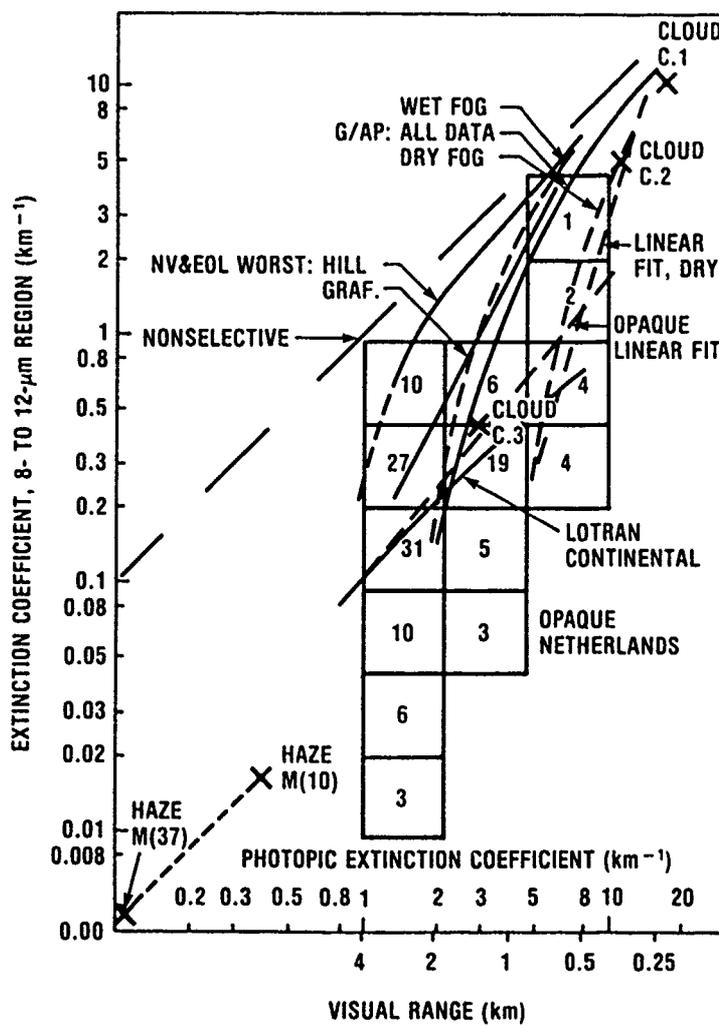


Figure A-3. Extinction coefficients for cloud, haze, and fog: additional models and expanded distribution of data.

APPENDIX A

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APPENDIX B.--VISIBILITY MEASUREMENT AND EXTINCTION COEFFICIENT

APPENDIX B

CONTENTS

	<u>Page</u>
B-1. INTRODUCTION	67
B-2. METHOD BASED ON VISIBILITY	68
B-3. METHOD BASED ON TRANSMISSION	70
B-4. METHOD BASED ON SCATTERING	72
LITERATURE CITED	74

FIGURES

B-1. Frequency distribution of values of ϵ calculated from 1000 observations	68
B-2. Visibility as function of time at five sites near San Diego	69
B-3. Stations measuring visibility	70
B-4. Relative error in visual range as function of measured transmittance	71
B-5. Backscattering coefficient versus extinction coefficient for cloud, white phosphorus (WP) smoke, and dust	73

B-1. INTRODUCTION

The methods--based on visibility, transmission, and scattering--are used to determine the extinction coefficient. Each method has special problems associated with its use in the field. In calculating, it is not easy to relate the extinction coefficient determined by one method to that obtained by other methods, at different wavelengths or in other types of aerosols.

The method based on visibility (sect. B-2) relies on observation by a human observer of the range at which a standard or test object can be just seen. Because of the problems in determining reliable estimates of V_r using standard meteorological observations, many experts have advocated the use of instruments to determine visibility. The use of instruments at least assigns a number to the atmospheric side of the problem. Such instruments are of two types, those that measure transmission (extinction) (sect. B-3) and those that measure scattering by the atmosphere (sect. B-4). The purpose for which the information is needed determines which type is used. If information on horizontal visibility is needed, an instrument based on extinction is used, a transmissometer. If information on vertical visibility or back scattering is needed, an instrument based on scattering is used, a nephelometer (sect. B-4).

Use of estimates of V_r to obtain σ depend on how well the contrasts are known and how uniform the path is over which V_r was estimated. Koschmieder assumes that $\epsilon = 0.02$. Middleton¹ discusses a study (fig. B-1) providing frequency distributions of ϵ based on forced choice detection (the observer knows that the object is there) that ranges from near 0 to 0.20, with an average of 0.031. When the criterion used is recognition rather than forced choice detections, the World Meteorological Organization recommends² $\epsilon = 0.05$.^{*} The above discussion assumes that ϵ is a constant. Actually, it is a function of the angular size of the object and background luminance; ϵ increases as these parameters decrease. However, in the field, with objects subtending 0.1 deg or more and in normal daylight, assuming ϵ to be a constant does not introduce large errors.

The variation of contrast of the object with the background is not usually taken into account for routine meteorological observations because the observer can choose either black or dark objects against a clear sky. However, in field determinations of visibility, the objects are often tall buildings that are not black and may not have the sky as a background.

To bound this problem, Douglas and Booker develop a concept of visibility factors.³ In one case, visibility is adjusted when the inherent contrast varies from $C_o = 0$, for a gray object that blends with the sky, to as high as $C_o = 5$, for a white object in direct sunlight. In another case, visibility is adjusted for backgrounds ranging from sun on snow to a low sun shining through haze on grass.

¹W. E. K. Middleton, *Vision Through the Atmosphere*, University of Toronto Press, Toronto (1952).

²World Meteorological Organization, *Guide to Meteorological Instruments and Observing Practices* (1971).

³C. A. Douglas and R. L. Booker, *Visual Range: Concepts, Instrumental Determination and Aviation Applications*, National Bureau of Standards Monograph 159 (June 1977).

* $\epsilon = 0.055$ is used for transmissometer measurements in the United States.

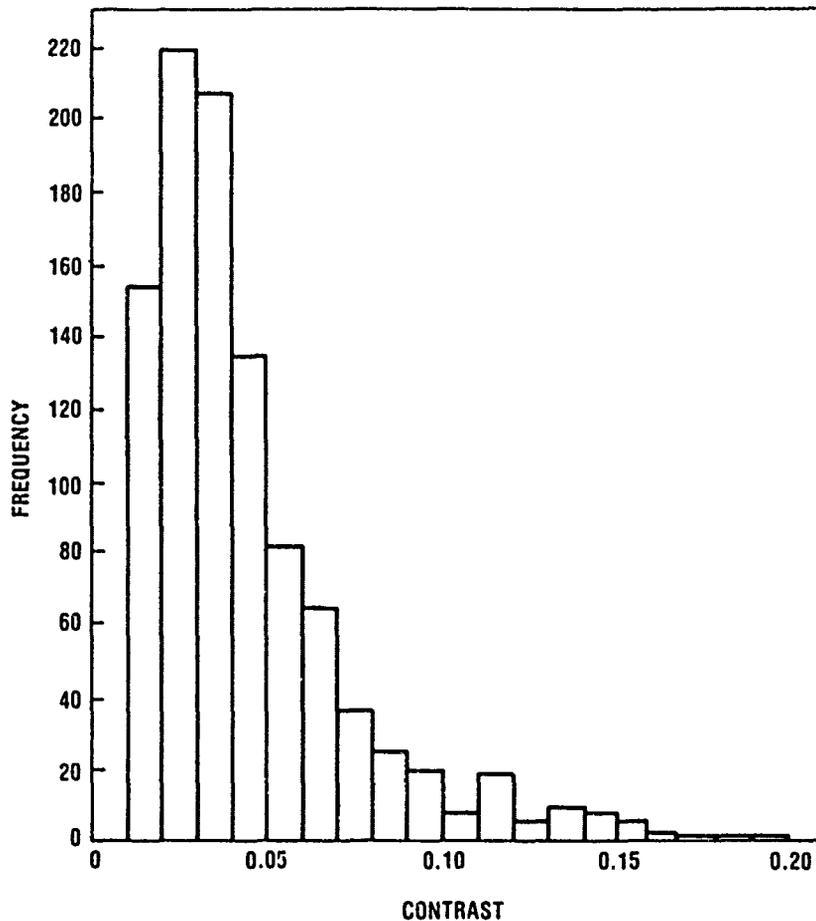


Figure B-1. Frequency distribution of values of ϵ calculated from 1000 observations.

B-2. METHOD BASED ON VISIBILITY

In natural fog and haze, the only parameter regularly included in meteorological reports is visibility. Airports and the Navy have been very concerned with it. The most available data are for visibility, yet special problems are associated with its measurement. Much information in this section has been extracted from the reports of Douglas and Booker³ and Noonkester.⁴

Meteorological visibility or visual range, V_r , is related to the inherent contrast, C_o , of the object viewed (ideally, a black object against a clear sky has $C_o = 1$); the extinction coefficient, σ ; and the limiting contrast, ϵ , by

³C. A. Douglas and R. L. Booker, *Visual Range: Concepts, Instrumental Determination and Aviation Applications*, National Bureau of Standards Monograph 159 (June 1977).

⁴V. R. Noonkester, *Meteorological "Visibility" and EO Systems*, Naval Ocean Systems Center Technical Note 167 (May 1977).

$$\epsilon = C_0 e^{-\sigma V_r}, \quad |C_0| > \epsilon. \quad (\text{B-1})$$

Rearrangement yields Koschmieder's equation,

$$V_r \sigma = \ln |C_0 / \epsilon| \quad (\text{B-2})$$

$$= \text{constant}.$$

In the Federal Meteorological Handbook, No. 1, visibility is defined as "the greatest distance at which an object of specified characteristics can be seen and identified with an unaided eye."⁵

The reported visibility is almost always horizontal visibility. Vertical variations in visibility can often be rapid and are unspecified when horizontal visibility is reported. Azimuthal or temporal variations are sometimes averaged and called the prevailing visibility. The details of the sometimes large variations are usually not reported. In rarely seen visio-meter data, Noonkester shows how visibility varies with time at sites only a few miles apart near San Diego, CA (fig. B-2, B-3).⁴ The physical characteristics of the obscurant, such as drop size and concentration, are seldom measured. Therefore, extending visibility data to wavelengths other than optical ones is ambiguous at best.

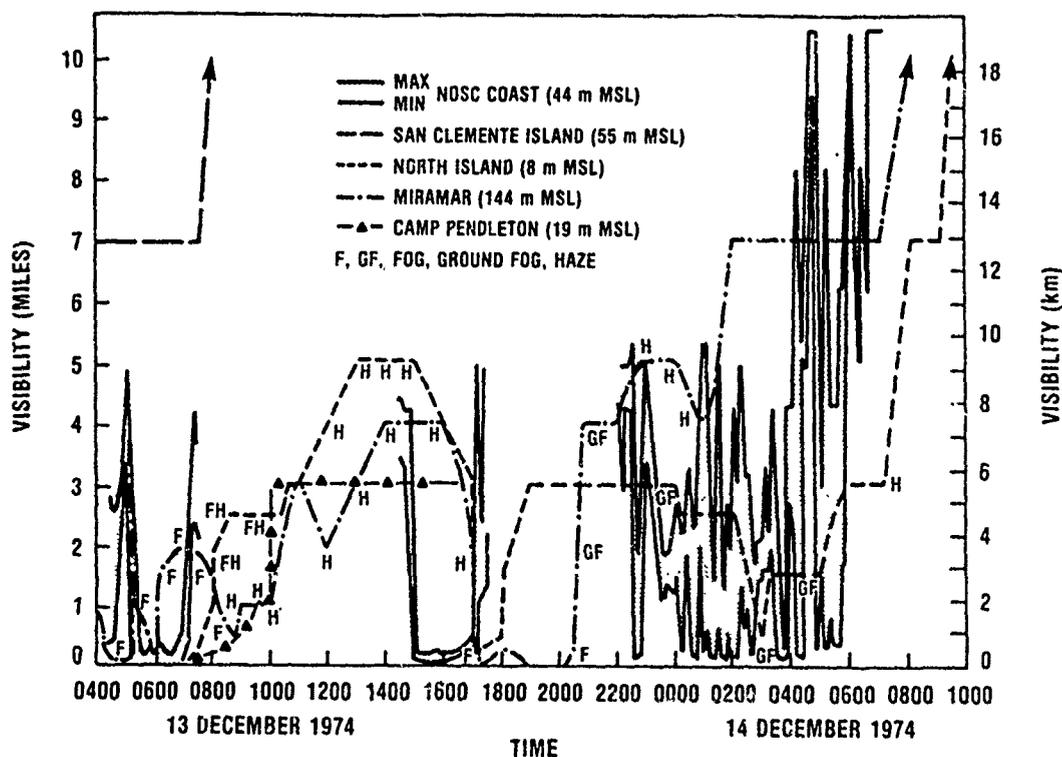


Figure B-2. Visibility as function of time at five sites near San Diego (from Naval Ocean Systems Center note 167).

⁴V. R. Noonkester, *Meteorological "Visibility" and EO Systems*, Naval Ocean Systems Center Technical Note 167 (May 1977).

⁵Federal Meteorological Handbook, 1, *Surface Observations*, Washington, DC (January 1972).

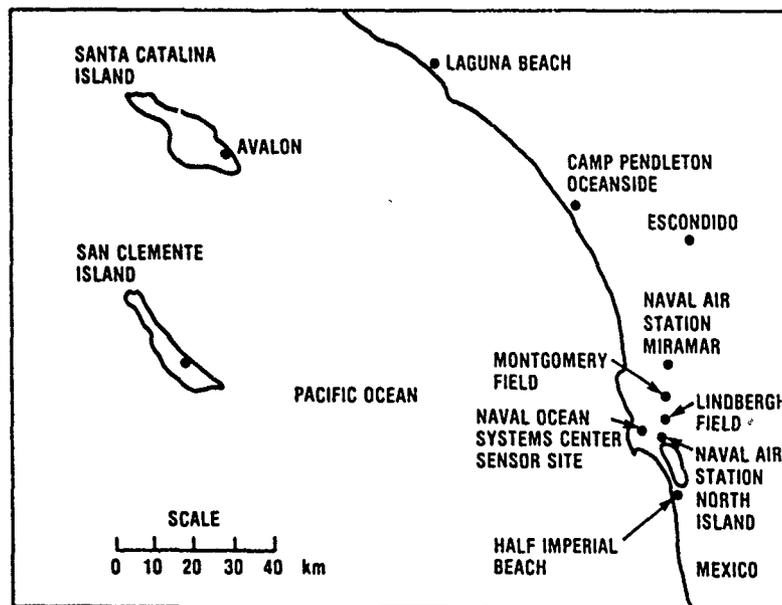


FIGURE B-3. STATIONS MEASURING VISIBILITY (from NOSC note 167).

Figure B-3. Stations measuring visibility (from Naval Ocean Systems Center note 167).

B-3. METHOD BASED ON TRANSMISSION

Many instruments, such as the transmissometer discussed in this section, have been designed to measure visibility. The more objective ones use a projector as the light source at some range, a telescope as the receiver, and a photocell as the detector. For the simplest instrument, the light source is placed at a straight line distance and viewed directly with the receiver. The path length can be folded to fit into the available site, or additional receivers can extend the range of the extinction coefficient that can be measured.

Light can enter the receiver in three ways: (1) directly from the source, (2) after scattering by the atmosphere into the receiver aperture, and (3) from background or other stray sources. Any light other than direct light from the source incident on the detector can cause an observational error. In well-designed instruments, the background light can be corrected or subtracted out.

The selection of a baseline for the transmissometer is important. Middleton discusses the case in which a photoelectric measurement is made.¹

¹W. E. K. Middleton, *Vision Through the Atmosphere*, University of Toronto Press, Toronto (1952).

The baseline should be selected so that the transmittance is between 3 and 90 percent if the error in visibility is to be less than 10 percent, assuming a 1-percent error in the transmission measurement (fig. B-4). To determine $\sigma < 0.001 \text{ m}^{-1}$ with an error less than 10 percent, the baseline needs to be greater than 1000 m. To determine $\sigma > 0.1 \text{ m}^{-1}$ with an error less than 10 percent, the baseline needs to be less than 35 m. To achieve an error less than 5 percent in the extinction coefficient for conditions where $\sigma \geq 0.001 \text{ m}^{-1}$ is expected, the 100-percent point must be calibrated with the transmissometer on clear days.

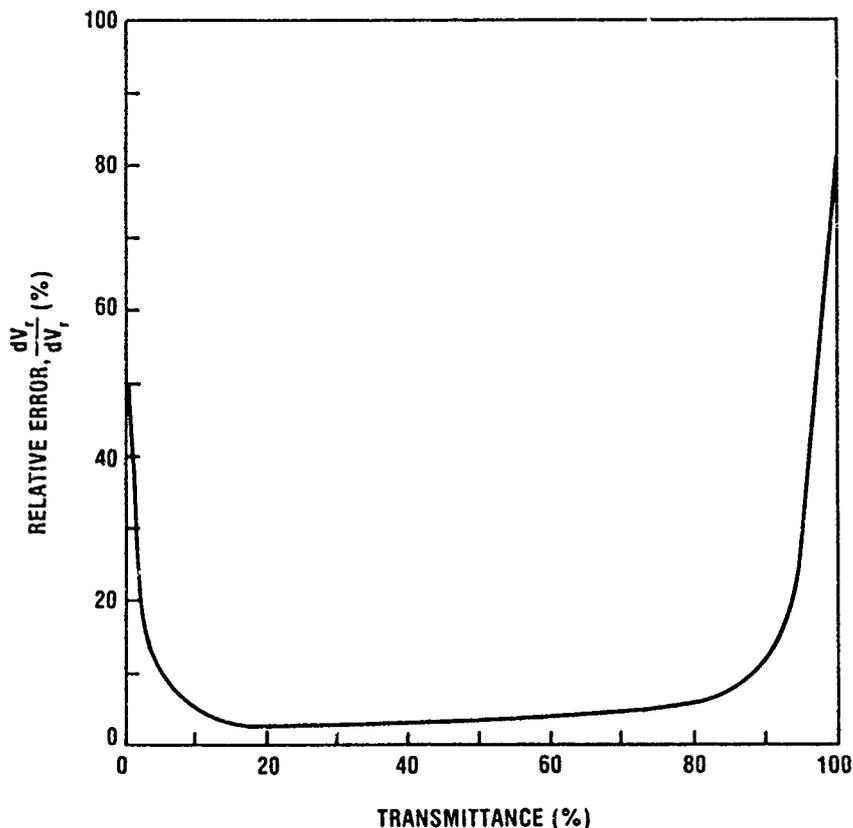


Figure B-4. Relative error in visual range as function of measured transmittance.

The problem is to maintain this calibration with changes in temperature and other factors. With a folded baseline, a small part of the transmitted energy can be diverted back into the receiver. On narrow-beam laser transmitters, the receiver can be moved near the transmitter and then repositioned at the end of the baseline. The major source of error is that path lengths are not uniform in the atmosphere.

APPENDIX B

B-4. METHOD BASED ON SCATTERING

When it is difficult to place a reflector at a distance, as in measurements on clouds, or when the information desired is the scattered energy, a nephelometer can be used to measure visibility. The principles of operation of such instruments are described by Humphrey.⁶

Light is lost from a beam by scattering or absorption. In water aerosols, such as cloud and fog, the amount of light lost by absorption is small. However, in smoke and dust, the amount of light lost by absorption is large. The light lost from the beam is described by the extinction coefficient, which is defined by

$$\sigma = \alpha + \gamma \quad , \quad (B-3)$$

where

α = scattering coefficient,

γ = absorption coefficient.

The angular distribution of the scattered light lost from the beam is described by the volume scattering function in direction θ , $\mu(\theta)$, which is defined by the ratio

$$\mu(\theta) = \frac{(\text{power scattered})/(\text{unit path length})/(\text{unit solid angle})}{\text{power incident on volume element of aerosol}} \quad .$$

Nephelometers have been designed and used to measure the light scattered over large solid angles or at only one angle. One instrument has been designed to measure the light scattered in fog. Donald Mary⁷ is interested mainly in the backscattering direction ($\theta = \pi$) and evaluation of the scattering function, $F(\pi)$, which is defined by

$$F(\pi) = \mu(\pi)/\sigma \quad , \quad (B-4)$$

where $\mu(\pi)$ is the volume backscattering coefficient. A receiver looks at a defined region that is illuminated by the transmitter in a coaxial system. The return power from the aerosol is compared with the return power from a standard reflector in clear air.

A second instrument, described by Giglio,⁸ is a dual-channel nephelometer consisting of two narrow-beam transmitters and two receivers. Imaging is used to define a near scattering region (D_n) and a far scattering region

⁶Robert G. Humphrey, *Properties of an Active Optical System*, Harry Diamond Laboratories HDL-TR-1281 (April 1965).

⁷Donald J. Mary, *A Backscatter Nephelometer*, Harry Diamond Laboratories HDL-TM-65-11 (February 1965).

⁸D. A. Giglio, B. J. Rod, and H. M. Smalley, *Nephelometer Mapping of Backscatter and Attenuation Coefficients of Clouds*, Harry Diamond Laboratories HDL-TR-1660 (February 1974).

(D_f). By use of the two scattering measurements, both σ and $\mu(\pi)$ can be determined at the same time with no separate transmission measurement needed. The fog must be uniform over the path length. The value of σ is determined from D_n/D_f , and $\mu(\pi)$ is determined from the scattering signal from either of the two channels. The range characteristics of both channels must be measured in clear air by using a standard reflecting surface.

Besides measuring visibility in fog, the dual-channel nephelometer can be used to measure the scattering properties of smoke or dust. It also indicates particle size, since for a given wavelength $F(\theta)$ depends largely on particle size distribution. Sztankay⁹ presents the results of using the nephelometer to determine σ and $\mu(\pi)$ for clouds and manmade smoke and dust (fig. B-5). The data indicate that $\mu(\pi)/\sigma$ can be used to characterize aerosols.

The dual-channel nephelometer has errors similar to those of a transmissometer. Because of the short baseline (4 m), the accuracy is greatest for large extinction coefficients.

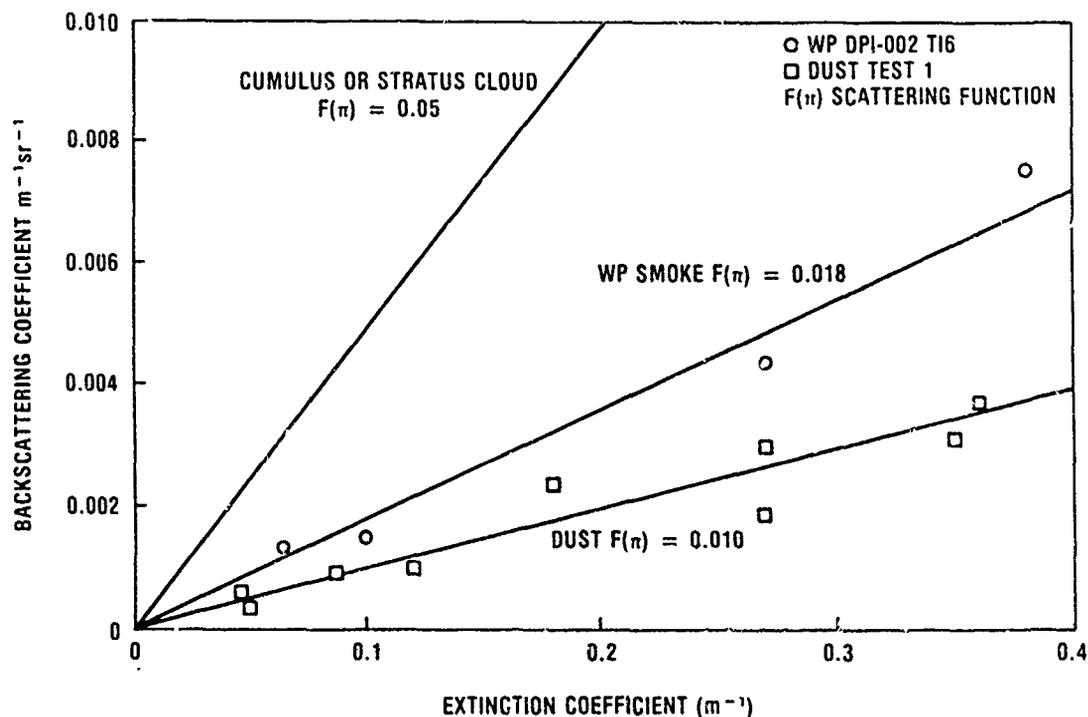


Figure B-5. Backscattering coefficient versus extinction coefficient for cloud, white phosphorus (WP) smoke, and dust.

⁹Zoltan G. Sztankay, *Measurements of the Localized Optical Characteristics of Natural Aerosols, Smoke, and Dust, Proceedings of Smoke Symposium II, Office of Project Manager for Smoke/Obscurants DRCPM-SMK-T-004-78 (April 1978)*.

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APPENDIX C.--DEFINITIONS OF REFLECTANCE FOR ELECTRO-OPTICAL APPLICATIONS

APPENDIX C

CONTENTS

	<u>Page</u>
C-1. INTRODUCTION	77
C-2. CONVENTIONAL DEFINITION	77
C-3. NEW DEFINITION	78
C-4. RADAR CROSS SECTION	79
LITERATURE CITED	80

C-1. INTRODUCTION

Two definitions of reflectance are in general use. The older (conventional) definition assumes cosine or Lambertian distribution of the reflected radiation, while the newer, more sophisticated definition avoids that assumption. This appendix reviews the definitions of reflectivity and their application to electro-optical (EO) systems and target measurements.

C-2. CONVENTIONAL DEFINITION

Consider a source producing an illuminating beam with incident power, P_i , at the target in a spot with an area, A_i , smaller than the target. Then consider a receiver at a distance, R , from the target and generally in the direction of illumination. The target is assumed to be an opaque, planar, or equivalent planar, surface illuminated and viewed approximately normally and obeying a cosine characteristic (Lambertian)--hence, the factor π in the denominator. The irradiance, H_r , at the receiver is

$$H_r = P_i \rho / \pi R^2 \quad , \quad (C-1)$$

where ρ is the reflectance. Hence,

$$\rho = \pi R^2 H_r / P_i \quad . \quad (C-2)$$

Introducing the illuminated area, equations can be written for the incident irradiance, H_i , and the reflected apparent radiance, N_r :

$$H_i = P_i / A_i \quad , \quad (C-3)$$

$$N_r = H_r / (A_i / R^2) \quad . \quad (C-4)$$

Equation (C-4) satisfies the definition of radiance and can be interpreted intuitively as viewing the illuminated spot on the target through a reference 1 cm^2 aperture at the receiver. The geometry must be such that the spot fills the reference aperture from the point of view.

By combining equations, the conventional definition of reflectance becomes

$$\rho = \pi N_r / H_i \quad . \quad (C-5)$$

As is well known, real reflectors seldom obey the cosine relationship. Lambert's Law was formulated to describe self-emitting sources. Its adoption into the definition of reflectance is a bizarre occurrence in scientific thought that must be attributed to a lack of understanding of the physical phenomena involved. For reflectance standards, the traditional standard is

APPENDIX C

the MgO smoked plate, which is one of the few surfaces exhibiting Lambertian behavior.¹ However, the usually homemade MgO plates, prepared by burning magnesium ribbon, are giving way to standards such as the National Bureau of Standards ceramic plates. With these ceramic plates, angles of illumination and reflection are carefully specified, and there is no attempt to mimic Lambert's law.

C-3. NEW DEFINITION

In view of those difficulties, a new definition of reflectance is coming into use:^{2,3}

$$\rho = N_r/H_i \quad . \quad (C-6)$$

Here, π has been dropped, and measurements may be reported as reflectance per steradian or just reflectance. But frequently ρ is loaded with burdensome superscripts, subscripts, and arguments to specify incidence and reflection angles and states of polarization.

The new definition of ρ goes a long way to clearing up the concept of reflectance. However, one assumption remains: the target is assumed to be a plane surface with a well-defined normal. Since that geometry is not usual for military targets, the sophistication has limited appeal in target signature measurements.

In EO weapon system analysis, the conventional definition of reflectance as expressed in equation (C-1) or (C-5) is usually used because most military target data are in those terms. Polarization effects are usually not considered since EO system designers rarely can afford the luxury of throwing away any signal. Whatever advantages polarization offers seldom justify the reduced signal-to-noise ratio or performance range resulting when the undesired component of polarization is rejected. Directional reflectance, in which the source and the receiver are together (for example, in laser rangefinders or active optical fuzes), is distinguished from bidirectional reflectance, in which the source and the receiver are usually at different angles (for example, in laser terminal homing).

¹Donald J. Mary, *Determination of the Reflecting Properties of Pressed MgO Powder*, Harry Diamond Laboratories HDL-TM-65-12 (March 1965).

²F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, *Geometric Considerations and Nomenclature for Reflectance*, National Bureau of Standards Monograph 160 (October 1977).

³Target Signature Analysis Center: *Data Compilation, 11th Supplement; I, Bidirectional Reflectance: Definition, Discussion and Utilization; II, Bidirectional Reflectance: Graphic Data*, Willow Run Laboratories, Ann Arbor, MI AFAL-TR-72-226 (October 1972). I (AD904999) and II (AD905000)

C-4. RADAR CROSS SECTION

Related to definitions of reflectance is the definition of radar cross section. With most radars, the beam is assumed to be larger than the target, and the angular distribution of the reflected power is assumed to be isotropic. Using the conventions, the definition can be extended to radar reflectance, ρ_{rad} . The defining equation is of the form

$$\rho_{\text{rad}} = 4\pi N_r / H_i \quad . \quad (\text{C-7})$$

Now A_i is the cross-sectional area of the target, all of which is illuminated:

$$N_r = H_r R^2 / A_i \quad . \quad (\text{C-8})$$

The definition of radar cross section is⁴

$$4\pi \frac{(\text{power per unit solid angle scattered back toward transmitter})}{(\text{power per unit area striking target})} \quad .$$

In equation (C-7), H_i can be identified as the denominator of the definition, or the power per unit area striking the target. Also $H_r R^2$, which is equivalent to radiant intensity, J_r , can be rewritten

$$J_r = H_r R^2 \quad (\text{C-9})$$

and is identified as the numerator of the definition, the power per unit solid angle scattered back toward the transmitter. The optical interpretation of the definition of the radar cross section, σ , combined with C-7, C-8, and C-9 becomes:

$$\sigma = 4\pi J_r / H_i = \rho_{\text{rad}} A_i \quad . \quad (\text{C-10})$$

In the optical interpretation, σ is the product of reflectance and target area, except that reflectance is defined with the 4π factor for an assumed angular distribution. That, of course, is the angular distribution for a perfectly conducting (specular) sphere, frequently used as a reflection standard for radar. The additional condition, that radar cross section assumes the beam to be larger than the target, is not the usual geometry in optics.

⁴Reference Data for Radio Engineers 4th ed., International Telephone and Telegraph Corp., New York (1956).

APPENDIX C

In the near millimeter wave region, the optical and radio frequency regions overlap, and the divergent definitions must be resolved. The incident beam is not necessarily larger than the target in the near millimeter wave region. Consider, for example, a diffraction limited system of 1-mm wavelength with a transmitter antenna of 1-m diameter. At 1 km, 80 percent of the beam power is inside a 1-m-diameter circle within the Airy disc.⁵ This beam diameter is smaller than an armored target, for example, and will provide nonuniform target illumination. For such a geometry, the traditional radar description of target signatures in terms of cross section is unreliable.

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