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ORD-RM 7910-3

# VISUAL DETECTION AND RECOGNITION OF CAMOUFLAGED PERSONNEL (U)

*By:* MURRAY GREYSON and J. ROLAND PAYNE

*May 1971*

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT CENTER
FORT BELVOIR, VIRGINIA

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Menlo Park, California 94025

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SUMMARY

Research was performed to (1) identify the essential elements and pertinent parameters for a visual model for surveillance of camouflaged personnel in various terrains, weathers, and combat environments, and (2) develop the mathematics and logic of the visual model. The research included a search and study of the available pertinent literature and discussions with many of the recognized experts in vision research and countersurveillance.

A model was developed to account for the effects of luminance and color contrasts in the detection process. It accounts for intrinsic luminance and color contrasts at the target and the effects of the atmosphere and range between the observer and the object.

The state of knowledge concerning the effects of movement and form discrimination was found to be fairly primitive despite the extensive research that has been performed. It was not possible to develop a sufficiently detailed analytical model for the effects of either of these important parameters.

Since it is considered necessary to include a human's judgment in modeling the process of recognizing military objects, empirical data derived from human observers' performance of form recognition, in conjunction with a classification system for backgrounds, are required for developing a realistic empirical model of form discrimination.

## FOREWORD

The research reported in this memorandum has been performed under Contract DACA76-69-Q-0003 for the United States Army Mobility Equipment Research and Development Center (USAMERDC). Project support has been provided by Mr. John Hopkins, USAMERDC, Authorized Representative of the Contracting Officer, and Mr. Kemper Flint, USAMERDC.

This interim report documents the research performed on Phase I of the task to develop models that can be used in determining requirements for and measuring the effectiveness of camouflage systems for personnel. As the work continues on Phases II and III, the results discussed in this interim report may be modified for presentation in the final report.

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# I INTRODUCTION

The goal of the research has been to develop an objective measurement method for determining requirements for and measuring the effectiveness of camouflage systems for personnel.

The method of approach for attaining the goal has been to (1) conduct a search of the applicable literature, (2) visit personnel and agencies that are recognized for their work in areas significant to passive countersurveillance, (3) determine the most important essential elements and pertinent parameters to be considered, (4) examine available models for useful submodels and logic, (5) identify measures of effectiveness, (6) develop and exercise models describing the detection-concealment process for personnel in various environments, and (7) design a field experiment to test the output of the above models in satisfying the study objective.

The research required in this method of approach has been divided into three phases:

Phase I: Visual Systems

- Perform the literature search and make the background visits
- Determine the essential elements and pertinent parameters for the visual model for surveillance of camouflaged personnel in various terrains, weathers, and combat environments
- Develop the logic and mathematics for the visual models

Phase II: Nonvisual Systems

- Determine the essential elements and pertinent parameters for nonvisual systems such as optical, infrared, and radar
- Develop the logic and mathematics for the nonvisual models.

Phase III: Model Integration and Field Experiment Design

- Program the visual and nonvisual system models
- Incorporate the visual and nonvisual system models into the SRI Countersurveillance-Reconnaissance Effectiveness Evaluation (SCREEN) model[1,2]*
- Exercise the computer models
- Develop the preliminary design for a field experiment to test results of the model study

This document reports the research conducted during Phase I of the study effort.

*The references are listed at the end of the main body of the report.

# II INVESTIGATIONS

## A. Literature Search

The library resources of SRI, Stanford University, Defense Documentation Center, RECON Central, Medlars, and the Reconnaissance Data Base at Rome Air Development Center were searched. Special collections of documents related to countersurveillance and surveillance, target acquisition and night observation (STANO), located at the U.S. Army Natick Laboratories, Project MASSTER, and the Combat Developments Command Institute of Systems Analyses, were referenced as well as the personal libraries of some of the experts consulted during background visits. The publications obtained from these sources supplemented the literature study that had been conducted for the earlier tasks of this contract involved with (1) the identification of measures of effectiveness for countersurveillance for tactical units and their equipment, (2) a method of classification of targets for countersurveillance purposes, and (3) the development of SCREEN.

Reports studied had varied orientations, including mathematics, physics, chemistry, electronic and electrical engineering, psychology, physiology, ophthalmology, military sciences, military operations, history, surveillance technology, and countersurveillance methodology. They included textbooks, journal reports, technical reports, professional magazine articles, battle action reports, notes, and field and training manuals. They were written as early as 1802 and as late as 1970.

Although the literature search was extensive, most of the time allocated to studying the collected documents was dedicated to the relatively few documents that were of particular importance in the development of a visual model for studying the effects of camouflage for personnel. The fact that the majority of the documents appear to be of marginal value for our research can be better appreciated after reading the discussion in the next section of the multiplicity of parameters and the rather primitive state of the understanding of the interrelations among them.

## B. Background Visits

Discussions were held with the persons listed below and with co-workers at their organizations. Discussing with these experts the work that has been done by them and their organizations provided an opportunity to obtain (1) their latest ideas on the aspects of countersurveillance for personnel that are of most interest to each of them, and (2) their perspectives on the important parameters and how they are related.

| Person Visited | Organization |
|---|---|
| Dr. Leon Williams | Honeywell, Inc. |
| Mr. Ray Schaefer | Honeywell, Inc. |
| Dr. H. Richard Blackwell | Ohio State University, Institute for Research in Vision |
| Dr. Wilson Tanner | University of Michigan, Institute of Science and Technology |
| Mr. Richard LeGeault | University of Michigan, Institute of Science and Technology |
| Mr. Frank Rizzo | Natick Laboratories |
| Dr. Walter Lawson | Night Vision Laboratory, Fort Belvoir |
| Mr. John Hopkins | U.S. Army Mobility Equipment Research and Development Center |
| Mr. Arthur Stein | Cornell Aeronautical Laboratories |
| Dr. McAdams | Kodak Research Laboratories |
| Dr. Robert Boynton | University of Rochester, Institute for Vision Research |
| Mr. Art Woods | Project MASSTER, Fort Hood |
| Mr. Ray Attarian | Combat Developments Command Institute for Systems Analyses |
| MGen. William Fulton | STANSM/ACSFOR |
| Dr. Siebert Duntley | Scripps Institute of Oceanography, Visibility Laboratory |

The Symposium on Tactical Reconnaissance jointly sponsored by the Office of Director of Defense Research and Engineering, DOD, and Electronics Industries Association on 13-15 April 1971 was also attended.

## C. Essential Elements and Pertinent Parameters

The devising of a method of stating quantitative requirements for measuring the effectiveness of camouflage for personnel requires not only a logical, quantitative understanding of how the sensor systems work but also of the way that various camouflage techniques might degrade the value of the conclusions that are in part derived from information obtained from the sensor systems. The essential elements to be considered should therefore include the basic passive countersurveillance methodology, the characteristics and signatures of the personnel using the camouflage, the background and environment containing the personnel, the atmosphere between the personnel and the sensor system, the sensor, the data processing, and the intelligence synthesis processes.

These various essential elements are most properly studied from differing viewpoints. The expertise of the military specialist is needed to identify the deployment parameters of the personnel and sensors in the environment and military situation of interest, the countersurveillance specialist to identify the parameters of known camouflage methods and techniques, the physicist to identify the parameters for describing the energy flow from source to camouflaged personnel to sensor, the physicist and engineer or physiologist to identify signal processing parameters within the sensor system, the engineer and/or psychologist to identify parameters for display and data extraction, the psychologist and intelligence specialist to identify features of the intelligence synthesis process, and the operations/systems analyst to identify a logical structure for integrating the parameters identified by the preceding specialists.

Discussions with and reports by specialists of the above types that have been concerned with the visual process have led to the identification of a myriad of parameters pertinent to the present model development task. These discussions and reports also indicated the areas where research has had some success in relating various parameters, qualitatively and quantitatively, and the areas where only qualitative or vague connections between parameters have been identified, even after a considerable amount of research effort. The state of knowledge is particularly primitive on such questions as how humans recognize complex forms (such as other humans) in complex backgrounds (such as in military situations), and how intelligence is synthesized from extracted data.

Broadly stated, the purpose of camouflage is to hide, blend, disguise, or deceive. Depending on the particular purpose a particular camouflage technique is designed to achieve, emphasis is put on trying to defeat the enemy sensor and intelligence systems at a number of different places. If the basic purpose is to hide or blend, then primary emphasis is likely to be aimed at denying detection and/or recognition by the sensor system, with secondary emphasis on confusing the data extraction and intelligence synthesis processes. However, if the basic purpose of the camouflage is to disguise or deceive, then primary emphasis is placed on causing the data extraction and intelligence synthesis processes to produce erroneous or untimely output. The current knowledge of these processes suggests that for the foreseeable future, experienced men should be used to account for the output of these processes in models incorporating them.[3,4]

It was therefore decided that this operations analysis research would probably be most beneficial if it were restricted and directed primarily to the task of modeling the physics and psychophysics involved in the visual detection and recognition of personnel camouflaged for the purpose of hiding and/or blending. With this restricted scope, the primary measures of effectiveness are functions of the probabilities of detection and recognition of personnel. Thus the most pertinent parameters are those that significantly affect the visual detection and recognition processes.

The study was consequently directed toward modeling the effects on the detection and recognition processes of (1) luminous and color contrasts between the camouflaged person and his background, (2) movement, and (3) shape and form. A discussion of these categories of parameters, and the relationships among them, is contained in Section III.

A quantitative model developed to describe the way luminance and color contrasts contribute to the detection process is presented in the appendix.

Only qualitative discussions of the effects of movement, shape and form are possible at this time.[5,6] The inability to produce meaningful quantitative models in these areas is primarily due to the primitive state of understanding of how people perceive motion; and to the fact that most of the extensive research on shape and form has concerned itself with simple geometric shapes on noncomplex backgrounds, which is not readily extrapolated to complex forms in three dimensional complex backgrounds.[7]

## III PERTINENT PARAMETERS FOR VISUAL DISCRIMINATION OF CAMOUFLAGED PERSONNEL

To visually detect and recognize an object (e.g., a camouflaged soldier) an observer's eye must receive a signal from the object and/or cue objects that is sufficiently strong to be noticeable by the observer, and sufficiently different from the signals from the surround of the object that the observer can distinguish the object sufficiently well to classify it. The perception of the signal and the realization that the signal is from a potentially interesting object (i.e., detection) depends directly on a sufficiently strong signal-to-noise ratio at the retina of the observer's eye, and the state of awareness of the observer.

### A. Major Pertinent Parameters--for Detection

The human eye is a remarkably sensitive sensor.* However, certain conditions have to exist before a signal from an object can be detected as a potentially interesting signal (interesting in terms of discerning camouflaged personnel). For objects that do not contain a light source there must be a source of illumination incident on the object, some kind of contrast between the object and its surround, and line-of-sight between the object and observer.

Given these conditions a description of the detection and recognition processes depends on a number of pertinent parameters, many of which have large permissible ranges.

#### 1. Illumination

The source of illumination influences the detection process primarily as a function of the brilliance or intensity of the illumination. Bright sources such as direct sunlight enable the eye to perceive

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*In 1942, Hecht, Schlaer, and Pirenne performed an experiment basic to much of the psychological work concerned with vision and perception. The results of the experiment show that under optimum conditions a normal human observer will report a flash 60 percent of the time when only about 9 or 10 quanta from the flash are absorbed by the visual pigment in the retina.[8] For comparison, a typical lighted flashlight bulb radiates about $2 \times 10^{15}$ quanta per millisecond.

color, cause shadows, contribute to good resolution, and permit the use of filters if desired. If the light source is diffuse (e.g., daylight on cloudy days, starlight) then shadows do not occur. As the light level is decreased a point is reached after which color cannot be discerned, and foveal vision becomes of minor value so that the resolution capability is reduced. Artificial illumination can be used in low ambient light conditions, but the penalty is often noise from backscattered light.

2. Contrast

Contrast is a result of the object (or a part of the object) and its surround having different luminous flux in the direction of the observer, or different colors, or both.

a. Luminance

Differences in luminous flux are contributed to by differences in reflectances of the materials in the object and background, the textures, the orientations to the illuminant and observer, and shadows. The reflectance of a material is a function of wavelength, the composition of the material, its texture, and the angles of incident illuminant and observer with the material. For certain angles and textures, a specular reflection of the illumination source (e.g., sun) may occur in the direction of the observer. This specular reflection, or shine, can make objects easily detectable, even if the area of the object is below the resolution limit of the eye for nonspecular reflectance of the illuminant. Shine is a function of the distance from which the material is viewed. For example, burlap is a nearly perfect diffuse reflector when viewed at short ranges; however, at long ranges it can appear to be bright when viewed from certain directions.

b. Color

Differences in color are primarily attributable to different reflectance versus wavelength characteristics for the object and its surround. However, the apparent colors and textures vary as a function of the distance and resolution detail obtained at the time of observation. Materials that appear multicolored when viewed in detail may appear as a single color when viewed under poor resolution conditions and the apparent color may change as the distance is varied (see the Appendix).

3. <u>Line-of-Sight</u>

If there is no opaque material on the straight line between the object and observer, then line-of-sight is said to exist. However, the atmosphere may contain smoke, fog, and/or rain, and there may be vegetation along the path. Thus the amount of light signal leaving the object toward the observer may combine with light from these intervening sources so that the signal is hard or impossible to detect. This degradation also causes a loss in effective resolution.

4. <u>Movement</u>

If illumination, contrast, and line-of-sight conditions are such that a signal from the object exists at the observer, then movement is likely to enhance the probability of detection. However, it is not understood what causes this phenomenon,* despite the research that a number of psychologists have conducted over a long period of time.[8-13] Their research has demonstrated that the contribution of motion to the detection process is a function of (1) direction of motion--the chance of detection being best when movement is lateral, and worst when radial to the observer, (2) speed, (3) extent of movement, (4) region of retina that the image is on, and (5) the state of eye adaptation. Motion appears to be perceived either by noting that (1) different adjacent receptors in the retina are receiving the image as time passes, or (2) the object is occupying different positions as time passes. Whatever the mechanism is, the human observer is very sensitive to the perception of motion.

5. <u>Search Process</u>

From the viewpoint of countersurveillance, it is desirable to know the observer's search procedures, his familiarity with his area of responsibility, his expectations of finding enemy elements, and his alertness. Knowledge of the observers' coverage of the area as a function of time would enable a countersurveillance plan to be worked out that would expose the personnel for the shortest expected time, and perhaps when the observer is fatigued or not particularly expecting to detect his enemy. Although it is known that observers tend to search

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*In the preface to his book, "Visual Perception," T.N. Cornsweet writes, "I have excluded many topics ... and others because I do not know enough about them to explain them plausibly (for example, the perception of motion)."[6]

first those areas they consider most likely to be occupied by the enemy, it is not known how they select the next place to look, nor how they become aware of more detail as time progresses.[14] An observer's knowledge of the size of the things for which he is searching limits him to the speed with which he can search an area. For example, an airborne observer must search a smaller swath width from the aircraft track when searching for personnel than when searching for armored vehicles or buildings.

6. Clues

An observer rarely searches for his enemy with his eyes only and without some knowledge of his enemy. His ears or nose may alert him to look in specific directions, especially at night. Other intelligence sources may have alerted him to expect enemy personnel at a particular place at a particular time. Or he may observe animals or detect spoor that indicate personnel have recently been or may even still be at the place he is observing.

B. Additional Major Pertinent Parameters--for Recognition

Recognition is a classification process that basically requires the observer to relate the things he is observing to things he has learned in the past. This may be a direct matching such as matching an outline of a helmet and shoulders to his recollection of what a soldier looks like in the open, or it may be a complex combination of matching and deductive reasoning. All the parameters discussed above for detection, except the search process, remain pertinent for the recognition process. Additionally, to classify a detected anomaly of potential interest parameters such as the following can be of major importance: size, resolution, form, clutter, and context as well as the knowledge, training, and motivation of the observer, and any time constraints under which he may be operating.

1. Size

The size of a detected anomaly enables the observer to rule out quickly those anomalies that are much too large or small. The size is also a major factor in computing the maximum distance at which an object can be recognized.

2. <u>Resolution</u>

The resolution capability of an observer looking at a detected object is a function of his visual acuity, the light level, the size of the object, the contrast, and the intervening atmosphere. Countersurveillance can possibly affect several of these parameters to reduce the effective resolution capability of the observer. For recognition, the object must effectively subtend four to six or more resolvable elements at the sensor.[15]

3. <u>Form</u>

In 1957, Dr. H. R. Blackwell, at the symposium on "Form Discrimination as Related to Military Problems," sponsored by the Armed Forces--NRC Committee on Vision,[7] stated "...we don't know enough to solve a single military problem in the field of form discrimination." Discussions with him, Dr. Duntley, and Dr. Harris this year, and study of K. S. Fu's book[5] indicate the concerted opinion that it probably will still be a long time before sufficient progress is made to model the functions a human observer performs when he recognizes the features of an object of interest imbedded in a cluttered background. Most of the progress made in the fields of form discrimination and feature extraction has been on the basis of relatively simple two-dimensional geometric objects on simple backgrounds, with or without clutter.

However, form and features are at the heart of the recognition problem and work continues in this area in diverse ways. Image interpreters develop keys that are designed to help them recognize and classify features of forms that may be partially hidden in complex surroundings. A great deal of effort is being expended by the computer industry to produce reliable optical character readers (OCRs) that can tolerate more degrees of freedom than the early OCRs allowed. Research groups are working to improve automatons that can "see" and distinguish simple three-dimensional geometric shapes. And others are working directly on the problem of machine recognition of military objects in real backgrounds. However, the state of the art must still be considered inadequate for the purposes of delineating the process of recognizing military objects in relatively simple backgrounds from different perspectives, scales, light conditions, and so on, and is certainly inadequate for recognizing camouflaged military objects. Thus is is not expected that models which take form into account can be built until more data are developed on targets and the environment in which they are found. A recommendation on a direction to pursue in this area is found in Section IV-D. Until more work is accomplished, it probably will be necessary to incorporate the judgment of a human into those parts of models of the visual process that account for the effect of form.

### 4. Clutter

Clutter is important to the countersurveillance planner because he can use and control it relative to the form of the personnel he is trying to protect. He can reduce the probabilities of detection and recognition by increasing the clutter so that, in effect, the signal to noise ratio is reduced. Clutter can be used instead of direct concealment as a means of making the personnel harder for the observer to detect and recognize. In practice, detection (this term implies potential interest) and recognition occur almost simultaneously when an observer is viewing a cluttered field of view. The amount of time it takes to detect a form or pattern in a cluttered field of view varies with the amount of clutter, the size of the elements causing clutter relative to the size of the objects being sought, and the geometric distribution of the clutter elements. This time can probably be shortened for a particular observer by training and experience.

### 5. Context

The trained observer uses his training and prior knowledge of the enemy scene and environment to aid in searching for the enemy and for clues that may lead to the enemy. The clues he may observe and cues that he may receive from other sensors direct his search to areas that he is willing to spend more time examining in detail than other areas within his field of view. Prior estimates (correct or false) of the enemy's strength and intentions can cause varying amounts of motivation and alertness in the observer.

### 6. Knowledge and Training

Action reports indicate that soldiers who were raised in the country are significantly better observers in the jungle and countryside than are the soldiers who grew up in the city. However, it appears that this basic difference can be compensated for by thorough training on target signatures, clues, and search techniques. A thorough understanding of the possible countersurveillance techniques the enemy may use will be of help to the observer, especially against disguise and deception. Similarly, a camouflaged person's knowledge of the enemy's sensor systems and training to defeat them aids in maintaining good camouflage discipline.

7. Motivation

Very little of an observer's time is actually spent detecting and recognizing enemy soldiers. Fatigue and boredom are certainly factors to be considered in an observer's performance. Experiments have been done to evaluate the effects of artificial rewards and punishments on the performance of observers, but no quantitative data are available to indicate the effect of motivation deriving from battlefield pressures and the rewards and punishments of life and death. Motivation varies with time on duty, with the observer's assessment of the likelihood of finding anything, and the potential consequences if he does or does not. Thus, if a sufficient light signal for detection and recognition arrives at the observer from the camouflaged soldier, the probability of the observer detecting the soldier is dependent on the observer's motivation and consequent alertness. Although this is a major area of uncertainty, very little data exist to indicate the distribution of the probability of detection as a function of motivation or alertness.

8. Time

An airborne observer usually constrains the area that he searches because of the time that any one area is within his line-of-sight. The width of the area he can cover depends upon the size of the objects for which he is searching, the amount of clutter, the aircraft speed, and the cockpit geometry. Because of time constraints he may elect to search a given wider area less thoroughly, relying on cues and knowledge of the enemy to make such a decision quickly. For example, he may spend most of his time searching areas that are immediately adjacent to suspected enemy lines of communication, while only cursorily looking at the large areas a short distance away and within his line-of-sight.

The ground observer in an observation post is likely to have sufficient time to search his area of responsibility in the detail he feels is adequate to detect soldiers. However, his search process is likely to vary with time, as is his efficiency. Observers on patrol and moving will often have to sacrifice searching in sufficient detail to find enemy soldiers within their line-of-sight. Thus the efficiency of their search process is likely to be reduced when they are moving through a cluttered area. On the other hand, movement and time allow the patrol to view detected anomalies from different aspects to aid in the recognition process.

On clear days the shadows change with time. The resulting change in the form of the shadows gives the aerial observers optimal times for flight to take advantage of the shadow for both detection and recognition. The changing shadow patterns must also be considered seriously by the soldier employing countersurveillance discipline to take advantage of shadows of natural objects and to minimize the value of his own shadow to any observer.

## IV MODELING EFFORTS

### A. General

The desire has been to develop a model of the visual process that would correctly relate the parameters described in Section III to permit the calculation of the probabilities of detection and recognition of camouflaged personnel in military situations. It has become increasingly evident that an adequate cause and effect model cannot be developed at this time since the theory explaining the relationships among many of the parameters is not well developed, nor is likely to be in the near future. Although much of the theory for the physics of light as used in this application is understood, and applicable data have been generated and collated, little theory or useful data exist for modeling the effects of the psychologically oriented parameters. This deficiency is particularly grave because the degree of success of camouflage techniques for personnel is critically dependent on the human observer's ability to recognize forms or patterns related to camouflaged personnel and to synthesize the pieces of data he perceives into intelligence.

Much of the germane research done by psychologists has been aimed at describing and quantifying the variability of specific parameters from observer to observer and even with the same observer at different times. For example, experiments have been performed to determine the probability distributions on such parameters as:

(1) The minimum light intensity threshold of the eye[6]
(2) The minimum luminance contrast required to recognize simple shapes on homogeneous backgrounds[16]
(3) The minimum differences in color that can be detected[17]
(4) The minimum detectable motion of a light source.[8]

Most of the experiments have necessarily been tightly constrained to try to evaluate the variability of the parameter of interest as a function of another parameter or two. Thus the experiments are sterile insofar as each attacks only one aspect of the many faceted problem of a soldier in the field trying to detect and recognize a camouflaged enemy soldier.

The data and theory that have resulted from previous research and modeling efforts indicate that luminance contrast, color contrast, movement, and form are basic elements in the visual process of detecting and identifying a camouflaged soldier. An attempt was made to develop models for the effects of each of these basic elements and their associated pertinent parameters, with the intent of then integrating the resulting models into a single model that would be useful in studying the visual detection, recognition, and concealment processes for personnel in various environments.

## B. Luminance and Color Contrasts

A model for the determination of the effects of luminance and color contrasts on target detection was developed and is presented as the appendix of this report so that it can be used as an independent document. The appendix presents theory on color contrasts and luminance contrasts separately and then combines them to yield a model of their combined effects on target detection. The appendix constitutes the main analytical contribution of this research effort to the community's tools and understanding of the visual process.

## C. Movement

The attempts to account realistically for the effects of movement were frustrating and unsuccessful from the point of view of being able to develop a model that combines the factors important to the perception of motion in a deterministic or probabilistic manner. Neither were sufficient data identified to permit the development of an empirical model. The basic reason for not being successful in this effort is probably the relatively primitive state of knowledge of the perception of motion, as pointed out earlier. A contributing reason is that the detection of movement of an object with respect to its background is dependent on a luminance or color contrast existing, so that basic experiments are somewhat harder to design.

## D. Form Discrimination

Similarly, the primitive state of knowledge about shape, form, or pattern discrimination precludes the development of a sophisticated submodel for that part of the visual process. Since form discrimination is the key to the recognition of camouflaged personnel, it is important that an adequate model be developed. As also indicated earlier, a great deal of research is being conducted in this basic area for a variety of applications. However, not enough data have yet been developed about military target forms in relation to the environment in which such targets are found.

It does not appear feasible to develop a cause and effect model of form discrimination in the near future. To develop an empirical model for this process, whether or not a human is involved in exercising the model, an empirical data base to use in classifying targets and target backgrounds is needed. A method for classifying military targets is presented in an earlier report of this project,[18] but a method of classifying backgrounds--or more properly, surrounds of the targets--is needed.

Although the exact nature and number of the background parameters that affect the visual perception process are not well known, it would appear that a complete set of such parameters, at a minimum, would include qualitative and quantitative indices for the following factors:

- Nature of the elements within a background
- Size distributions of elements within a background
- Extent of the background that is viewed by the observer
- Relative mix of elements within the background
- Degree of order or disorder of elements, both with respect to individual form and grouping
- Color and luminance contrasts within the observer's field of view
- Illumination level

Unfortunately, the present state of knowledge does not permit such detailed indexing to be performed. The result is that the basic research efforts to classify backgrounds should be designed around the subjective abilities in background classification of individuals experienced and knowledgeable in visual observation.

To develop the basic research data, a group of such individuals would be required to select a set of representative visual backgrounds that are of military interest. The visual backgrounds might be presented in the form of large photographic prints. The group would then be asked on an individual basis to separate the photographs into a finite number of sets of similar scenes and to state the characteristics of the scenes that governed the selections. In this phase of the experiment, care would have to be exerted to ensure that different views of the same scene were included.

On the basis of an analysis of the group classifications, a preliminary set of characteristics would then be chosen. In this step, attempts would be made to relate the characteristics defined by the group to the factors listed previously and to other factors unknown at present. When enough characteristics have been defined, sufficient data will exist for the conduct of the subsequent experiment of placing one or more targets within such backgrounds and determining the ability of visual observers to recognize such targets. The second experiment would be designed to discover the significance and interactions among the parameters.

Until such experiments fill the present void of data on the characterization of target backgrounds, little can be done to construct analytical visual models that incorporate the effect of shape, form, or pattern.

## V CONCLUSIONS AND RECOMMENDATIONS

There is inadequate theory and data to formulate analytic models for assessing quantitatively the contributions of movement and form on the process of visual detection and recognition of camouflaged personnel.

Provisions for enhancing the probability of detection to account for some of the effects of target motion can be incorporated when the model developed for color and luminance effects is incorporated into SCREEN. However, the magnitude of the enhancement will have to be determined on the basis of empirical data that do not yet exist.

It will probably be necessary (and to some extent desirable) to use human judgment in models that account for form discrimination in sufficient detail to recognize camouflaged personnel.

It will also be necessary to use men to perform the intelligence synthesis function and hence to a large extent the evaluation of deception techniques.

The model developed to account for the effects of color and luminance contrasts is of potential use in application areas such as the analysis of

(1) Uniform colors
(2) Camouflage colors and patterns
(3) The value of visual filter systems
(4) The effect of visual screening systems
(5) The use of colored signal systems

To provide the possibility of modeling the effects of movement and form discrimination data should be developed on the basis of a classification system, with empirical data on representative elements in each category of the classification system. In particular, data should be generated and used in developing a classification system for backgrounds in environments likely to be encountered in military conflicts. Both Dr. Blackwell of Ohio State University and Dr. Duntley of Scripps Institute of Oceanography are working on methods of quantifying an observer's performance of a visual task. Once a classification system is developed, their methods could perhaps be used to obtain the empirical inputs needed for a model of form discrimination. Note that in both of their approaches a human is used to perform the visual task and recognition judgments.

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Appendix

A MODEL FOR THE DETERMINATION OF THE EFFECTS OF COLOR AND LUMINANCE ON TARGET DETECTION

Appendix

# A MODEL FOR THE DETERMINATION OF THE EFFECTS OF COLOR AND LUMINANCE ON TARGET DETECTION

## 1. Introduction

The ability of a visual observer to detect objects at a distance depends on a number of factors, included among which are luminance and color contrast. For many years, technologists active in the area of visual surveillance and surveillance-system countermeasures have tended to avoid the quantitative physical and psychological (psychophysical) aspects of distant color discrimination, justifying their actions by the statement that color differences tend to disappear rapidly as the ranges between an observer and sets of objects increase. Despite this lack of attention to the more fundamental aspects of color discrimination color research of an empirical nature continues within agencies and organizations concerned with photography and camouflage. This research probably could be materially assisted by basic information on the impact of color on the detection process. Moreover, there is reason to believe that, out to a few kilometers--ranges that encompass almost the total capability of a visual observer in typical tactical environments--color differences can have significant effects on the detection process.

In October 1970, SRI was requested by the U.S. Army Mobility Equipment Research and Development Command (USAMERDC), as part of the research activity under Contract No. DACA-76-69-C-0003, to develop a detailed model for the visual discrimination of camouflaged personnel. In partial response to that request, designated as Task 6 of the contract, a detailed visual model incorporating both color and luminance contrast factors has been developed.

This Appendix describes the work that was performed and the models that were developed. Section 2 summarizes the historical background of luminance and color discrimination, and discusses the derivations of color mixture equations. Quantitative relationships for the atmospheric degradation of luminance and color contrast are developed in Section 3. Section 4 summarizes the results of some sample computations done with the models in Sections 2 and 3. The Appendix is concluded with two annexes: Annex A contains color coordinate and spectral reflectance data for selected objects; and Annex B describes methods for the determination of atmospheric extinction coefficients.

## 2. The Characterization of Color and Luminance

### a. General

In 1802, Young postulated that human color vision might be explained by the existence of individual retinal receptors composed of a number of fibers, each of which was sensitive to a specific color. To illustrate his hypothesis, he discussed a receptor consisting of three fibers, each of which was sensitive to one of the primary colors. Fifty years later, Helmholtz pointed out that it was unnecessary to postulate three types of fibers, provided that a single fiber could transmit three different color messages to the brain. Five years later, in 1857, J. C. Maxwell provided an experimental foundation for the trichromatic nature of human color vision by demonstrating that a monochromatic light could be simulated to a human observer by a combination of two other monochromatic lights and a white light. These measurements were extremely significant in that they provided a set of quantitative facts that ultimately permitted the development of quantitative color scales.

Since Maxwell, much has been learned in the field of human color vision. The physics and photochemistry of the eye and its component parts have been more or less clearly elucidated, and theories describing the visual mechanisms of the retina and the basic nature of human psychological responses to color have been classified. Most important, however, methods for the quantitative characterization of color in terms of a "standard" human observer have been developed. The existence of these color "metrics," as complex and as imperfect as they are has permitted much to be done in standardizing color and light sources, and in determining the effects of environmental factors on human color vision.

Below are described some of the relationships that are significant in the determination of color and luminance differences among objects. The methods used follow the treatments of Graham,[1*] Judd and Wyszecki,[2] and LeGrand.[3]

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*References for this Appendix are shown at its end.

## b. The Basic Relationship

### 1) Monochromatic Radiation

Let $L_1$, $L_2$, and $L_3$ be the luminance of a selected set of monochromatic light sources $S_1$, $S_2$, and $S_3$, and let $L_w$ be the luminance of a white light source, $S_w$. By adjustment of luminance levels, it can be shown that with respect to a human observer, the color obtained by the illumination of a perfectly diffusing reflector by two of the monochromatic lights can be matched, both in color and luminance, by the other monochromatic source and the white light. Mathematically, the relationship can be written

$$L_1 + L_2 \equiv L_3 + L_w \quad , \tag{1}$$

where the symbol $\equiv$ implies both color and luminance match.* The wavelength of the source, $S_3$, is called the dominant wavelength of the color mixture $S_1 + S_2$.

The terms in Eq. (1) can be treated as algebraic quantities, and a generalized expression for monochromatic color mixtures can be written as:

$$L_p + L_q + L_r \equiv L_w \quad . \tag{2}$$

A negative luminance value for a monochromatic source, which has no physical meaning, implies that the source so represented is the one that must be mixed with the white light to obtain the desired color mixture match.

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*It should be noted that a luminance match can exist without a color match, i.e., $L_1 + L_2 = L_3 + L_4$, and vice versa.

Let a set of light sources be selected so that

$$L_p' + L_q' + L_r \equiv L_w \quad . \tag{3}$$

Since the choice of wavelengths is somewhat arbitrary, the white reference source, in theory, can be matched by another set of lights,

$$L_p'' + L_q'' + L_\lambda \equiv L_w \quad . \tag{4}$$

Subtraction of Eq. (4) from Eq. (3) and rearranging yields the general law of color mixtures,

$$L_p + L_q + L_r \equiv L_\lambda \quad , \tag{5}$$

where

$$L_p \equiv L_p' - L_p'' \quad , \tag{6}$$

and

$$L_q \equiv L_q' - L_q'' \quad . \tag{7}$$

The law states that with respect to a human observer, any monochromatic light source can be considered to be the sum of three other monochromatic light sources.

2) Multichromatic Radiation

Let a set of three monochromatic sources illuminate a screen. By Eq. (5), we have,

$$\left.\begin{aligned} L_1 &\equiv L_p + L_q + L_r \\ L_2 &\equiv L_s + L_t + L_u \\ L_3 &\equiv L_v + L_w + L_x \end{aligned}\right\} \quad . \tag{8}$$

Summing each column, there obtains

$$L_1 + L_2 + L_3 \equiv \left(L_p + L_s + L_v\right) + \left(L_q + L_t + L_w\right) + \left(L_r + L_u + L_x\right) \quad . \tag{9}$$

But by Eq. (5) it is true that

$$\left.\begin{aligned} L_p + L_s + L_v &\equiv L_a \\ L_q + L_t + L_w &\equiv L_b \\ L_r + L_u + L_x &\equiv L_c \end{aligned}\right\} , \qquad (10)$$

and thus,

$$L_1 + L_2 + L_3 \equiv L_a + L_b + L_c \quad . \qquad (11)$$

Equation (11) can be generalized and for any set of n monochromatic lights it can be shown that

$$L_n \equiv \sum_{i=1}^{n} L_i \equiv L_\alpha + L_\beta + L_\gamma \quad , \qquad (12)$$

where $L_n$ represents the color and luminance of the mixture of the n lights, and $S_\alpha$, $S_\beta$, and $S_\gamma$ are some selected set of monochromatic sources.

3) The Primary Sources

In the development of Eq. (5) it was stated that $S_r$ could be replaced by $S_\lambda$ and a match could be obtained by a suitable adjustment of the luminance levels of the other two sources, $S_p$ and $S_q$. This statement is true only if none of the individual sources, $S_p$, $S_q$, or $S_r$ can be matched by a combination of the other two. Thus, the selection of the reference light system is arbitrary, subject to the constraint listed, and any light source can be matched by a proper selection of the luminance levels of the three monochromatic reference sources. The reference sources so selected are referred to as "primaries."

4) Changes in Primaries

Equation (12) can be represented as a vector equation of the following form:

$$\underline{x} = x_1 \underline{i}_1 + x_2 \underline{i}_2 + x_3 \underline{i}_3 = \sum_{k=1}^{3} x_k \underline{i}_k \quad ,^* \tag{13}$$

where $\underline{x}$ represents the luminance and color of the source, $\underline{i}_k$ is a unit luminance along the $k^{th}$ primary color axis, and $x_k \underline{i}_k$ is the luminance level of the $k^{th}$ primary. Define a new set of primaries for which the unit luminance along each of the new color axes is:

$$\left.\begin{aligned} \underline{i}_1' &= q_{11} \underline{i}_1 + q_{12} \underline{i}_2 + q_{13} \underline{i}_3 \\ \underline{i}_2' &= q_{21} \underline{i}_1 + q_{22} \underline{i}_2 + q_{23} \underline{i}_3 \\ \underline{i}_3' &= q_{31} \underline{i}_1 + q_{32} \underline{i}_2 + q_{33} \underline{i}_3 \end{aligned}\right\} ,$$

or

$$\underline{i}_k' = \sum_{r=1}^{3} q_{kr} \underline{i}_r \quad , \quad (k = 1, 2, 3) \quad , \tag{14}$$

in terms of the old color axes. In the new primary system, the color vector $\underline{x}$ becomes

$$\underline{x} = x_1' \underline{i}_1' + x_2' \underline{i}_2' + x_3' \underline{i}_3'$$

$$\underline{x} = \sum_{k=1}^{3} x_k' \underline{i}_k' \quad . \tag{15}$$

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*Since the discussion that follows deals primarily with both color and luminance, the symbol ≑ has been dropped for simplicity in favor of the equal sign. Where only luminance is indicated, specific statements will be made in the text.

Substituting Eq. (14) into (15), there obtains

$$\underline{x} = \sum_{k=1}^{3} \sum_{r=1}^{3} x_k' \, q_{kr} \, \underline{i}_r \tag{16}$$

$$\underline{x} = \sum_{r=1}^{3} \left( \sum_{k=1}^{3} x_k' \, q_{kr} \right) \underline{i}_r \quad , \tag{17}$$

so that

$$x_r = \sum_{k=1}^{3} q_{kr} \, x_k' \quad . \tag{18}$$

Thus, the relationship between the coefficient in each primary system may be determined from the vector equation

$$\underline{x} = Q^T \, \underline{x}' \tag{19}$$

$$Q^T = \begin{vmatrix} q_{11} & q_{21} & q_{31} \\ q_{12} & q_{22} & q_{32} \\ q_{13} & q_{23} & q_{33} \end{vmatrix} \tag{20}$$

and Q is the coefficient matrix of Eq. (14)

$$Q = \begin{vmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{vmatrix} \tag{21}$$

Since the unit vectors of the new primaries are linearly independent (i.e., one primary is not a mixture of the other two, an inverse matrix, $(Q^T)^{-1}$, exists and

$$\underline{x}' = \left(Q^T\right)^{-1} \underline{x} \quad . \qquad (22)$$

By these arguments, it can be seen that the specification of color and luminance of a color mix can be made in terms of sets of three linearly independent monochromatic primaries, all of which can be related to one another.

It can also be shown by a sequential application of Eq. (13) that the primaries need not be monochromatic. In such instances, as in the monochromatic case, a negative primary luminance coefficient identifies the source that is mixed with the white source. However, in the multichromatic case, the negative luminance value can also imply a requirement for filtering.

c. Tristimulus Value and Chromaticity Coordinates

1) Tristimulus Value

Let $P_i$ be the radiant flux* from a source, $S_i$. Accordingly, the luminous flux, $F_i$, is given by

$$F_i = K_m V_i P_i \quad , \qquad (23)$$

where

$V_i = K_i/K_m$ = relative luminous efficiency of $S_i$,

$K_i$ = luminous efficiency of $S_i$, and

$K_m$ = maximum luminous efficiency (680 lumens/watt).

In colorimetry, it is often convenient to use units of different magnitudes for different primaries. Thus, let a tristimulus value be defined as:

$$C_i = \frac{P_i}{e_i} \quad , \qquad (24)$$

*See Annex A for unit definitions (in Tables A-13 to A-15).

where $e_i$ is the unit of radiant flux for the source. Substituting back into Eq. (23), the tristimulus value becomes:

$$C_i = \frac{F_i}{\ell_i} \qquad (25)$$

where $\ell_i$ is the luminous unit of the source and is equal to

$$\ell_i = K_m V_i e_i \quad . \qquad (26)$$

2) Relation between Tristimulus Value and Luminous Flux

The luminous flux, $F_s$, of any source, S, can be expressed as the sum of the luminous fluxes of the primary components that match the luminance and color of the source, i.e.,

$$F_s = F_1 + F_2 + F_3 \quad ,$$

and (27)

$$C_s = C_1 + C_2 + C_3 \quad ,$$

where $F_1$, $F_2$, and $F_3$ are the luminous fluxes and $C_1$, $C_2$, and $C_3$ are the tristimulus values of the primaries. It follows that

$$F_s = \ell_1 C_1 + \ell_2 C_2 + \ell_3 C_3 \quad . \qquad (28)$$

It should be noted that these relationships are developed in terms of a human observer. Thus, a color and luminance match does not imply an equality of $e_1 C_1 + e_2 C_2 + e_3 C_3$ with the radiant flux of the source.

3) Chromaticity Coordinates

In many problems, only the color variables are of interest and only relative values of the tristimulus values are required. To treat such problems, the term chromaticity coordinate has been defined as:

$$c_i = \frac{C_i}{C_1 + C_2 + C_3} = \frac{C_i}{C_s} \qquad (29)$$

where

$$c_1 + c_2 + c_3 = 1 \quad , \tag{30}$$

and

$$\ell_s = \frac{F_s}{C_s} = \ell_1 C_1 + \ell_2 C_2 + \ell_3 C_3 \quad . \tag{31}$$

The term $\ell_s$ is called the trichromatic unit of the source, S, and is a function only of the color of the source.

It follows from the definition of the chromaticity coordinate that a two-dimensional grid system, with two of the coordinates comprising the axes, could provide a geometrical representation for a color system. Figure 1 illustrates a chromaticity diagram developed by Wright in 1929, based on a monochromatic red-green-blue primary system in which the units of the red and blue primaries are chosen so that equal tristimulus values of each with a small negative blue component produce visual stimulation equivalent to yellow radiation of wavelength 582 $m\mu$, and equal tristimulus values of the blue and green primaries with appreciable negative red components produce visual stimulation equivalent to 494 $m\mu$. The curve on the figure, called the spectrum locus encompasses all of the visible wavelengths. The equienergy source depicted is a source that emits equal energies at all wavelengths.

As can be seen from the diagram, Wright's system required that certain colors below 530 $m\mu$ and above 650 $m\mu$ be defined in terms of negative chromaticity coordinates, a situation that was unsatisfactory to the workers at that time. There is also some difficulty in defining the source colors and primaries in an unambiguous manner.

4) The Distribution Coefficients

To make color comparisons, it is sometimes necessary to compute tristimulus values from source energy distribution curves. Consider a source, S, and the radiation from that source in a finite waveband $\Delta\lambda_j$. The radiant flux from the source in the waveband is $E_{\lambda_j} \Delta\lambda_j$. Since the tristimulus values are additive, this energy flux corresponds to a tristimulus value of $\Delta C_{\lambda_j}$ for the waveband. By definition, the chromaticity coordinates of the waveband are

$$c_{i\Delta\lambda_j} = \frac{\Delta C_{i\lambda_j}}{\Delta C_{\lambda_j}} \quad . \tag{32}$$

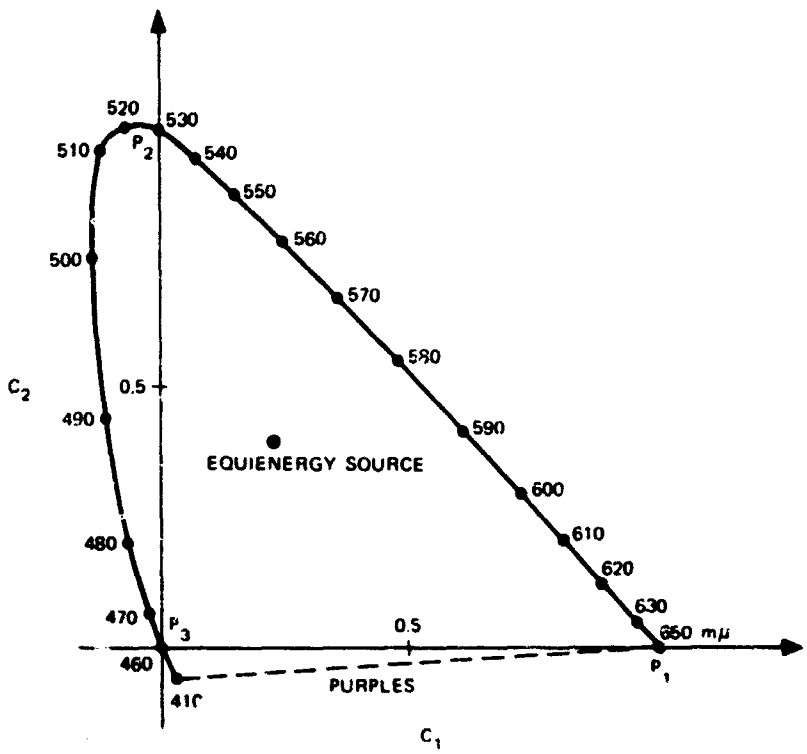


FIGURE 1 WRIGHT'S CHROMATICITY DIAGRAM

Similarly, for the total emission from the source, we have

$$C_i = \sum_j \Delta C_{i\lambda_j} = \sum_j c_{i\Delta\lambda_j} \Delta C_{\lambda_j} \quad , \tag{33}$$

where the summation is done over all wavelengths in the source, the luminous flux corresponding to the radiant flux is

$$\Delta F_{\lambda_j} = K_m V_{\lambda_j} E_{\lambda_j} \Delta\lambda_j \quad , \tag{34}$$

and if $\ell_\lambda$ is the luminous unit for wavelength $\lambda$, then

$$\Delta C_{\lambda_j} = \frac{\Delta F_{\lambda_j}}{\ell_{\lambda_j}} = \frac{K_m V_{\lambda_j} E_{\lambda_j} \Delta\lambda_j}{\ell_{\lambda_j}} \tag{35}$$

which by Eq. (33) yields

$$C_i = Km \sum_j \left( \frac{C_{i\lambda_j} V_{\lambda_j} E_{\lambda_j} \Delta\lambda_j}{\ell_{\lambda_j}} \right) \tag{36}$$

Define a distribution coefficient

$$\bar{c}_{i\Delta\lambda_j} = \frac{C_{i\lambda_j} V_{\lambda_j}}{\ell_{\lambda_j}} \quad . \tag{37}$$

Substituting Eq. (37) into (36) yields

$$C_i = K_m \sum_j \bar{c}_{i\lambda_j} E_{\lambda_j} \Delta\lambda_j \quad , \tag{38}$$

a relationship that permits the relatively simple computation of tristimulus values and chromaticity coordinates from tables of source distribution coefficients and radiant energy distributions. From Eqs. (38) and (31), it can be seen that

$$V_{\lambda_j} = \sum_{i=1}^{3} \ell_i \bar{c}_{i\lambda_j} \quad , \tag{39}$$

and

$$\ell_{\lambda_j} = \sum_{i=1}^{3} \ell_i c_{i\lambda_j} \quad . \tag{40}$$

d. <u>The XYZ System</u>

In 1931, the CIE* proposed that the XYZ primary system be adopted as an international reference system. The system is based on the use of a set of hypothetical primaries with the following characteristics:

(1) The points representing the primaries X and Z were assumed to have no luminance characteristics, permitting the total luminous flux of the color to be represented by the value of the Y primary, the luminous unit of which was chosen arbitrarily to be unity.

(2) The sides XZ and YZ of the triangle formed by the primaries are tangent to the spectrum locus, thus ensuring positive values for all chromaticity coordinates.

(3) An equienergy source is equidistant from both the XZ and YZ axes.

From the characteristics of the primaries, i.e.,

$$\ell_x = \ell_z = 0$$

$$\ell_y = 1 \tag{41}$$

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*Commission Internationale de l'Eclairage.

and Eq. (37), distribution coefficients in the XYZ system become

$$\bar{x}_{\lambda_j} = \frac{V_{\lambda_j} x_{\lambda_j}}{y_{\lambda_j}} \quad , \quad \bar{y}_{\lambda_j} = V_{\lambda_j} \quad , \quad \bar{z}_{\lambda_j} = \frac{V_{\lambda_j} z_{\lambda_j}}{y_{\lambda_j}} \quad . \qquad (42)$$

Curves of the distribution coefficients for the visible wavelengths in the XYZ system are shown in Figure 2, and the spectrum locus for the visible wavelengths is shown in Figure 3. Numerical values for the distribution coefficients of the visible wavelengths of selected sources are given in Annex A.

e. The Determination of Tristimulus and Coordinate Values in the XYZ System

In the XYZ system, the tristimulus values of any source, S, are:

$$\left.\begin{aligned} X_s &= K_m \sum_j \bar{x}_{\lambda_j} \Delta\lambda_j \\ Y_s &= K_m \sum_j \bar{y}_{\lambda_j} E_{\lambda_j} \Delta\lambda_j \\ Z_s &= K_m \sum_j \bar{z}_{\lambda_j} E_{\lambda_j} \Delta\lambda_j \end{aligned}\right\} \qquad (43)$$

where $Y_s$ is equal to the luminance of the source. Thus, the tristimulus values and chromaticity coordinates can be compared directly from absolute radiant energy data. However, in most instances, published radiant energy data are relative. Thus, it is necessary to convert Eq. (43) into a form that will handle relative energy distribution values to computer chromaticity coordinates.

All radiant energy distribution tables are of a form such that

$$\frac{E_{\lambda_j} \Delta\lambda_j}{R_T} = \frac{W_{\lambda_j} \Delta\lambda_j}{\sum_j W_{\lambda_j} \Delta\lambda_j} \quad . \qquad (44)$$

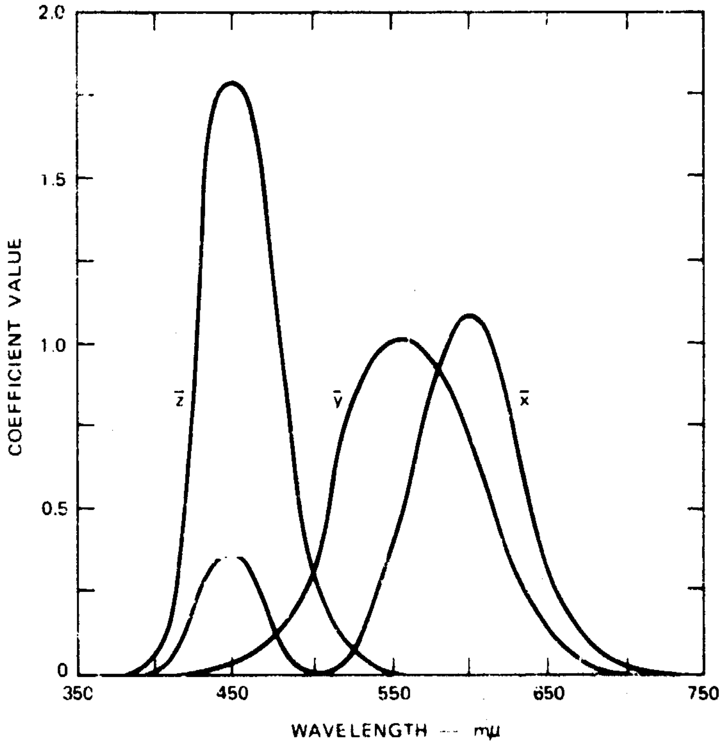



FIGURE 2 DISTRIBUTION COEFFICIENTS, XYZ PRIMARIES

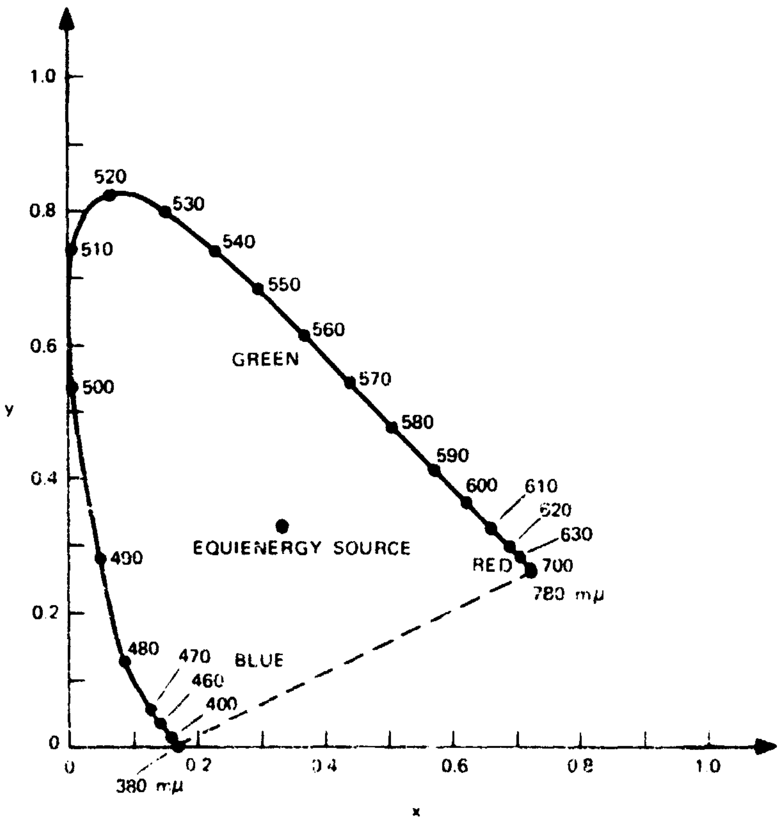



FIGURE 3 XYZ CHROMATICITY DIAGRAM

where $R_T$ is the total emitted radiation of the source, $W_{\lambda_j}$, $\Delta\lambda_j$, is the table entry for the wavelength interval $\Delta\lambda_j$, and $\sum_j W_{\lambda_j} \Delta\lambda_j$ is the sum of all table entries. Substituting Eq. (44) into (43), rearranging, and dividing by $K_m \sum_j W_{\lambda_j} \lambda_j / R_T$, there is obtained a set of relative tristimulus values

$$X_s' = \sum_j \bar{x}_{\lambda_j} W_{\lambda_j} \Delta\lambda_j$$

$$Y_s' = \sum_j \bar{y}_{\lambda_j} W_{\lambda_j} \Delta\lambda_j \qquad (45)$$

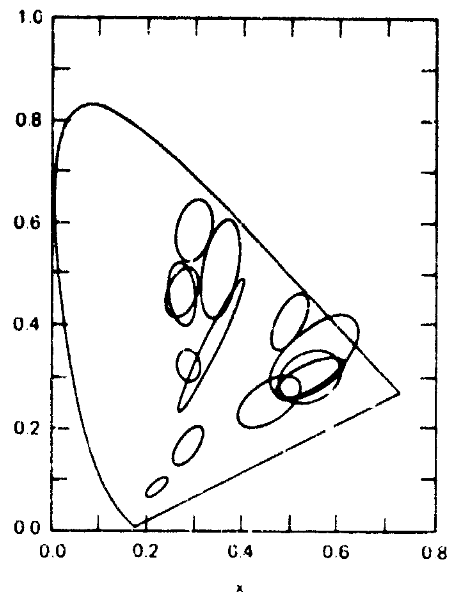
$$Z_s' = \sum_j \bar{y}_{\lambda_j} W_{\lambda_j} \Delta\lambda_j$$

which can be used to compute chromaticity coordinates and compare unit luminosities. Values of $W_{\lambda_j}$ for Standard illuminants A and C are summarized in Table A-5 of Annex A.

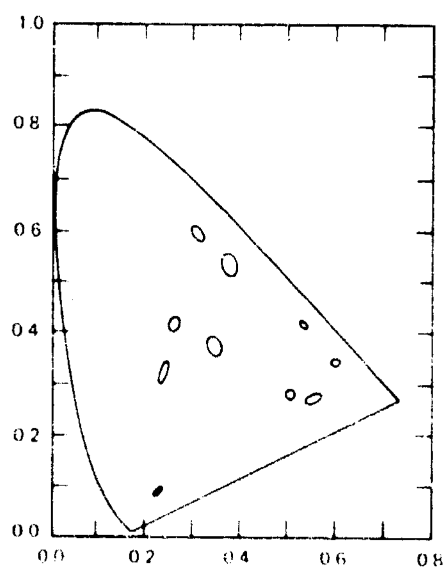
f. Detectable Chromaticity Differences

Studies of detectable differences in chromaticity have been made by MacAdam,[4-6] Brown,[7] and others.[8] Of these efforts, the most significant is the work of MacAdam[6] in which he compared the ability of visual observers to detect chromaticity differences for 3' and 4.2° fields of view. Figure 4 summarizes the result of his studies. For the smaller fields of view, which correspond to a man at a range of approximately 2 kilometers from an observer, colors having chromaticity-coordinate differences of the order of $10^{-2}$ units are differentiable by the average observer; for larger fields of view, differentiable differences are of the order of $10^{-3}$ chromaticity coordinate units.

It is interesting that the apparent color of an object is a function of the field of view subtended by the object at the observer's position. Middleton quotes Wright, who found that by the time a field has been reduced to 15' of arc, the mixture data (chromaticity coordinates) had changed markedly from the actual color mixture data.[9] Middleton and Holms[10] showed that when observers identified colored test patches subtending fields of view of 2' of arc, the coordinates of the patches called by the observers were offset from the actual values, with the




**(a) CONSTANT LUMINANCE-DISCRIMINATION ELLIPSES FOR 3' FIELD (ELLIPSES ENLARGED 10 TIMES)**




**(b) CONSTANT LUMINANCE-DISCRIMINATION ELLIPSES FOR 4.4' FIELD (ELLIPSES ENLARGED 10 TIMES)**

FIGURE 4 DISCRIMINATION ELLIPSES FOR TWO FIELDS OF VIEW yellow, green, and yellow-greens being called more blue than they actually were; the blues, violets, and crimsons being called less blue than they were; and the reds, oranges, and blue-greens being called essentially the same as the actual colors. In general, the color-mixture data called by the observers for the small patches were offset from the actual coordinates along a line roughly parallel to the y coordinate axis toward a line intersecting the monochromatic locus at approximately 490 and 600 mμ. In all instances, the change in color was dependent on the observer and varied significantly with specific individuals. However, despite these apparent changes in color data with object size, the observers maintained an ability to detect relatively small chromatic differences.

### 3. The Color and Luminance of Distant Objects

#### a. General

The apparent luminance of an object in a specific wavelength interval at a distance is determined by two concurrent processes: light emanating from the object is attenuated by scattering and absorption in the atmosphere over the path distance, and atmospheric or "air light" is scattered into the line of sight of the observer from other regions of the atmosphere all along the path of sight. The sum of radiation striking the observer's retina determines the apparent luminance of the object at the observer's position.

The atmosphere can be regarded as a material that diffuses light and is illuminated throughout by natural sources, such as the sun or moon. Many models have been developed concerned with the reduction of luminance by the atmosphere[11] and the detection of military targets.[12,13] However, only limited treatments have been given to the effect of the atmosphere on the colors of distant objects.[9] Described below are some of the effects the atmosphere has on color and luminance.

#### b. The Reduction of Luminance by the Atmosphere

With reference to Figure 5, let an extended source at 0 having a luminance, $L_\lambda(0)$, in the wavelength interval, $\Delta\lambda$, in the direction, $\theta$, be observed by an observer at P. The path of sight, OP, can be divided into a large number of infinitesimally small slabs of atmosphere, whose faces are normal to the line of sight. At a distance, r, from the source, the luminance, $L_\lambda(r)$, is diminished by scattering and absorption in passing through thickness, dr, the magnitude of the

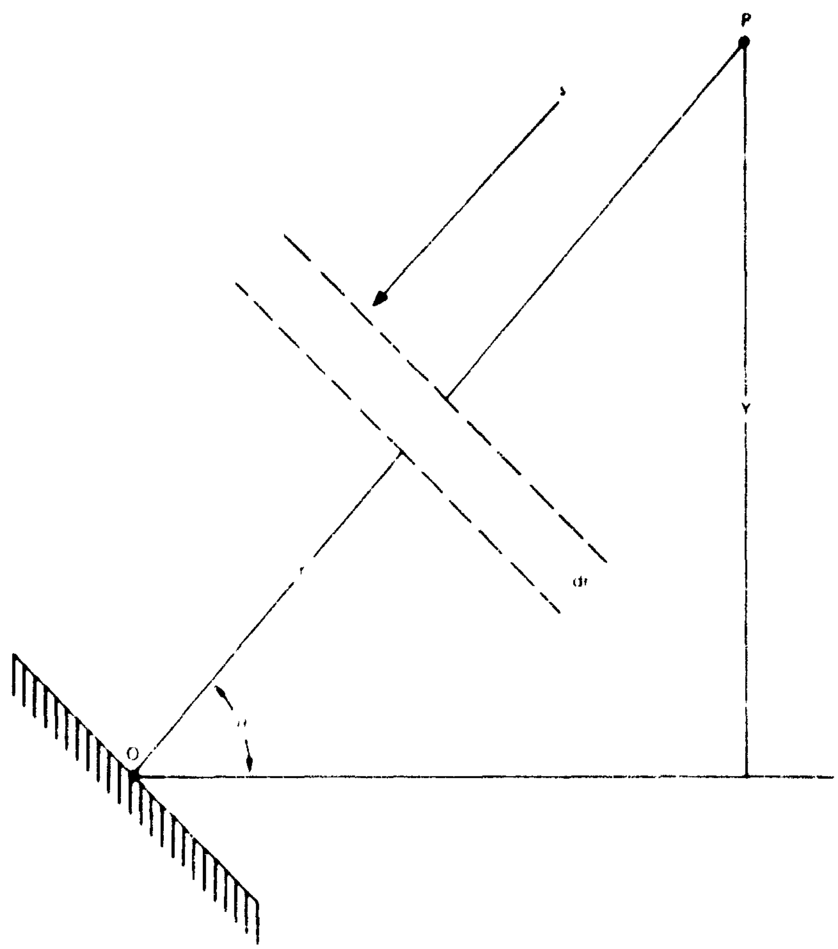



FIGURE 5 MODEL FOR LUMINANCE REDUCTION IN ATMOSPHERE

change being proportional to the luminous flux. At the same time, the flux is augmented in the lamina of atmosphere by air light, $\ell_\lambda(r)$, and by backscattering from the flux, s, moving in the direction toward the source. The total change in flux becomes

$$\frac{dL_\lambda(r)}{dr} = \beta_\lambda(r)\, L_\lambda(r) + \ell_\lambda(r) + b_\lambda(r)s_\lambda \quad , \qquad (46)$$

where $\beta_\lambda(r)$ is the atmospheric extinction coefficient (see Annex B), and $b_\lambda(r)s_\lambda$ is the backscattered energy from the flux.

The term $\ell_\lambda(r)$ is a function of the luminous density of the atmosphere, and the backscattering from the flux, $b_\lambda(r)s_\lambda$ makes a negligible contribution to the luminous density of the lamina, except for backscattered energy arising from objects that are very much brighter than the air light. Accordingly, the sum $\ell_\lambda(r) + b_\lambda(r)s_\lambda$ can be replaced by $\gamma_\lambda(r)q_\lambda(r)$, where $\gamma_\lambda(r)$ is the scattering coefficient and $q_\lambda(r)$ is the luminous density of the atmosphere. Substituting into Eq. (46), there results

$$\frac{dL_\lambda(r)}{dr} = -\beta_\lambda(r)L_\lambda(r) + \gamma_\lambda(r)q_\lambda(r) \quad . \qquad (47)$$

For a homogeneous atmosphere that is uniformly illuminated, $\beta_\lambda(r)$, $\gamma_\lambda(r)$, and $q_\lambda(r)$ are constant, and the integrated form of the equation over the distance R becomes

$$\int_{L_\lambda(O)}^{L_\lambda(R)} \frac{dL_\lambda(r)}{-\beta_\lambda(r)L_\lambda(r) + \gamma_\lambda q_\lambda} = \int_O^R dr \quad , \qquad (48)$$

which yields

$$L_\lambda(R) = L_\lambda(O)\, e^{-\beta_\lambda R} + \left(1 - e^{-\beta_\lambda R}\right)\frac{\gamma_\lambda q_\lambda}{\beta_\lambda} \quad . \qquad (49)$$

At large values of R, the equation reduces approximately to

$$L_\lambda(R) = \frac{\gamma_\lambda q_\lambda}{\beta_\lambda} = L_\lambda(m) \quad , \tag{50}$$

where $L_\lambda(m)$ is the luminance of the attenuating atmosphere.* Equation (49) then becomes

$$L_\lambda(R) = L_\lambda(O)\, e^{-\beta_\lambda R} + \left(1 - e^{-\beta_\lambda R}\right) L_\lambda(m) \quad . \tag{51}$$

c. Luminance and Color Contrast

1) Luminance Contrast

Let $L_\lambda(R)$ and $L'_\lambda(R)$ be the apparent luminance of an object and its background at range R, and let $L_\lambda(O)$ and $L'_\lambda(O)$ be the inherent contrast of the object and its background at range 0. Define the inherent contrast of the object against its background as

$$C(O) = \frac{\sum_j \left[L_{\lambda_j}(O) - L'_{\lambda_j}(O)\right]}{\sum_j L'_{\lambda_j}(O)} \tag{52}$$

and the apparent contrast at range R as

$$C(R) = \frac{\sum_j \left[L_{\lambda_j}(R) - L'_{\lambda_j}(R)\right]}{\sum_j L'_{\lambda_j}(R)} \quad . \tag{53}$$

*For most situations, the luminance of the attenuating atmosphere is the luminance of the horizon sky. However, in some military situations, e.g., smoke screens, and under conditions of fog and mist, the more general term "attenuating atmosphere" is applicable.[12]

Substituting Eqs. (51) and (52) into (53), there obtains

$$C(R) = C(0)\left[\frac{\sum_j L'_{\lambda_j}(0)\, e^{-\beta_{\lambda_j}(R)}}{\sum_j L'_{\lambda_j}(R)}\right] , \qquad (54)$$

which is a general law for the reduction of contrast by an attenuating atmosphere. When the background is the horizon and the atmosphere is uniform, we have

$$\sum_j L'_{\lambda_j}(0) = \sum_j L'_{\lambda_j}(R) ,$$

and

$$C(R) = C(0)\, e^{-\beta_{\lambda_j} R} . \qquad (55)$$

2) The Ideal White Surface

For many situations, the incorporation of the contrast of a white surface against its background permits a major reduction of computational effort. Accordingly, consider a perfectly diffusing and reflecting white surface. Define the inherent contrast of the white surface against its atmospheric background at wavelength $\lambda$ as

$$C_\lambda(W) = \frac{L^{\circ}_\lambda(W) - L_\lambda(m)}{L_\lambda(m)} \qquad (56)$$

where $L^{\circ}_\lambda(W)$ is the inherent luminance of the white surface. Defining

$$\rho_\lambda = \frac{L_\lambda(0)}{L^{\circ}_\lambda(W)} . \qquad (57)$$

and summing over all wavelength bands, Eq. (51) becomes

$$L_T = \sum_j L_{\lambda_j}(R) = \sum_j \left( \alpha_{\lambda_j} \left[ C_{\lambda_j}(W) + 1 \right] L_{\lambda_j}(m) e^{-\beta_{\lambda_j} R} + L_{\lambda_j}(m) \left( 1 - e^{-\beta_{\lambda_j}} \right) \right), \quad (58)$$

where $L_T$ is the total luminance of the body at the observer's position. For nonself-luminance bodies illuminated by some source, $\alpha_{\lambda_j}$ is equal to the spectral reflectance.

### 3) Chromaticity Coordinates and Range

Combining Eqs. (57) and (51) yields

$$L_\lambda(R) = L_\lambda(m) \left[ 1 + \left( \frac{\alpha_\lambda L_\lambda^0(W)}{L_\lambda(m)} - 1 \right) e^{-\beta_\lambda R} \right] . \quad (59)$$

The quantity in the parentheses can be written in the form

$$\frac{\alpha_\lambda L_\lambda(W) - L_\lambda(m)}{L_\lambda(m)} , \quad (60)$$

which, upon adding and subtracting $\alpha_\lambda L_\lambda(m)$ in the numerator, becomes

$$\frac{\alpha_\lambda L_\lambda^0(W) - L_\lambda(m)}{L_\lambda(m)} = \frac{\alpha_\lambda L_\lambda(W) - \alpha_\lambda L_\lambda(m)}{L_\lambda(m)} + \frac{\alpha_\lambda L_\lambda(m)}{L_\lambda(m)} - \frac{L_\lambda(m)}{L_\lambda(m)}$$

$$= \alpha_\lambda C_\lambda(W) + \alpha_\lambda - 1 . \quad (61)$$

Substituting back into Eq. (59) yields

$$L_\lambda(R) = L_\lambda(m) \left[ 1 + \left( \alpha_\lambda C_\lambda(W) + \alpha_\lambda - 1 \right) e^{-\beta_\lambda R} \right] . \quad (62)$$

But

$$L_\lambda(m) = K_m V_\lambda E'_\lambda \Delta\lambda \qquad . \tag{63}$$

where $E'_\lambda \Delta\lambda$ is the spectral radiation of the air light. Thus, the luminance of the object at range R is

$$L_\lambda(R) = K_m V_\lambda E'_\lambda \Delta\lambda \left[1 + \left(\rho_\lambda C_\lambda(W) + \rho_\lambda - 1\right) e^{-\sigma_\lambda R}\right] \quad . \tag{64}$$

From Eq. (43), the luminance of the object in terms of chromaticity coordinate, $\bar{y}$, is $K_m \bar{y}_\lambda E_\lambda \Delta\lambda$. Remembering that $\bar{y}_\lambda = V_\lambda$, we have

$$K_m V_\lambda E_\lambda \Delta\lambda = K_m V_\lambda E'_\lambda \Delta\lambda \left[1 + \left(\rho_\lambda C_\lambda(W) + \rho_\lambda - 1\right) e^{-\sigma_\lambda R}\right] \quad , \tag{65}$$

and

$$E_\lambda \Delta\lambda = E'_\lambda \Delta\lambda \left[1 + \left(\rho_\lambda C_\lambda(W) + \rho_\lambda - 1\right) e^{-\sigma_\lambda R}\right] \quad . \tag{66}$$

Substituting in Eq. (43) and using the same methods that were used to develop Eq. (15), the relative tristimulus values become

$$\left.\begin{aligned} X' &= \sum_j W'_j \bar{x}_j \left|1 + \left(\rho_j C_j(W) + \rho_j - 1\right) e^{-\sigma_j R}\right| \Delta\lambda_j \\ Y' &= \sum_j W'_j \bar{y}_j \left|1 + \left(\rho_j C_j(W) + \rho_j - 1\right) e^{-\sigma_j R}\right| \Delta\lambda_j \\ Z' &= \sum_j W'_j \bar{z}_j \left|1 + \left(\rho_j C_j(W) + \rho_j - 1\right) e^{-\sigma_j R}\right| \Delta\lambda_j \end{aligned}\right\} \quad . \tag{67}$$

where $W'_j \Delta\lambda_j$ is the relative energy distribution of the atmospheric light in wavelength band $\Delta\lambda_j$. For an ideal white surface it can be assumed that

$$C_{\lambda_i}(W) = C_{\lambda_j}(W) = C(W) \quad ,$$

and the equations for the relative tristimulus values can be written

$$\left.\begin{aligned} X' &= \sum_j W'_{\lambda_j} \bar{x}_{\lambda_j} \left[ 1 + \left( \alpha_{\lambda_j} C(W) + \beta_{\lambda_j} - 1 \right) e^{-\sigma_{\lambda_j} R} \right] \Delta\lambda_j \\ Y' &= \sum_j W'_{\lambda_j} \bar{y}_{\lambda_j} \left[ 1 + \left( \alpha_{\lambda_j} C(W) + \beta_{\lambda_j} - 1 \right) e^{-\sigma_{\lambda_j} R} \right] \Delta\lambda_j \\ Z' &= \sum_j W'_{\lambda_j} \bar{z}_{\lambda_j} \left[ 1 + \left( \alpha_{\lambda_j} C(W) + \beta_{\lambda_j} - 1 \right) e^{-\sigma_{\lambda_j} R} \right] \Delta\lambda_j \end{aligned}\right\} \quad , \qquad (68)$$

Illuminant C in Table A-5 of Annex A resembles air light on a bright overcast day. The chromaticity coordinates can be computed directly from Eq. (68).

d. <u>The Probability of Detecting a Color and Luminance Difference between Two Objects</u>

Let $P_c(R)$ and $P_\ell(R)$ be the probabilities of detecting a chromatic and luminance contrast difference between two objects at range R. The probability of detecting either a chromatic or luminance difference between the objects at range R is

$$P_d(R) = P_c(R) + P_\ell(R) - P_{c\ell}(R) \qquad (69)$$

where $P_{c\ell}(R)$ is the probability of detecting both a chromatic and a luminance contrast simultaneously. Since chromatic[11] differences are independent of luminance contrast differences, we have

$$P_{c\ell}(R) = P_\ell(R) \left[ 1 - P_c(R) \right] \quad . \qquad (70)$$

and

$$P_d(R) = P_c(R) + P_\ell(R) \left[ 1 - P_c(R) \right] \quad . \qquad (71)$$

The determination of $P_c(R)$ is made possible by the work of MacAdams.[6] If it is assumed that MacAdams' color ellipses can be approximated by circles, the value of $P_c(R)$ can be determined from

$$P_c(R) \begin{cases} = 1.0 : d \geq 0.02, \ \phi \leq 15'; \ \ d \geq 0.002, \ \phi > 15' \\ = \ 0 : d < 0.02, \ \phi \leq 15'; \ \ d < 0.002, \ \phi > 15' \end{cases} , \qquad (72)$$

where

$$d = \left( \left[ x_2(R) - x_1(R) \right]^2 + \left[ y_2(R) - y_1(R) \right]^2 \right)^{\frac{1}{2}} \qquad (73)$$

$\phi$ = angle subtended by the smallest object at range R, and $x_i(R)$, $y_i(R)$ = chromatic coordinates of the $i^{th}$ object at range R.

The detection of luminance contrast is somewhat more involved. Blackwell and his coworkers[15] have shown that changing the stimulus contrast by a factor of four corresponds to a change in probability of detecting a luminous contrast difference from 10 to 95 percent.

This experimental finding permits the probability of detecting a luminance contrast difference to be determined, if the detection probability is known at one value of stimulus contrast. The result of Blackwell's research is shown in Figure 6, in which the detection probability is plotted as a function of relative contrast, i.e., the ratio of the stimulus contrast to the contrast at the 50-percent detection level. The results of tests to determine threshold (50-percent detection level) contrasts for circular stimuli of various sizes and background luminance relations are shown in Figure A-1 of Annex A. Although the values shown in that figure were determined for stimulus areas brighter than the background, subsequent experiments showed that they were also valid for stimulus areas darker than the background, except for large areas at low luminance levels, for which the values shown are 20 percent too high. The dashed portion of the curves are extrapolated values for situations normally encountered in military operations.[12] Also shown in Annex A are the angular subtenses of selected military targets (Figure A-2) and the luminance levels of the sky under various cloud conditions and times of day (Table A-6).

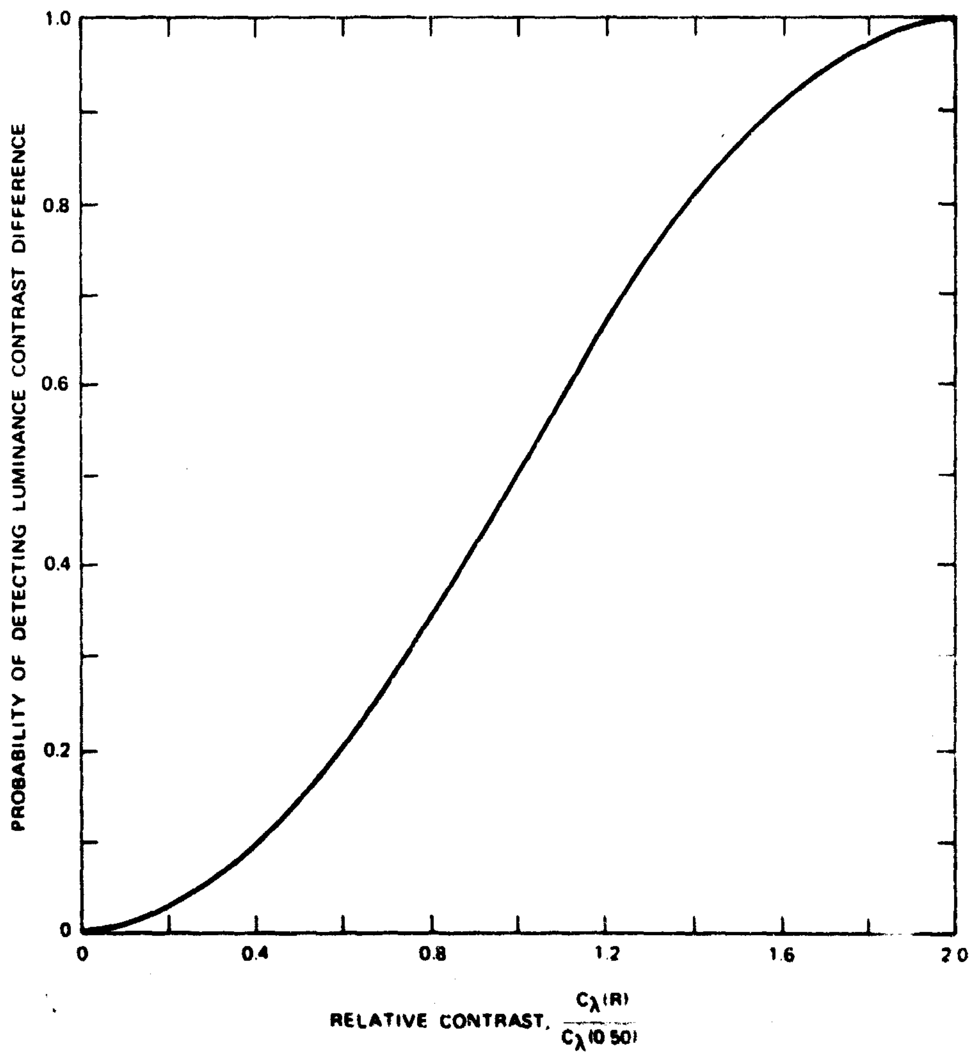



FIGURE 6 PROBABILITY OF DETECTION OF AN ACHROMATIC STIMULUS

4. Sample Computations

The computation of chromatic and luminance contrasts and the resulting probabilities of detection follow directly from an application of the relationships that have been developed. The use of these equations is illustrated below.

a. The Computational Model

1) The Color Equations

a) Tristimulus Values

The tristimulus values are given by:

$$\left.\begin{aligned} X &= \sum_j W_{\lambda_j} \bar{x}_{\lambda_j} \left[ 1 + Q_j e^{-\beta_{\lambda_j} R} \right] \Delta\lambda_j \\ Y &= \sum_j W_{\lambda_j} \bar{y}_{\lambda_j} \left[ 1 + Q_j e^{-\beta_{\lambda_j} R} \right] \Delta\lambda_j \\ Z &= \sum_j W_{\lambda_j} \bar{z}_{\lambda_j} \left[ 1 + Q_j e^{-\beta_{\lambda_j} R} \right] \Delta\lambda_j \end{aligned}\right\} \qquad (74)$$

where

$$Q_j = \sigma_{\lambda_j} C(W) + \rho_{\lambda_j} - 1 \quad . \qquad (75)$$

Values of $W_{\lambda_j}$ $\Delta\lambda_j$ are obtained from tables of spectral energy distributions (Table A-5), and values for $\bar{x}_{\lambda_j}$, $\bar{y}_{\lambda_j}$, and $\bar{z}_{\lambda_j}$ are obtained from tables of illuminant distribution coefficients (Tables A-2, A-3, and A-4). For nonself-luminous bodies, values for $\rho_\lambda$ are obtained from spectral reflectance tables (Tables A-7 through A-12). For self-luminous bodies, the values of $\rho_\lambda$ must be determined from the ratio of the luminance of the body to that of a perfectly white diffusing surface. The value of C(W) must be estimated.

The values for the atmospheric attenuation coefficient, $\beta$, can be determined in two ways. For situations in which the meteorological visibility, $V_R$, is known, i.e., the range at which the contrast of a black body against the horizon is 0.02, the value of $\beta$ is given by

$$\beta_h = \frac{3.9}{V_R} \quad . \tag{76}$$

For situations in which the meteorological visibility is not known, the attenuation is given by

$$\beta_m = \frac{3W}{d\rho} \qquad \text{(homogeneous aerosols)} \tag{77}$$

or

$$\beta_m = \frac{3W}{\rho} \sum_i \frac{v_i}{d_i} \qquad \text{(heterogeneous aerosols)} \tag{78}$$

where W and $\rho$ are the weight concentration and density of the aerosol material, d is the diameter of the homogeneous aerosol particle, $d_i$ is the diameter of the $i^{th}$ particle in the heterogeneous aerosol, and $v_i$ is the weight fraction of the particle having a diameter of $d_i$.

b) Chromaticity Coordinates

The chromaticity coordinates are computed directly from the tristimulus values

$$\left.\begin{aligned} x &= \frac{X}{X + Y + Z} \\ y &= \frac{Y}{X + Y + Z} \\ z &= 1 - (x + y) \end{aligned}\right\} \quad . \tag{79}$$

### 2) Luminance and Chromatic Contrast

#### a) Luminance Contrast

The relative luminances of an object, i, and its background, j, are equal to the Y tristimulus values. Thus, for object i against background j, the inherent contrast is

$$C_{ij}(0) = \frac{Y_i(0) - Y_j(0)}{Y_j(0)}, \ (R = 0) \quad . \qquad (80)$$

For object i against the horizon, we have

$$C_i(0) = \frac{Y_i(0)}{\sum_j W_{\lambda_j} \bar{y}_{\lambda_j} \Delta\lambda_j} - 1, \ (R = 0) \quad . \qquad (81)$$

For contrast at a range R from the observer, the contrast equations become

$$C_{ij}(R) = C_{ij}(0) \left(\frac{Y_i(0)}{Y_j(R)}\right) e^{-\sigma R} \quad , \qquad (82)$$

and

$$C_i(R) = C_i(0) \ e^{-\sigma R} \quad . \qquad (83)$$

#### b) Chromatic Contrast

The chromatic contrast between two bodies, i and j, is defined as the absolute difference between the chromaticity coordinates of the bodies. Thus, the chromaticity contrast is given by

$$D_{ij} = \left| \left[ \left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 \right]^{\frac{1}{2}} \right| \quad . \qquad (84)$$

3) Probabilities of Detection

a) Luminance Contrast

The probability of detecting a luminance contrast between an object and a background is a function of the angle subtended by the object, and the luminance level of the environment. The angle subtended by the object is determined from the range and longest division of the body (Figure A-2). The liminal (threshold) contrast value for a 50-percent detection probability is then determined from relationships among liminal contrast, stimulus angle, and adaptation brightness values (Figure A-1). The probability of detecting a luminance difference, $P_{\ell}$, between the body and its background is then determined from the ratio of the computed contrast to the liminal contrast for that size body (Figure 6).

b) Chromatic Contrast

Owing to the limited experimental data that are available, the probabilities of detecting a chromatic difference between an object and its background must be treated as a step function. Accordingly, the probabilities can be determined from

$$P_C(R) = \begin{cases} 1.0: & D_{ij} \geq 0.02, \phi < 15' \\ & D_{ij} \geq 0.002, \phi > 15' \\ 0: & D_{ij} < 0.02, \phi < 15' \\ & D_{ij} < 0.002, \phi > 15' \end{cases} \quad , \qquad (85)$$

where $\phi$ is the angle subtended by the object at range R.

c) Probability of Detecting an Object

The probability of detecting an object is given by

$$P_d(R) = P_c(R) + P_{\ell}(R)\left(1 - P_c(R)\right) \quad . \qquad (86)$$

4) Chromatic Combination

When the color pattern making up an object's surface is too small to be resolved by the human eye, the color observed by a human observer will appear as a weighted mix of the colors comprising the pattern. For equal pattern areas of two colors, the chromaticity coordinates of the resulting mix can be determined from

$$\left.\begin{aligned} x_{i+j} &= \frac{X_i + X_j}{X_i + X_j + Y_i + Y_j + Z_i + Z_j} \\ y_{i+j} &= \frac{Y_i + Y_j}{X_i + X_j + Y_i + Y_j + Z_i + Z_j} \\ z_{i+j} &= 1 - \left(x_{i+j} + y_{i+j}\right) \end{aligned}\right\} . \tag{87}$$

The probabilities of detecting such an object against its background can be determined from the previous equations using the combined values of the tristimulus values and coordinates for the object.

b. Sample Computations

1) Example Cases

A number of sample computations were made to illustrate the use of the model. All calculations were made assuming clear, bright, daylight conditions (Type C Illuminant, $10^4$ candles/$m^2$), a contrast, C(W), of a white surface against the horizon of 0.5, and spectral reflectivities as defined in Air Force Avionics Laboratory computations.[17] The specific spectral reflectivity data used are summarized in Tables A-7 through A-12 in Annex A. Computations were done for the following targets and backgrounds:

| Target (man) | Background |
|---|---|
| Fatigue uniform | Meadow in bloom |
| Fatigue uniform | Fresh snow |
| Olive drab uniform | Fresh snow |
| Fatigue uniform | Men in olive drab uniforms |
| International orange clothes | Meadow in bloom |

*In cases where the background of the object is another object, $\phi$ is the angle subtended by the smallest object.

All computations were made using the total visible waveband (380 mμ - 780 mμ). Two additional computations were made assuming an observer using filters: the first was made for the man in fatigue uniform against a meadow background using a filter that limited observable radiation to the region of 500-600 mμ; the second was made for a man in international orange clothes against a meadow background using a filter that limited observable radiation to the region of 600-700 mμ.

The results of the computations are shown in Figures 7 through 13 for meteorological visibilities of 5 kilometers and in Figure 14 for one case at a meteorological visibility of 18 kilometers. It is interesting that with the exception of the man in fatigues against a meadow background, color differences were evident in all cases. In this one case, color differences become significant as the meteorological visibility increased.

It is also interesting to note the effects of the filtered versus the unfiltered views. In the case of the man in fatigues against the meadow background (Figures 7 and 12), the use of filters enhances the color differences but not the probability of detecting a chromatic or luminance difference. However, in the case of the man in international orange against a meadow (Figures 11 and 13), the filters degrade the chromatic differences but enhance the overall probability of detecting a chromatic or luminance contrast.

One of the most surprising results of the computations was the slight differences in detectivity between the man in fatigues and the man in olive drab uniform. Figurres 8 and 9 show the chromatic range and probabilities of detection of these targets against fresh snow backgrounds. When the man in fatigues is viewed against a background of olive drab uniforms, the results are those shown in Figure 10. Thus, it can be concluded that under the visibility conditions specified, small differences in uniform color appear to produce small but significant changes in detectability.

The apparent change in chromaticity coordinates for the various targets and backgrounds are shown in Figure 15. Included in that figure is the color resulting from the mix of an international orange target and a meadow background. Range marks for 0, 1, and 10 km have been added.

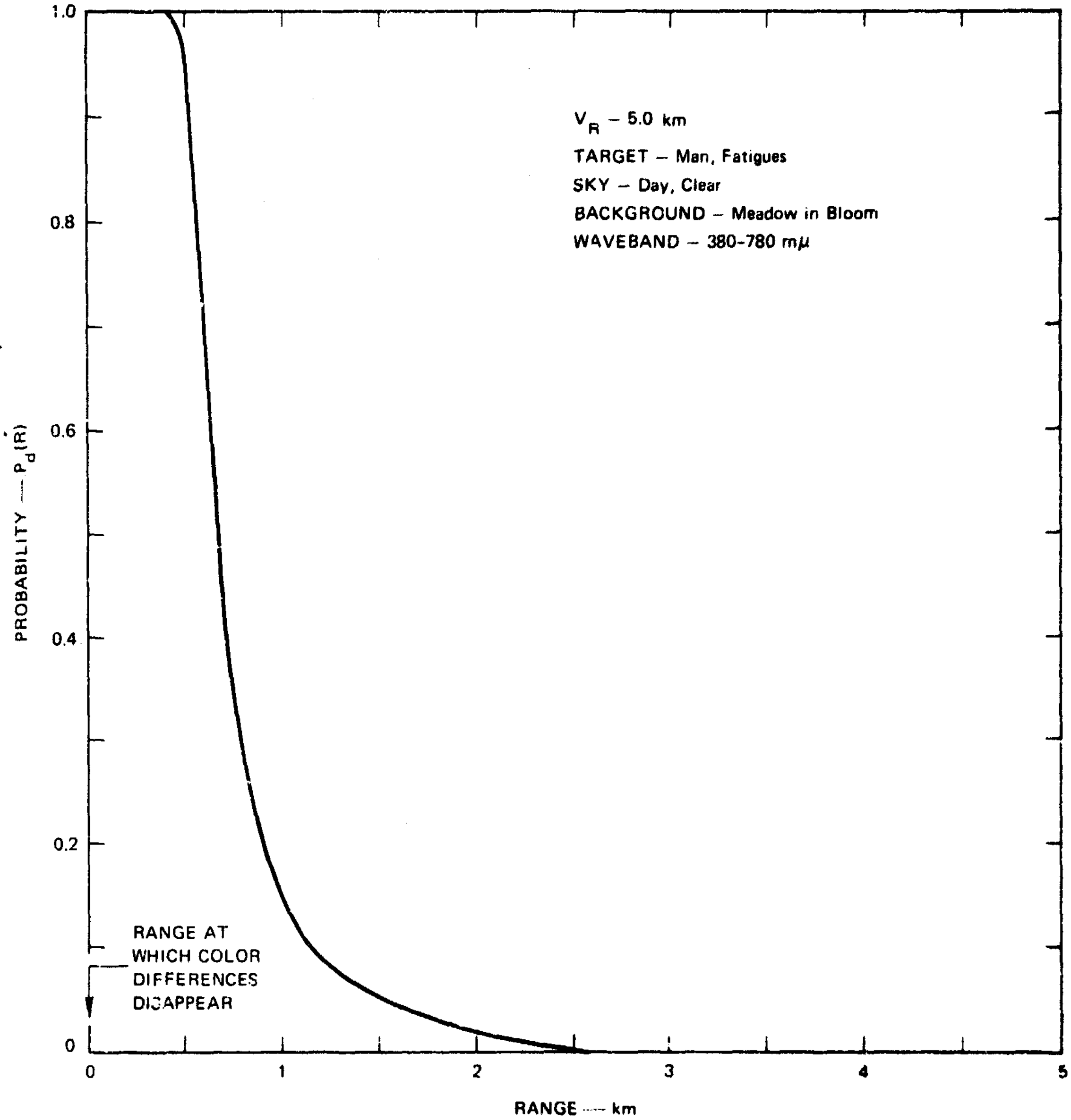



FIGURE 7 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

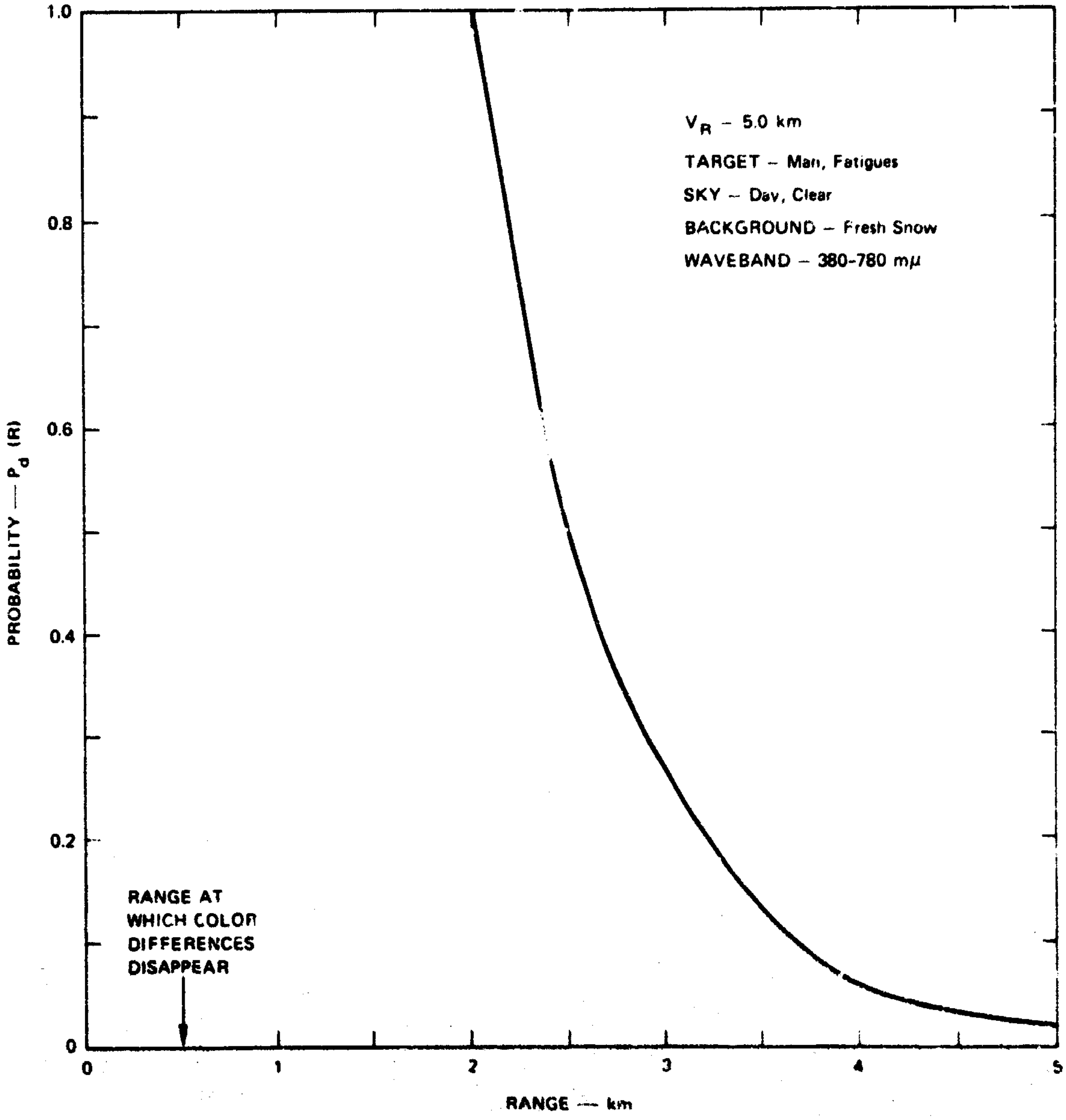



FIGURE 8 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

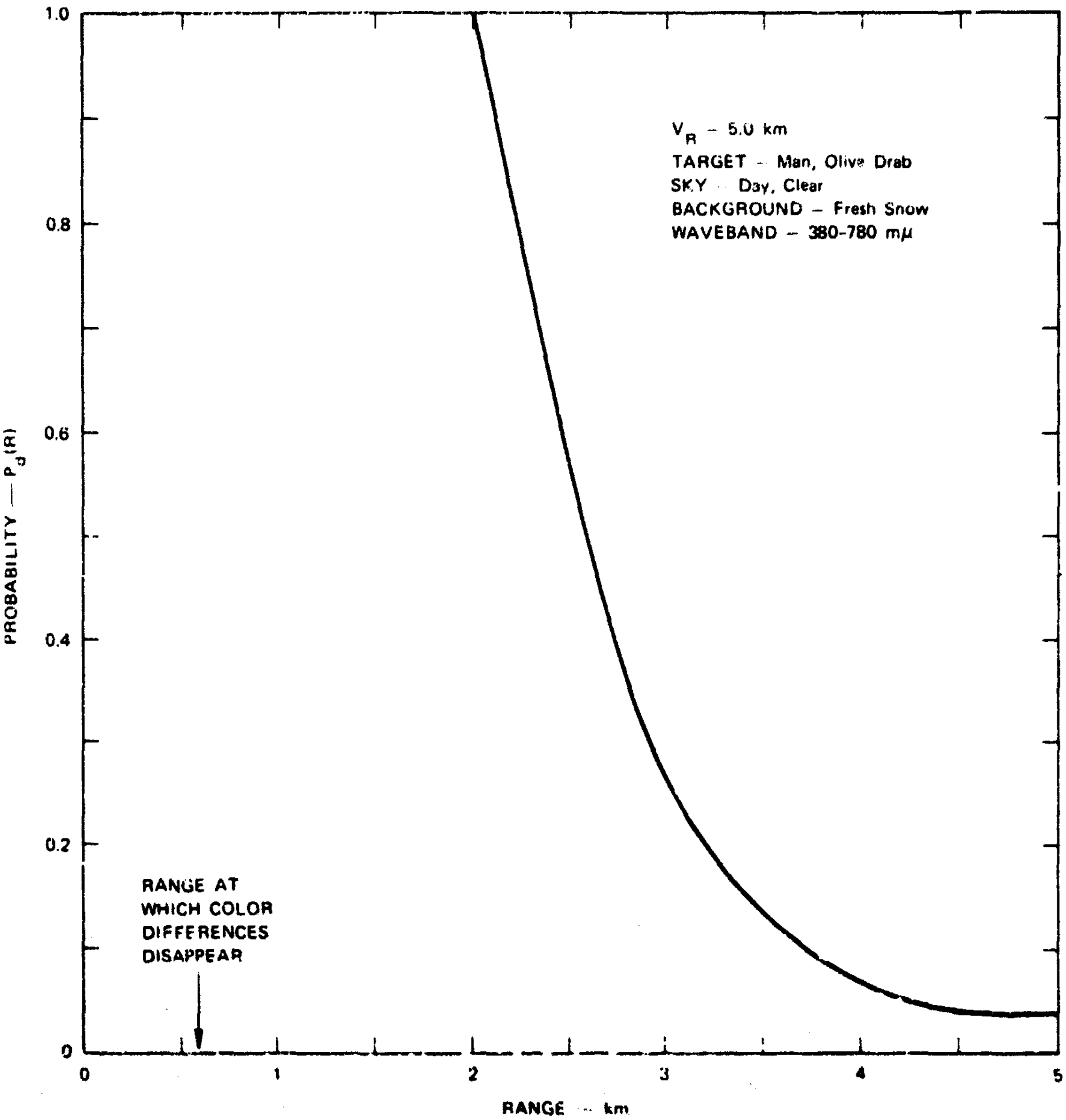



FIGURE 9 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

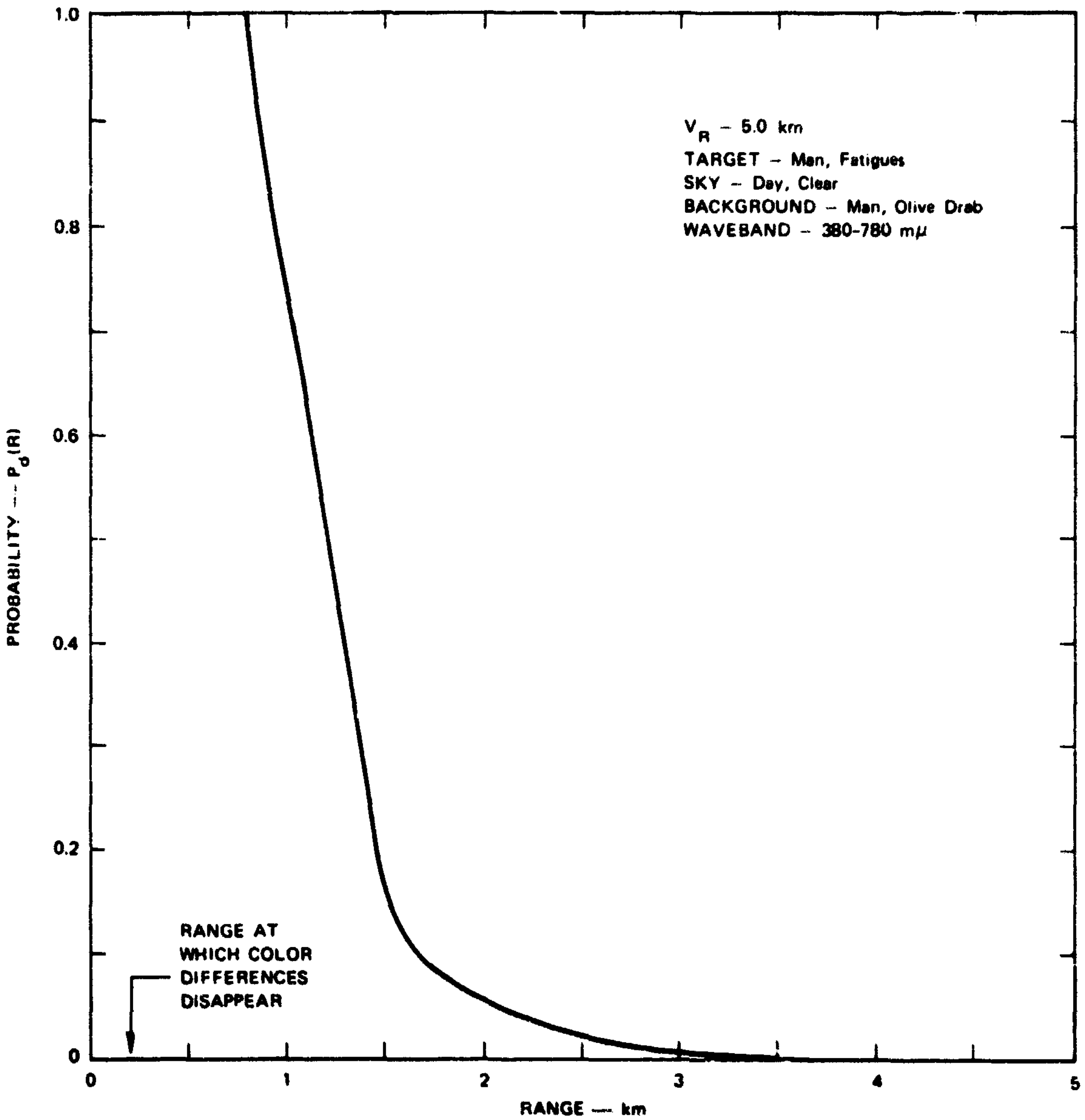



FIGURE 10 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

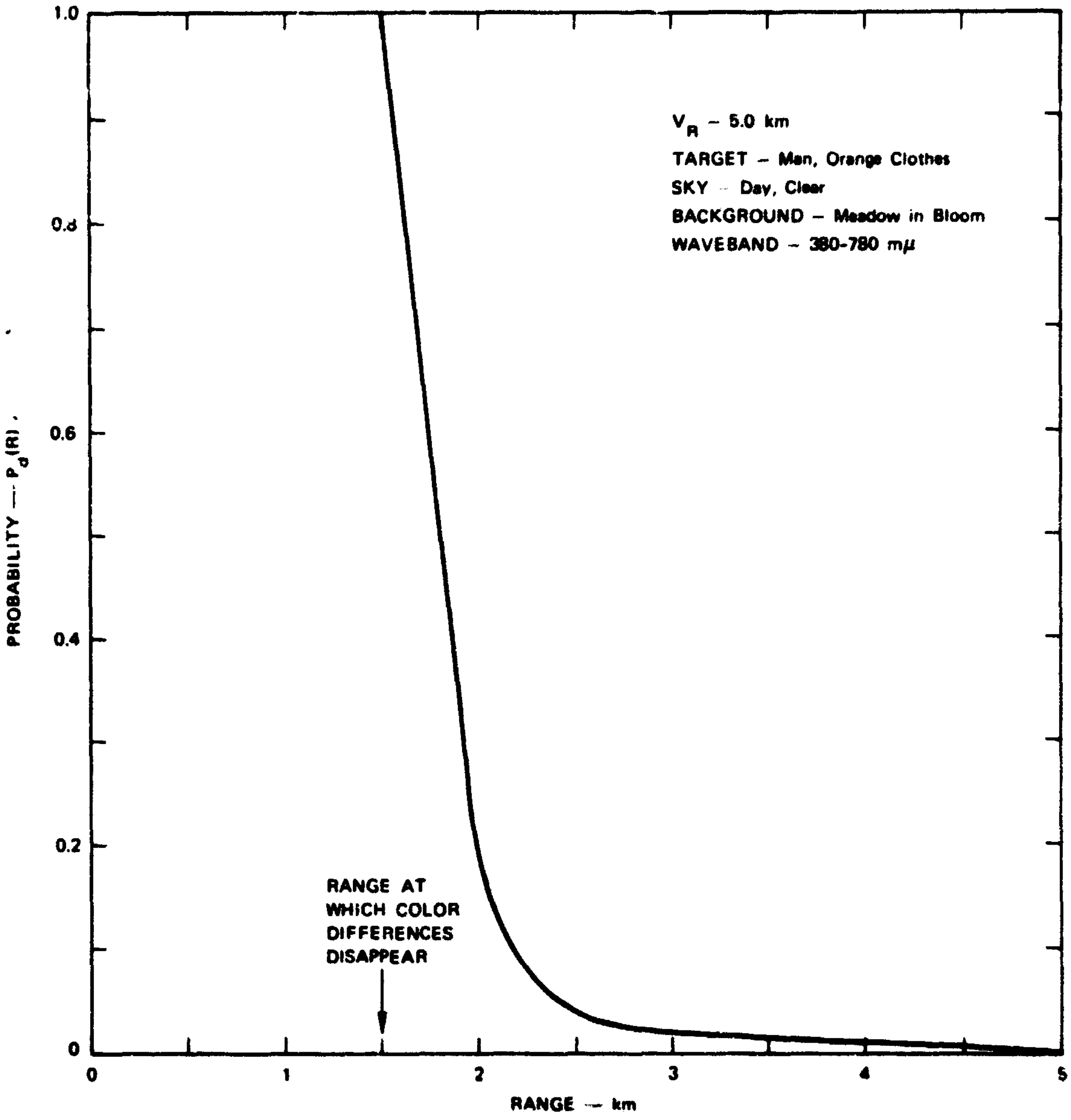



FIGURE 11 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

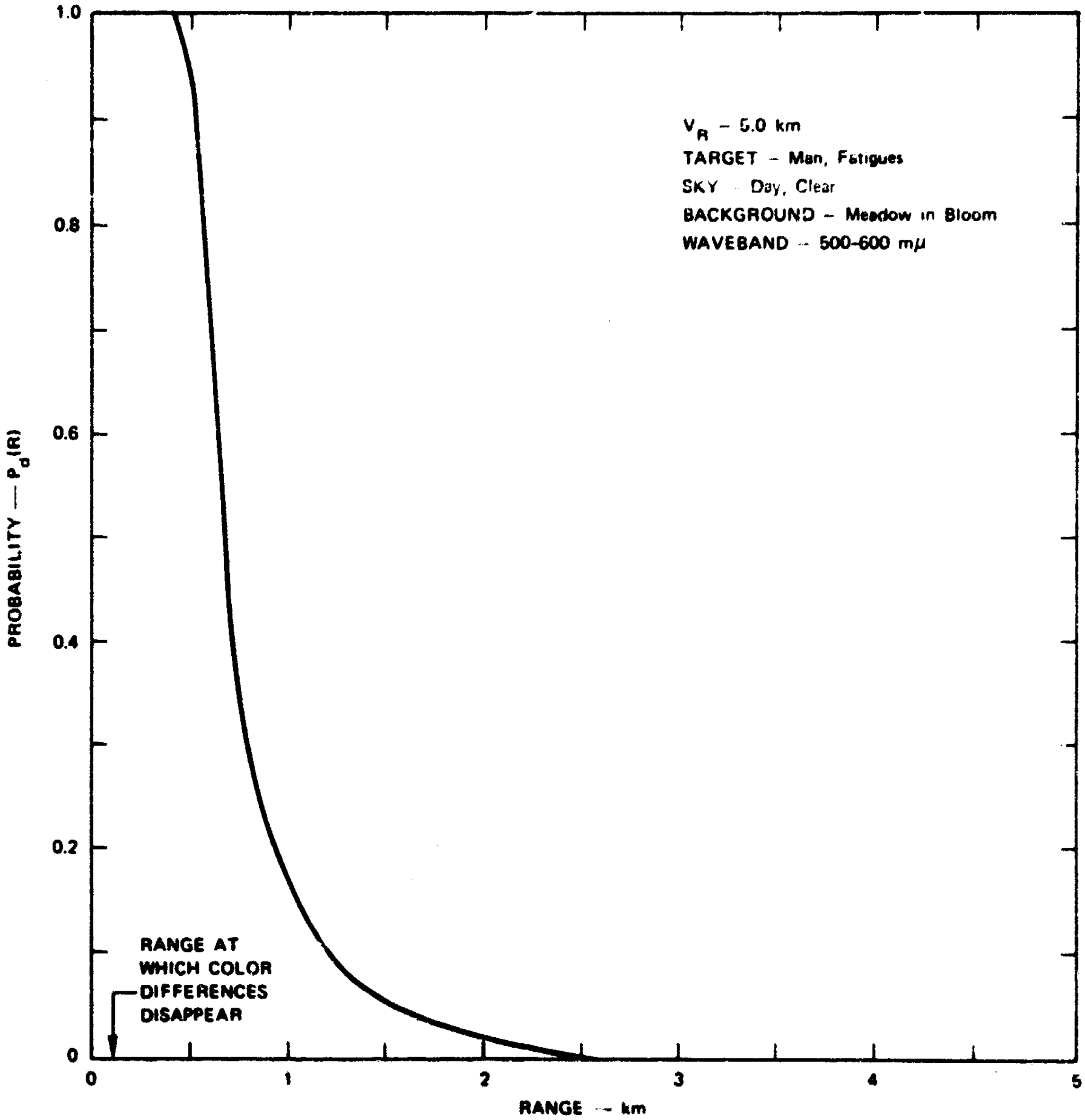



FIGURE 12 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

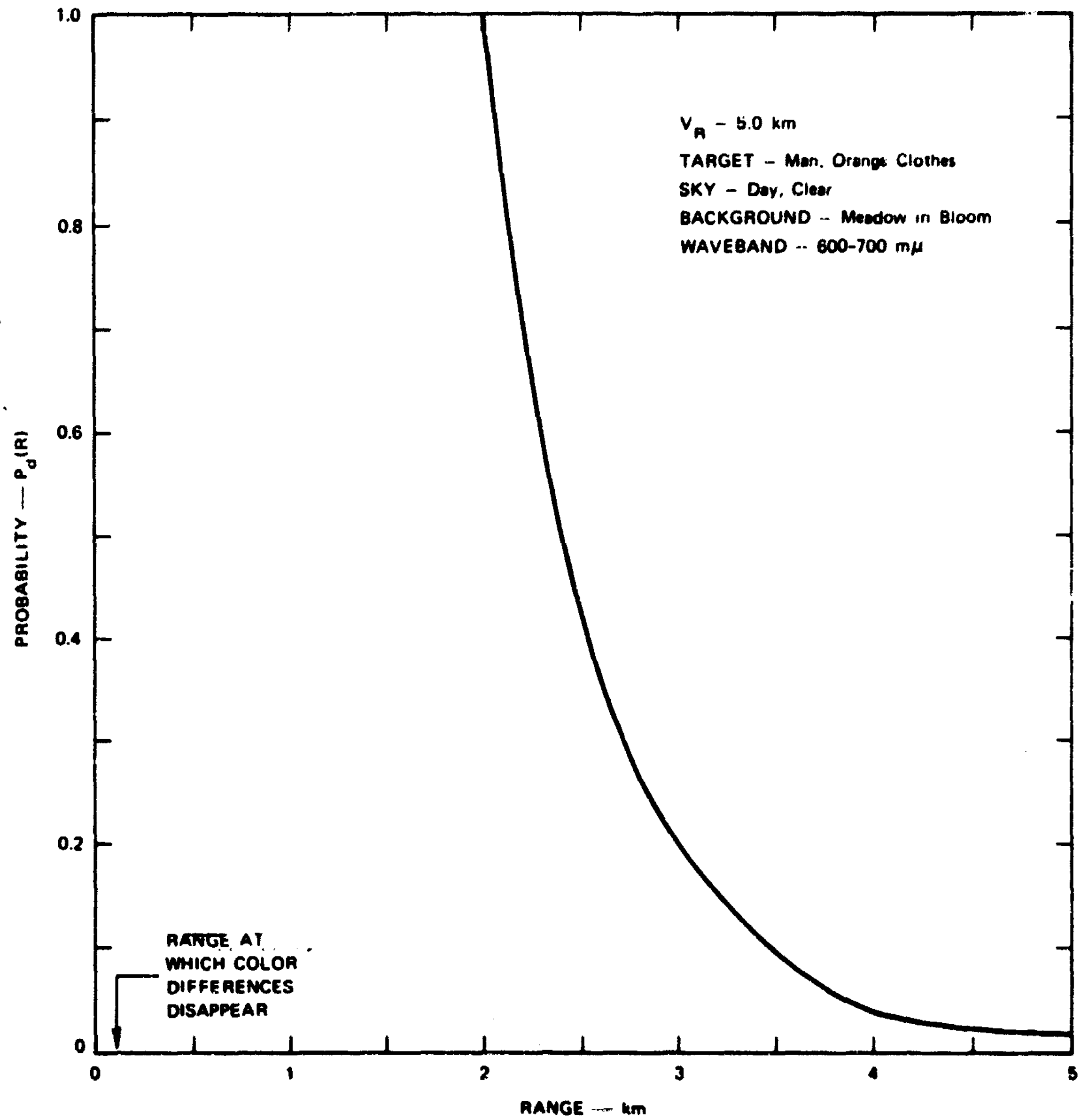



FIGURE 13 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

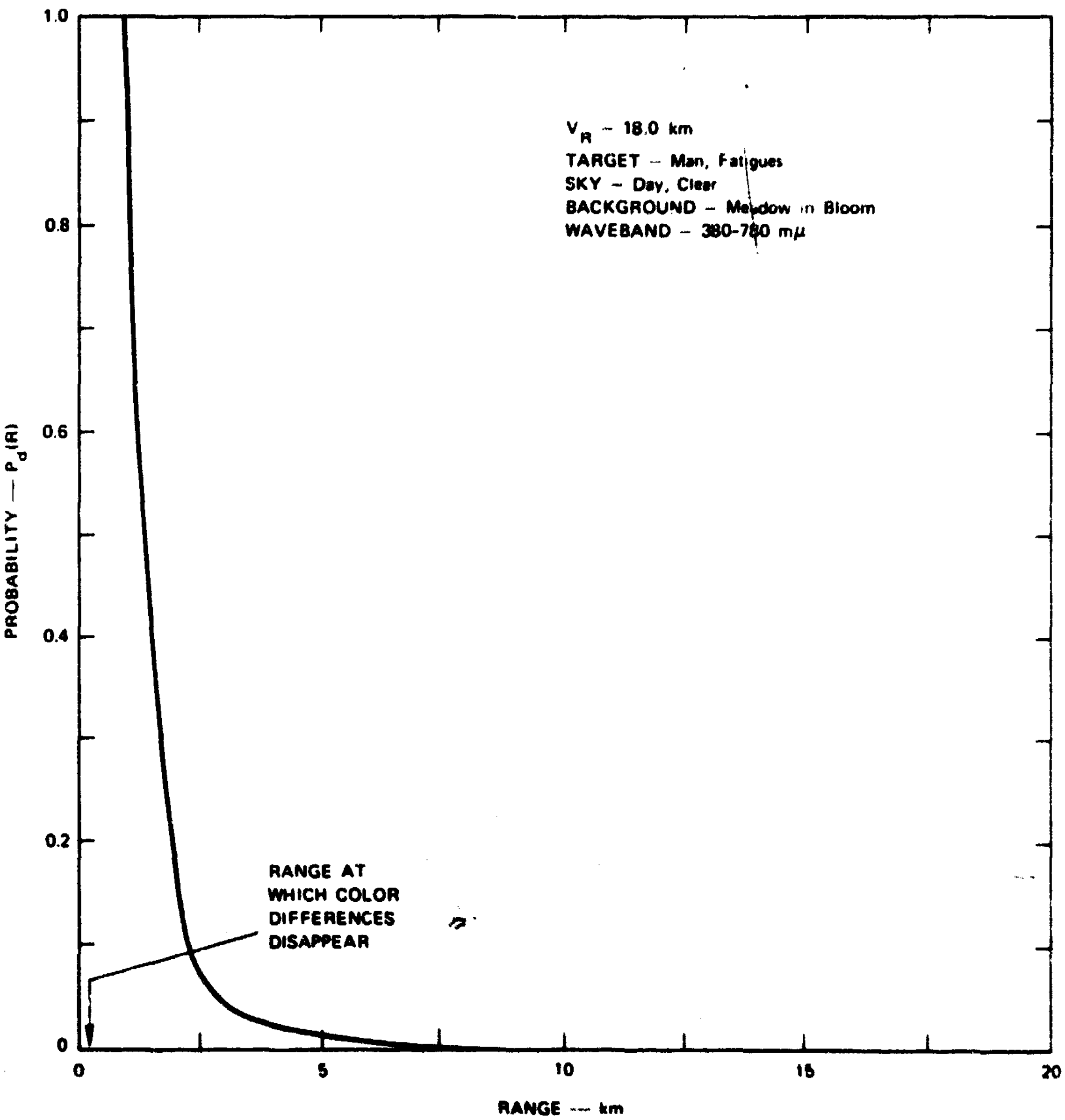



FIGURE 14 PROBABILITY OF DETECTING LUMINANCE OR CHROMATIC CONTRAST

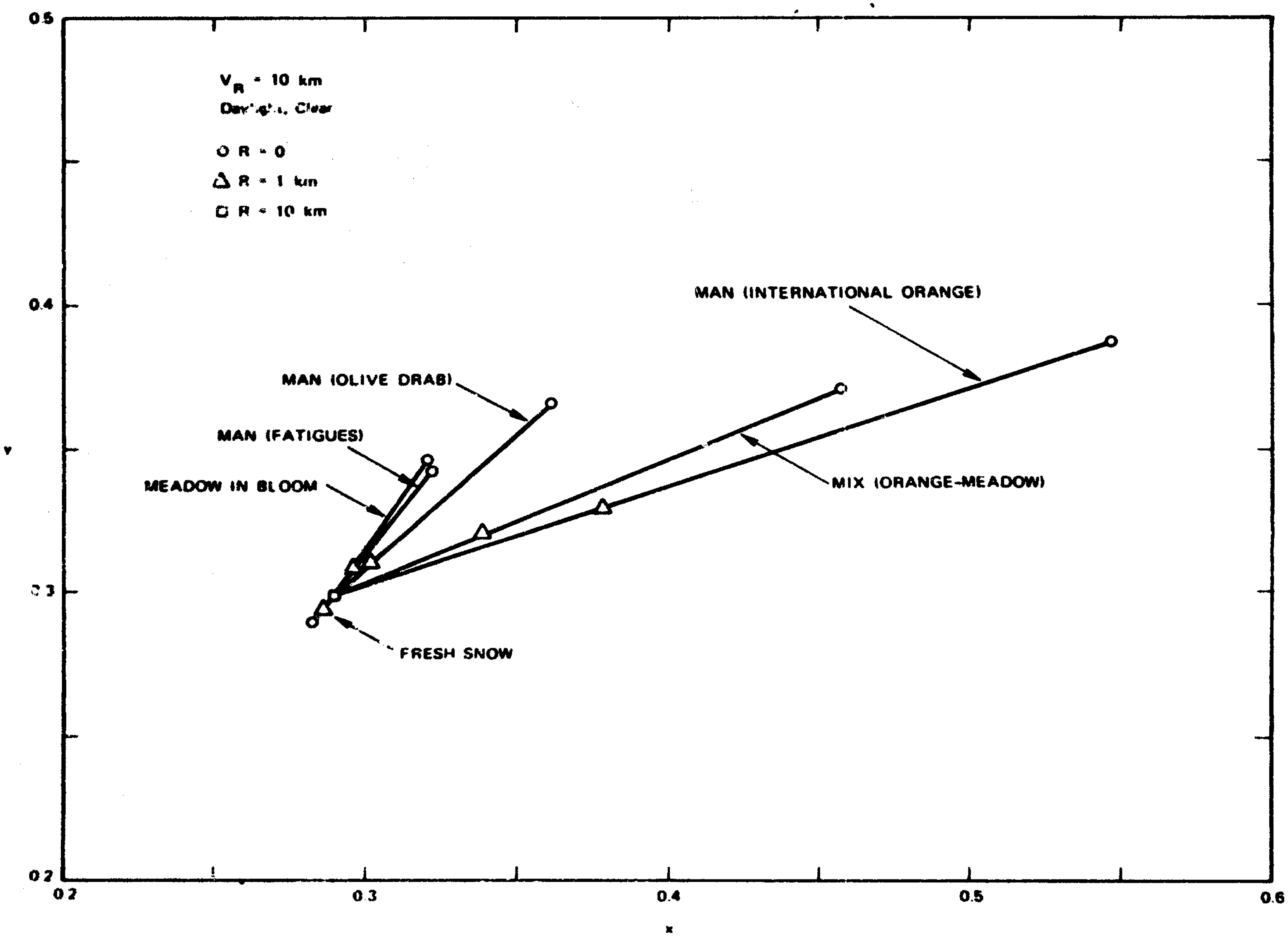



FIGURE 15 CHROMATICITY COORDINATES

## 5. Limitations and Potential Applications of the Model

### a. Model Limitations

The model that has been developed is designed for use in the analytical rather than the military planning process, and is based on relatively limited empirical data. Accordingly, any particularly interesting and potentially usable results obtained from the application of the model will require some form of field test evaluations. Since the chromatic treatment stems from theoretical work concerned with color matching, hue, and saturation, some caution must be exercised in application.

One of the most significant limitations of the model is concerned with the range over which the model is used. Since the model is designed to estimate the capabilities of human observers over short ranges in atmospheres containing relatively large diameter scatterers, only Mie scattering has been treated. No attempt is made to treat the scattering of radiation of wavelengths of the same order or larger than the scattering particle diameter (Rayleigh scattering), nor is any treatment of absorption of radiation by the attenuating atmosphere included. Most important, the model treats only homogeneous scattering atmospheres. Accordingly, the use of the model should be restricted to ranges up to 3-5 kilometers, ranges that encompass most of the capability of a visual observer searching for individual soldiers and small vehicles.

### b. Potential Applications

The model appears to provide a mechanism for the determination of chromatic and luminance differences between a target and its background over portions or all of the visible spectrum. It also has the capability to produce information on colors resulting from the mixing of two or more different colors.

These capabilities imply a potential utility for the model in a number of activities ranging from target detection to the examination of visual countermeasure systems such as smoke screening. Specifically, some of the potential applications are:

(1) Target Detection. The determination of chromatic and/or luminance differences between a target and its background.

(2) Analysis of Field Uniform Colors. The determination of the field uniform color(s) that provide the greatest potential for concealment within a specific combat environment.

(3) Camouflage Patterns and Colors. The analysis of camouflage colors and patterns for determining the implication of pattern size and colors (both individually and as mixes) on object detectability within the environment and as a function of range.

(4) Visual Filtering Systems. The analysis of filtering systems that might aid visual observers in the detection of targets of military interest, an application of potential use in counter-countersurveillance.

(5) Visual Screening Studies. In conjunction with filter-system studies, the model offers the capability to examine methods of contending with visual screening systems such as smoke systems.

(6) Signal System Studies. The use of colored signal flags and colored distress and rescue signals in combat environments is widespread. The model offers the capability for the analysis and determination of the colors of such devices that provide the highest probabilities of being seen within a specific environment.

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*The extension of scattering models to atmospheres containing varying concentrations of scatterers, although resulting in a somewhat more complex set of equations,[12] can be accomplished by relatively simple algebraic manipulations. It was not believed that this additional detail would add to the model utility, since the ranges over which a visual observer can see an individual soldier are usually short enough to be considered as containing a homogeneous atmosphere.

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Annex A

TABLES OF DISTRIBUTION COEFFICIENTS AND CHROMATICITY COORDINATES, RADIANT EMISSION DATA FOR SELECTED SOURCES, AND PHOTOMETRIC TERMINOLOGY

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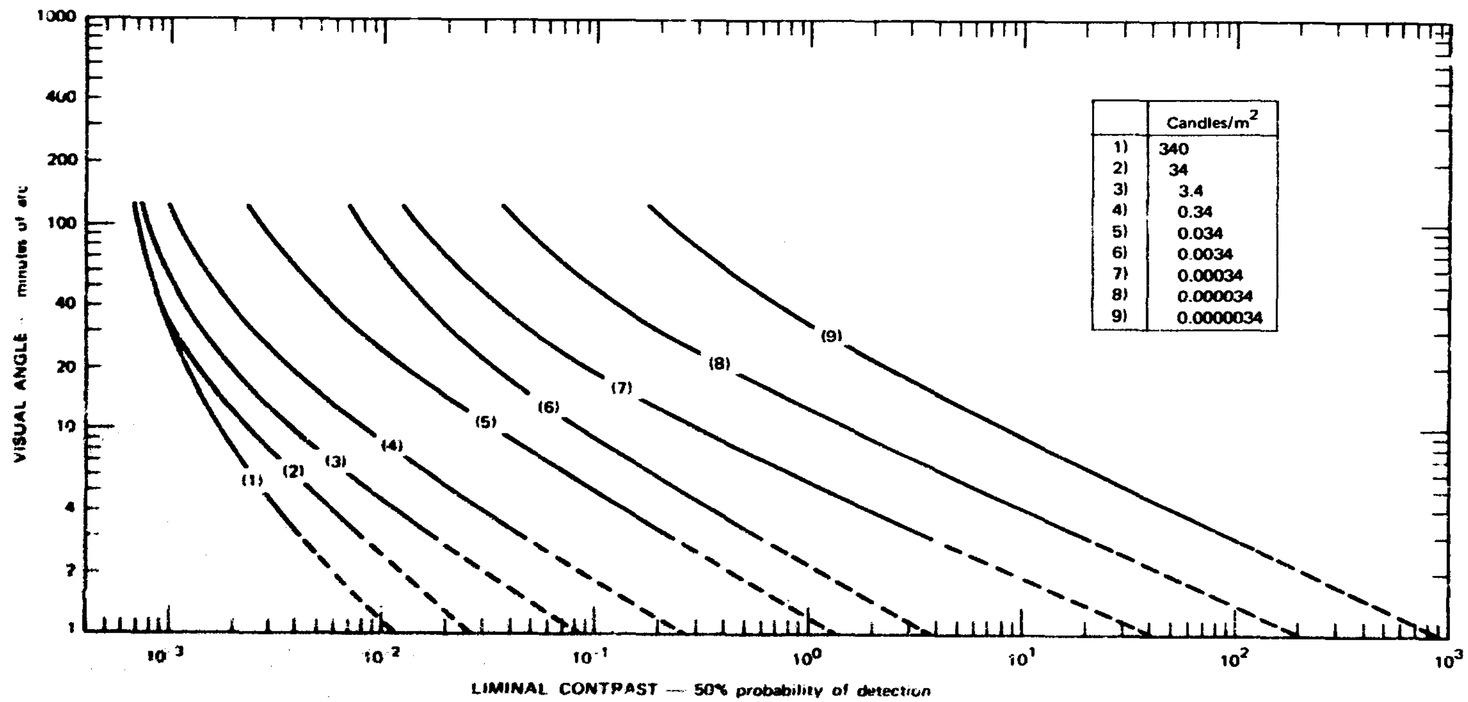



FIGURE A-1 RELATIONSHIP BETWEEN LIMINAL CONTRAST, STIMULUS AREA, AND ADAPTATION BRIGHTNESS

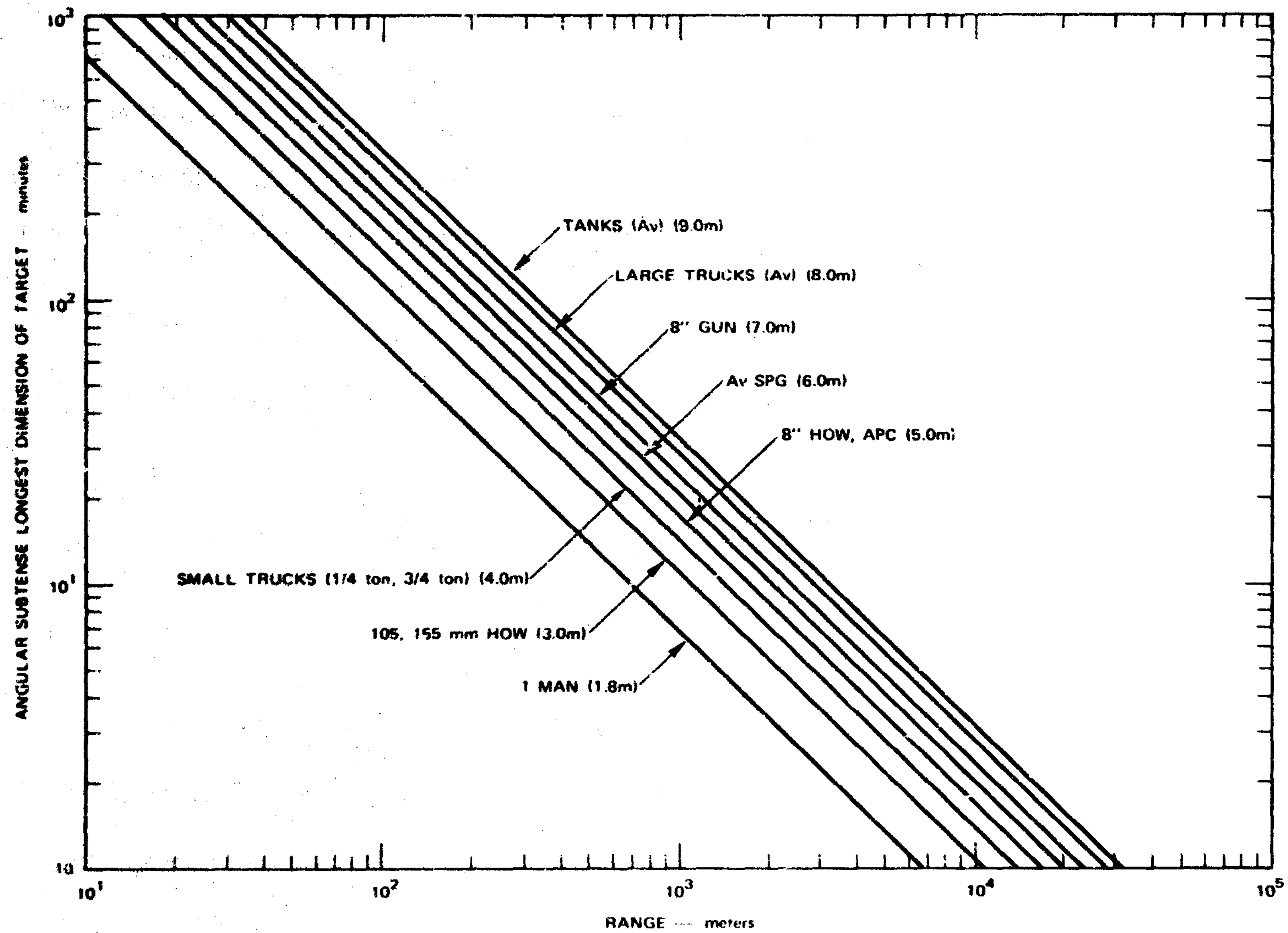



FIGURE A-2 ANGULAR SUBTENSE OF MILITARY TARGETS

Table A-1

CHROMATICITY COORDINATES--VISIBLE WAVELENGTHS[3]

| λ | x | y | z |
|---|---|---|---|
| 380 | 0.1741 | 0.0050 | 0.8209 |
| 385 | 0.17398 | 0.00495 | 0.82107 |
| 390 | 0.1738 | 0.0049 | 0.8213 |
| 395 | 0.17358 | 0.00484 | 0.82158 |
| 400 | 0.1733 | 0.0048 | 0.8219 |
| 405 | 0.17299 | 0.00478 | 0.82223 |
| 410 | 0.1726 | 0.0048 | 0.8226 |
| 415 | 0.1721 | 0.0048 | 0.8231 |
| 420 | 0.1714 | 0.0051 | 0.8235 |
| 425 | 0.1703 | 0.0058 | 0.8239 |
| 430 | 0.1689 | 0.0069 | 0.8242 |
| 435 | 0.1669 | 0.0086 | 0.8245 |
| 440 | 0.1644 | 0.0109 | 0.8247 |
| 445 | 0.1611 | 0.0138 | 0.8251 |
| 450 | 0.1566 | 0.0177 | 0.8257 |
| 455 | 0.1510 | 0.0227 | 0.8263 |
| 460 | 0.1440 | 0.0297 | 0.8263 |
| 465 | 0.1355 | 0.0399 | 0.8246 |
| 470 | 0.1241 | 0.0578 | 0.8181 |
| 475 | 0.1096 | 0.0868 | 0.8306 |
| 480 | 0.0913 | 0.1327 | 0.7760 |
| 485 | 0.0687 | 0.2007 | 0.7306 |
| 490 | 0.0454 | 0.2950 | 0.6596 |
| 495 | 0.0235 | 0.4127 | 0.5638 |
| 500 | 0.0082 | 0.5384 | 0.4534 |
| 505 | 0.0039 | 0.6548 | 0.3413 |
| 510 | 0.0139 | 0.7502 | 0.2359 |
| 515 | 0.0389 | 0.8120 | 0.1491 |
| 520 | 0.0743 | 0.8338 | 0.0919 |
| 525 | 0.1142 | 0.8262 | 0.0596 |
| 530 | 0.1547 | 0.8059 | 0.0394 |
| 535 | 0.1929 | 0.7816 | 0.0255 |
| 540 | 0.2296 | 0.7543 | 0.0161 |

| λ | x | y | z |
|---|---|---|---|
| 545 | 0.2658 | 0.7243 | 0.0099 |
| 550 | 0.3016 | 0.6923 | 0.0061 |
| 555 | 0.3373 | 0.6589 | 0.0038 |
| 560 | 0.3731 | 0.62448 | 0.00242 |
| 565 | 0.4078 | 0.58968 | 0.00162 |
| 570 | 0.4441 | 0.55470 | 0.00120 |
| 575 | 0.4788 | 0.52022 | 0.00098 |
| 580 | 0.5125 | 0.48664 | 0.00086 |
| 585 | 0.5448 | 0.45445 | 0.00075 |
| 590 | 0.5752 | 0.42415 | 0.00065 |
| 595 | 0.6029 | 0.39655 | 0.00055 |
| 600 | 0.6270 | 0.37255 | 0.00045 |
| 605 | 0.6482 | 0.35145 | 0.00035 |
| 610 | 0.6658 | 0.33395 | 0.00025 |
| 615 | 0.6801 | 0.31970 | 0.00020 |
| 620 | 0.6915 | 0.30834 | 0.00016 |
| 625 | 0.7006 | 0.29927 | 0.00013 |
| 630 | 0.7079 | 0.29200 | 0.00010 |
| 635 | 0.7140 | 0.28593 | 0.00007 |
| 640 | 0.7190 | 0.28095 | 0.00005 |
| 645 | 0.7230 | 0.27697 | 0.00003 |
| 650 | 0.7260 | 0.27399 | 0.00001 |
| 655 | 0.7283 | 0.2717 | |
| 660 | 0.7300 | 0.2700 | |
| 665 | 0.7311 | 0.2689 | |
| 670 | 0.7320 | 0.2680 | |
| 675 | 0.7327 | 0.2673 | |
| 680 | 0.7334 | 0.2666 | |
| 685 | 0.73397 | 0.26603 | |
| 690 | 0.7344 | 0.2656 | |
| 695 | 0.73461 | 0.26539 | |
| 700 | 0.73467 | 0.26533 | |
| 780 | 0.73467 | 0.26533 | |

Table A-2

DISTRIBUTION COEFFICIENTS OF THE EQUAL ENERGY SPECTRUM

| λ | $\bar{x}$ | $\bar{y}$ | $\bar{z}$ | λ | $\bar{x}$ | $\bar{y}$ | $\bar{z}$ |
|---|---|---|---|---|---|---|---|
| 380 | 0.00139 | 0.00004 | 0.0066 | 580 | 0.9162 | 0.8700 | 0.00154 |
| 385 | 0.00226 | 0.00006 | 0.0107 | 585 | 0.9785 | 0.8163 | 0.00135 |
| 390 | 0.00426 | 0.00012 | 0.0201 | 590 | 1.0266 | 0.7570 | 0.00116 |
| 395 | 0.00771 | 0.00022 | 0.0365 | 595 | 1.0566 | 0.6949 | 0.00096 |
| 400 | 0.0144 | 0.00040 | 0.0685 | 600 | 1.0620 | 0.6310 | 0.00076 |
| 405 | 0.0233 | 0.00064 | 0.1105 | 605 | 1.0453 | 0.5668 | 0.00056 |
| 410 | 0.0432 | 0.00120 | 0.2056 | 610 | 1.0028 | 0.5030 | 0.00038 |
| 415 | 0.0780 | 0.00218 | 0.3730 | 615 | 0.9387 | 0.4412 | 0.00028 |
| 420 | 0.1344 | 0.00400 | 0.6459 | 620 | 0.8545 | 0.3810 | 0.00020 |
| 425 | 0.2132 | 0.0073 | 1.0317 | 625 | 0.7515 | 0.3210 | 0.00014 |
| 430 | 0.2839 | 0.0116 | 1.3856 | 630 | 0.6424 | 0.2650 | 0.00009 |
| 435 | 0.3268 | 0.0168 | 1.6142 | 635 | 0.5419 | 0.2170 | 0.00005 |
| 440 | 0.3469 | 0.0230 | 1.7402 | 640 | 0.4479 | 0.1750 | 0.00003 |
| 445 | 0.3483 | 0.0298 | 1.7840 | 645 | 0.3609 | 0.1382 | 0.00002 |
| 450 | 0.3362 | 0.0380 | 1.7727 | 650 | 0.2835 | 0.1070 | |
| 455 | 0.3193 | 0.0480 | 1.7472 | 655 | 0.2186 | 0.0816 | |
| 460 | 0.2909 | 0.0600 | 1.6693 | 660 | 0.1649 | 0.0610 | |
| 465 | 0.2509 | 0.0739 | 1.5268 | 665 | 0.1212 | 0.0446 | |
| 470 | 0.1954 | 0.0910 | 1.2880 | 670 | 0.0874 | 0.0320 | |
| 475 | 0.1422 | 0.1126 | 1.0427 | 675 | 0.0637 | 0.0232 | |
| 480 | 0.0956 | 0.1390 | 0.8128 | 680 | 0.0468 | 0.0170 | |
| 485 | 0.0580 | 0.1693 | 0.6163 | 685 | 0.0329 | 0.0119 | |
| 490 | 0.0320 | 0.2080 | 0.4651 | 690 | 0.0227 | 0.0082 | |
| 495 | 0.0147 | 0.2586 | 0.3532 | 695 | 0.0158 | 0.00572 | |
| 500 | 0.0049 | 0.3230 | 0.2720 | 700 | 0.01135 | 0.00410 | |
| 505 | 0.0024 | 0.4073 | 0.2123 | 705 | 0.00806 | 0.00291 | |
| 510 | 0.0093 | 0.5030 | 0.1582 | 710 | 0.00581 | 0.00210 | |
| 515 | 0.0291 | 0.6082 | 0.1117 | 715 | 0.00411 | 0.00148 | |
| 520 | 0.0633 | 0.7100 | 0.0783 | 720 | 0.00291 | 0.00105 | |
| 525 | 0.1096 | 0.7932 | 0.0572 | 725 | 0.00204 | 0.00074 | |
| 530 | 0.1655 | 0.8620 | 0.0421 | 730 | 0.00144 | 0.00052 | |
| 535 | 0.2258 | 0.9149 | 0.0299 | 735 | 0.00100 | 0.00036 | |
| 540 | 0.2904 | 0.9540 | 0.0204 | 740 | 0.00069 | 0.00025 | |
| 545 | 0.3597 | 0.9802 | 0.0134 | 745 | 0.00048 | 0.00017 | |
| 550 | 0.4335 | 0.9950 | 0.00877 | 750 | 0.00033 | 0.00012 | |
| 555 | 0.5120 | 1.0002 | 0.00577 | 755 | 0.00023 | 0.00008 | |
| 560 | 0.5945 | 0.9950 | 0.00386 | 760 | 0.00017 | 0.00006 | |
| 565 | 0.6783 | 0.9786 | 0.00269 | 765 | 0.00012 | 0.00004 | |
| 570 | 0.7622 | 0.9520 | 0.00206 | 770 | 0.00008 | 0.00003 | |
| 575 | 0.8425 | 0.9154 | 0.00172 | sums | 21.3683 | 21.3714 | 21.3531 |

Table A-3

DISTRIBUTION COEFFICIENTS FOR STANDARD ILLUMINANT A[3]
(Equivalent to full radiation at 2854° K)

| $\lambda$ | $\bar{x}_A$ | $\bar{y}_A$ | $\bar{z}_A$ | $\lambda$ | $\bar{x}_A$ | $\bar{y}_A$ | $\bar{z}_A$ |
|---|---|---|---|---|---|---|---|
| 380 | 0.0006 | | 0.0030 | 580 | 4.8590 | 4.6139 | 0.0082 |
| 385 | 0.0012 | | 0.0054 | 585 | 5.3545 | 4.4665 | 0.0074 |
| 390 | 0.0024 | | 0.0113 | 590 | 5.7910 | 4.2703 | 0.0065 |
| 395 | 0.0048 | 0.0001 | 0.0226 | 595 | 6.1393 | 4.0381 | 0.0056 |
| 400 | 0.0098 | 0.0003 | 0.0467 | 600 | 6.3504 | 3.7733 | 0.0045 |
| 405 | 0.0174 | 0.0005 | 0.0827 | 605 | 6.4280 | 3.4852 | 0.0035 |
| 410 | 0.0354 | 0.0010 | 0.1685 | 610 | 6.3361 | 3.1780 | 0.0024 |
| 415 | 0.0697 | 0.0020 | 0.3334 | 615 | 6.0894 | 2.8625 | 0.0018 |
| 420 | 0.1308 | 0.0039 | 0.6286 | 620 | 5.6868 | 2.5357 | 0.0013 |
| 425 | 0.2252 | 0.0077 | 1.0895 | 625 | 5.1271 | 2.1901 | 0.0010 |
| 430 | 0.3246 | 0.0133 | 1.5841 | 630 | 4.4904 | 1.8523 | 0.0006 |
| 435 | 0.4034 | 0.0208 | 1.9928 | 635 | 3.8776 | 1.5528 | 0.0004 |
| 440 | 0.4614 | 0.0306 | 2.3145 | 640 | 3.2787 | 1.2812 | 0.0002 |
| 445 | 0.4980 | 0.0426 | 2.5504 | 645 | 2.7011 | 1.0347 | 0.0001 |
| 450 | 0.5155 | 0.0583 | 2.7183 | 650 | 2.1683 | 0.8183 | |
| 455 | 0.5239 | 0.0788 | 2.8671 | 655 | 1.7072 | 0.6369 | |
| 460 | 0.5098 | 0.1052 | 2.9256 | 660 | 1.3143 | 0.4861 | |
| 465 | 0.4685 | 0.1380 | 2.8513 | 665 | 0.9847 | 0.3622 | |
| 470 | 0.3882 | 0.1808 | 2.5588 | 670 | 0.7241 | 0.2651 | |
| 475 | 0.3000 | 0.2376 | 2.1995 | 675 | 0.5376 | 0.1961 | |
| 480 | 0.2138 | 0.3108 | 1.8175 | 680 | 0.4019 | 0.1461 | |
| 485 | 0.1370 | 0.4005 | 1.4578 | 685 | 0.2875 | 0.1042 | |
| 490 | 0.0800 | 0.5196 | 1.1619 | 690 | 0.2017 | 0.0729 | |
| 495 | 0.0388 | 0.6812 | 0.9306 | 695 | 0.1433 | 0.0518 | |
| 500 | 0.0136 | 0.8960 | 0.7545 | 700 | 0.1043 | 0.0377 | |
| 505 | 0.0071 | 1.1876 | 0.6190 | 705 | 0.0752 | 0.0272 | |
| 510 | 0.0285 | 1.5398 | 0.4842 | 710 | 0.0551 | 0.0199 | |
| 515 | 0.0935 | 1.9519 | 0.3584 | 715 | 0.0395 | 0.0143 | |
| 520 | 0.2126 | 2.3854 | 0.2629 | 720 | 0.0284 | 0.0102 | |
| 525 | 0.3850 | 2.7858 | 0.2010 | 725 | 0.0202 | 0.0073 | |
| 530 | 0.6068 | 3.1609 | 0.1545 | 730 | 0.0144 | 0.0052 | |
| 535 | 0.8635 | 3.4988 | 0.1141 | 735 | 0.0101 | 0.0037 | |
| 540 | 1.1566 | 3.7998 | 0.0811 | 740 | 0.0071 | 0.0026 | |
| 545 | 1.4905 | 4.0616 | 0.0555 | 745 | 0.0050 | 0.0018 | |
| 550 | 1.8663 | 4.2840 | 0.0378 | 750 | 0.0035 | 0.0013 | |
| 555 | 2.2884 | 4.4702 | 0.0258 | 755 | 0.0025 | 0.0009 | |
| 560 | 2.7548 | 4.6109 | 0.0179 | 760 | 0.0018 | 0.0006 | |
| 565 | 3.2557 | 4.6974 | 0.0129 | 765 | 0.0013 | 0.0005 | |
| 570 | 3.7856 | 4.7284 | 0.0102 | 770 | 0.0009 | 0.0003 | |
| 575 | 4.3259 | 4.7001 | 0.0089 | sums | 109.8439 | 100.0000 | 35.5641 |

Table A-4

DISTRIBUTION COEFFICIENTS FOR STANDARD ILLUMINANT C[a]
(A filtered version of Illuminant A corresponding to clearest daylight)

| λ | $\bar{x}_C$ | $\bar{y}_C$ | $\bar{z}_C$ |
|---|---|---|---|
| 380 | 0.0022 | | 0.0101 |
| 385 | 0.0042 | 0.0001 | 0.0200 |
| 390 | 0.0095 | 0.0003 | 0.0448 |
| 395 | 0.0200 | 0.0006 | 0.0945 |
| 400 | 0.0429 | 0.0012 | 0.2036 |
| 405 | 0.0784 | 0.0022 | 0.3727 |
| 410 | 0.1633 | 0.0046 | 0.7784 |
| 415 | 0.3279 | 0.0091 | 1.5681 |
| 420 | 0.6193 | 0.0184 | 2.9755 |
| 425 | 1.0595 | 0.0361 | 5.1258 |
| 430 | 1.4989 | 0.0612 | 7.3138 |
| 435 | 1.8070 | 0.0931 | 8.9263 |
| 440 | 1.9794 | 0.1312 | 9.9292 |
| 445 | 2.0194 | 0.1730 | 10.3424 |
| 450 | 1.9578 | 0.2213 | 10.3227 |
| 455 | 1.8551 | 0.2786 | 10.1418 |
| 460 | 1.6818 | 0.3469 | 9.6501 |
| 465 | 1.4527 | 0.4278 | 8.8404 |
| 470 | 1.1359 | 0.5291 | 7.4882 |
| 475 | 0.8287 | 0.6563 | 6.0761 |
| 480 | 0.5565 | 0.8088 | 4.7295 |
| 485 | 0.3346 | 0.9774 | 3.5578 |
| 490 | 0.1815 | 1.1790 | 2.6361 |
| 495 | 0.0808 | 1.4195 | 1.9391 |
| 500 | 0.0259 | 1.7004 | 1.4320 |
| 505 | 0.0122 | 2.0460 | 1.0665 |
| 510 | 0.0448 | 2.4165 | 0.7599 |
| 515 | 0.1352 | 2.8224 | 0.5183 |
| 520 | 0.2879 | 3.2309 | 0.3561 |
| 525 | 0.4983 | 3.6050 | 0.2601 |
| 530 | 0.7615 | 3.9671 | 0.1940 |
| 535 | 1.0598 | 4.2941 | 0.1401 |
| 540 | 1.3923 | 4.5742 | 0.0976 |
| 545 | 1.7561 | 4.7852 | 0.0654 |
| 550 | 2.1414 | 4.9156 | 0.0433 |
| 555 | 2.5409 | 4.9636 | 0.0286 |
| 560 | 2.9397 | 4.9203 | 0.0191 |
| 565 | 3.3161 | 4.7847 | 0.0131 |
| 570 | 3.6616 | 4.5736 | 0.0099 |
| 575 | 3.9624 | 4.3052 | 0.0081 |

| λ | $\bar{x}_C$ | $\bar{y}_C$ | $\bar{z}_C$ |
|---|---|---|---|
| 580 | 4.2081 | 3.9958 | 0.0070 |
| 585 | 4.3853 | 3.6580 | 0.0061 |
| 590 | 4.4932 | 3.3132 | 0.0051 |
| 595 | 4.5261 | 2.9770 | 0.0041 |
| 600 | 4.4735 | 2.6580 | 0.0032 |
| 605 | 4.3605 | 2.3643 | 0.0023 |
| 610 | 4.1632 | 2.0881 | 0.0015 |
| 615 | 3.8875 | 1.8275 | 0.0011 |
| 620 | 3.5351 | 1.5763 | 0.0008 |
| 625 | 3.1076 | 1.3275 | 0.0006 |
| 630 | 2.6549 | 1.0952 | 0.0004 |
| 635 | 2.2357 | 0.8954 | 0.0002 |
| 640 | 1.8466 | 0.7216 | 0.0001 |
| 645 | 1.4912 | 0.5713 | |
| 650 | 1.1744 | 0.4432 | |
| 655 | 0.9056 | 0.3378 | |
| 660 | 0.6808 | 0.2518 | |
| 665 | 0.4963 | 0.1825 | |
| 670 | 0.3542 | 0.1297 | |
| 675 | 0.2552 | 0.0931 | |
| 680 | 0.1845 | 0.0671 | |
| 685 | 0.1269 | 0.0460 | |
| 690 | 0.0854 | 0.0309 | |
| 695 | 0.0582 | 0.0210 | |
| 700 | 0.0407 | 0.0147 | |
| 705 | 0.0281 | 0.0101 | |
| 710 | 0.0198 | 0.0071 | |
| 715 | 0.0136 | 0.0049 | |
| 720 | 0.0093 | 0.0034 | |
| 725 | 0.0063 | 0.0023 | |
| 730 | 0.0044 | 0.0016 | |
| 735 | 0.0030 | 0.0011 | |
| 740 | 0.0020 | 0.0007 | |
| 745 | 0.0014 | 0.0005 | |
| 750 | 0.0009 | 0.0003 | |
| 755 | 0.0006 | 0.0002 | |
| 760 | 0.0005 | 0.0001 | |
| 765 | 0.0003 | 0.0001 | |
| 770 | 0.0002 | 0.0001 | |
| sums | 98.0535 | 100.0000 | 118.1305 |

Table A-5

SPECTRAL ENERGY DISTRIBUTIONS OF THE TWO STANDARD ILLUMINANTS A AND C[9]

| Wavelength (mμ) | Relative Energy A | Relative Energy C | Wavelength (mμ) | Relative Energy A | Relative Energy C |
|---|---|---|---|---|---|
| 380 | 9.79 | 33.00 | 580 | 114.44 | 97.80 |
| 385 | 10.90 | 39.92 | 585 | 118.08 | 95.43 |
| 390 | 12.09 | 47.40 | 590 | 121.73 | 93.20 |
| 395 | 13.36 | 55.17 | 595 | 125.39 | 91.22 |
| 400 | 14.71 | 63.30 | 600 | 129.04 | 89.70 |
| 405 | 16.15 | 71.81 | 605 | 132.70 | 88.83 |
| 410 | 17.68 | 80.60 | 610 | 136.34 | 88.40 |
| 415 | 19.29 | 89.53 | 615 | 139.99 | 88.19 |
| 420 | 21.00 | 98.10 | 620 | 143.62 | 88.10 |
| 425 | 22.79 | 105.80 | 625 | 147.23 | 88.06 |
| 430 | 24.67 | 112.40 | 630 | 150.83 | 88.00 |
| 435 | 26.64 | 117.75 | 635 | 154.42 | 87.86 |
| 440 | 28.70 | 121.50 | 640 | 157.98 | 87.80 |
| 445 | 30.85 | 123.45 | 645 | 161.51 | 87.99 |
| 450 | 33.09 | 124.00 | 650 | 165.03 | 88.20 |
| 455 | 35.41 | 123.60 | 655 | 168.51 | 88.20 |
| 460 | 37.82 | 123.10 | 660 | 171.96 | 87.90 |
| 465 | 40.30 | 123.30 | 665 | 175.38 | 87.22 |
| 470 | 42.87 | 123.80 | 670 | 178.77 | 86.30 |
| 475 | 45.52 | 124.09 | 675 | 182.12 | 85.30 |
| 480 | 48.25 | 123.90 | 680 | 185.43 | 84.00 |
| 485 | 51.04 | 122.92 | 685 | 188.70 | 82.21 |
| 490 | 53.91 | 120.70 | 690 | 191.93 | 80.20 |
| 495 | 56.85 | 116.90 | 695 | 195.12 | 78.24 |
| 500 | 59.86 | 112.10 | 700 | 198.26 | 76.30 |
| 505 | 62.93 | 106.98 | 705 | 201.36 | 74.36 |
| 510 | 66.06 | 102.30 | 710 | 204.41 | 72.40 |
| 515 | 69.25 | 98.81 | 715 | 207.41 | 70.40 |
| 520 | 72.50 | 96.90 | 720 | 210.36 | 68.30 |
| 525 | 75.79 | 96.78 | 725 | 213.26 | 66.30 |
| 530 | 79.13 | 98.00 | 730 | 216.12 | 64.40 |
| 535 | 82.52 | 99.94 | 735 | 218.92 | 62.80 |
| 540 | 85.95 | 102.10 | 740 | 221.66 | 61.50 |
| 545 | 89.41 | 103.95 | 745 | 224.36 | 60.20 |
| 550 | 92.91 | 105.20 | 750 | 227.00 | 59.20 |
| 555 | 96.44 | 105.67 | 755 | 229.58 | 58.50 |
| 560 | 100.00 | 105.30 | 760 | 232.11 | 58.10 |
| 565 | 103.58 | 104.11 | 765 | 234.59 | 58.00 |
| 570 | 107.18 | 102.30 | 770 | 237.01 | 58.20 |
| 575 | 110.80 | 100.15 | 775 | 239.37 | 58.50 |
| 580 | 114.44 | 97.80 | 780 | 241.67 | 59.10 |

Table A-6

LUMINANCE LEVELS OF SKY[12]

| Sky Condition | Luminance Level (Candles/m$^2$) |
|---|---|
| Day, Clear | $10^4$ |
| Day, Overcast | $10^3$ |
| Day, Heavy Overcast | $10^2$ |
| Sunset, Heavy Overcast | $10^1$ |
| Sunset, Clear, 1/4 hour after | $10^0$ |
| Sunset, Clear, 1/2 hour after | $10^{-1}$ |
| Night, Clear, Bright Moon | $10^{-2}$ |
| Night, Clear, Moonless | $10^{-3}$ |
| Night, Overcast, Moonless | $10^{-4}$ |

Table A-7

SPECTRAL REFLECTANCE

Fresh Snow

| Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| 380 | 0.838 | 385 | 0.836 | 390 | 0.834 | 395 | 0.832 | 400 | 0.830 |
| 405 | 0.828 | 410 | 0.826 | 415 | 0.824 | 420 | 0.822 | 425 | 0.820 |
| 430 | 0.818 | 435 | 0.816 | 440 | 0.814 | 445 | 0.812 | 450 | 0.810 |
| 455 | 0.808 | 460 | 0.806 | 465 | 0.804 | 470 | 0.802 | 475 | 0.800 |
| 480 | 0.798 | 485 | 0.796 | 490 | 0.794 | 495 | 0.792 | 500 | 0.790 |
| 505 | 0.788 | 510 | 0.786 | 515 | 0.784 | 520 | 0.782 | 525 | 0.780 |
| 530 | 0.778 | 535 | 0.776 | 540 | 0.774 | 545 | 0.772 | 550 | 0.770 |
| 555 | 0.768 | 560 | 0.766 | 565 | 0.764 | 570 | 0.762 | 575 | 0.760 |
| 580 | 0.758 | 585 | 0.756 | 590 | 0.754 | 595 | 0.752 | 600 | 0.750 |
| 605 | 0.748 | 610 | 0.745 | 615 | 0.743 | 620 | 0.741 | 625 | 0.739 |
| 630 | 0.736 | 635 | 0.734 | 640 | 0.732 | 645 | 0.730 | 650 | 0.727 |
| 655 | 0.725 | 660 | 0.723 | 665 | 0.721 | 670 | 0.718 | 675 | 0.716 |
| 680 | 0.714 | 685 | 0.712 | 690 | 0.709 | 695 | 0.707 | 700 | 0.705 |
| 705 | 0.703 | 710 | 0.700 | 715 | 0.698 | 720 | 0.696 | 725 | 0.694 |
| 730 | 0.691 | 735 | 0.689 | 740 | 0.687 | 745 | 0.685 | 750 | 0.682 |
| 755 | 0.680 | 760 | 0.678 | 765 | 0.676 | 770 | 0.673 | 775 | 0.671 |
| 780 | 0.669 | | | | | | | | |

Table A-8

SPECTRAL REFLECTANCE

Men (Fatigue Shirts)

| Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | 385 | 0.100 | 390 | 0.100 | 395 | 0.100 | 400 | 0.100 |
| [illegible] | [illegible] | 410 | 0.100 | 415 | 0.100 | 420 | 0.100 | 425 | 0.100 |
| [illegible] | [illegible] | 435 | 0.100 | 440 | 0.100 | 445 | 0.100 | 450 | 0.100 |
| [illegible] | [illegible] | 460 | 0.106 | 465 | 0.109 | 470 | 0.112 | 475 | 0.115 |
| [illegible] | [illegible] | 485 | 0.121 | 490 | 0.124 | 495 | 0.127 | 500 | 0.130 |
| [illegible] | [illegible] | 510 | 0.136 | 515 | 0.139 | 520 | 0.142 | 525 | 0.145 |
| [illegible] | [illegible] | 535 | 0.151 | 540 | 0.151 | 545 | 0.157 | 550 | 0.160 |
| [illegible] | [illegible] | 560 | 0.159 | 565 | 0.159 | 570 | 0.159 | 575 | 0.158 |
| [illegible] | [illegible] | 585 | 0.158 | 590 | 0.157 | 595 | 0.157 | 600 | 0.157 |
| [illegible] | [illegible] | 610 | 0.156 | 615 | 0.156 | 620 | 0.155 | 625 | 0.155 |
| [illegible] | [illegible] | 635 | 0.154 | 640 | 0.154 | 645 | 0.154 | 650 | 0.153 |
| [illegible] | [illegible] | 660 | 0.153 | 665 | 0.152 | 670 | 0.152 | 675 | 0.152 |
| [illegible] | [illegible] | 685 | 0.151 | 690 | 0.151 | 695 | 0.150 | 700 | 0.150 |
| [illegible] | [illegible] | 710 | [illegible] | 715 | 0.157 | 720 | 0.160 | 725 | 0.162 |
| [illegible] | [illegible] | 735 | 0.467 | 740 | 0.170 | 745 | 0.172 | 750 | 0.175 |
| [illegible] | [illegible] | 760 | 0.180 | 765 | 0.183 | 770 | 0.185 | 775 | 0.188 |
| [illegible] | [illegible] | | | | | | | | |

Table A-9

**SPECTRAL REFLECTANCE**

Men (Olive Drab Clothes)

| Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) | Wavelength (m.) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | 0.050 | 385 | 0.050 | 390 | 0.050 | 395 | 0.050 | 400 | 0.050 |
| [illegible] | [illegible] | 410 | 0.050 | 415 | 0.050 | 420 | 0.050 | 425 | 0.050 |
| [illegible] | [illegible] | 435 | 0.050 | 440 | 0.050 | 445 | 0.050 | 450 | 0.050 |
| [illegible] | 0.052 | 460 | 0.053 | 465 | 0.055 | 470 | 0.057 | 475 | 0.058 |
| [illegible] | 0.060 | 485 | 0.064 | 490 | 0.069 | 495 | 0.073 | 500 | 0.078 |
| [illegible] | 0.082 | 510 | 0.087 | 515 | 0.091 | 520 | 0.096 | 525 | 0.100 |
| [illegible] | 0.100 | 535 | 0.100 | 540 | 0.100 | 545 | 0.100 | 550 | 0.100 |
| [illegible] | 0.100 | 560 | 0.100 | 565 | 0.100 | 570 | 0.100 | 575 | 0.100 |
| [illegible] | 0.100 | 585 | 0.100 | 590 | 0.100 | 595 | 0.100 | 600 | 0.100 |
| [illegible] | 0.110 | 610 | 0.120 | 615 | 0.130 | 620 | 0.140 | 625 | 0.150 |
| [illegible] | 0.160 | 635 | 0.170 | 640 | 0.180 | 645 | 0.190 | 650 | 0.200 |
| [illegible] | 0.210 | 660 | 0.220 | 665 | 0.230 | 670 | 0.240 | 675 | 0.250 |
| [illegible] | 0.260 | 685 | 0.270 | 690 | 0.280 | 695 | 0.290 | 700 | 0.300 |
| [illegible] | [illegible] | 710 | 0.326 | 715 | 0.339 | 720 | 0.352 | 725 | 0.365 |
| [illegible] | 0.378 | 735 | 0.391 | 740 | 0.404 | 745 | 0.417 | 750 | 0.430 |
| [illegible] | [illegible] | 760 | 0.456 | 765 | 0.469 | 770 | 0.482 | 775 | 0.495 |
| [illegible] | [illegible] | | | | | | | | |

Table A-10

SPECTRAL REFLECTANCE

Small Truck (Covered with Green Camouflage Cloth)

| [illegible] | [illegible] | [illegible] | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | 0,060 | 390 | 0,060 | 395 | 0,060 | 400 | 0,060 |
| [illegible] | [illegible] | [illegible] | 0,060 | 415 | 0,060 | 420 | 0,060 | 425 | 0,060 |
| [illegible] | [illegible] | [illegible] | 0,060 | 440 | 0,060 | 445 | 0,060 | 450 | 0,060 |
| [illegible] | [illegible] | 460 | 0,060 | 465 | 0,150 | 470 | 0,060 | 475 | 0,060 |
| [illegible] | [illegible] | [illegible] | [illegible] | 490 | 0,060 | 495 | 0,070 | 500 | 0,080 |
| [illegible] | [illegible] | [illegible] | 0,100 | 515 | 0,110 | 520 | 0,120 | 525 | 0,130 |
| [illegible] | [illegible] | [illegible] | 0,122 | 540 | 0,128 | 545 | 0,111 | 550 | 0,110 |
| [illegible] | [illegible] | [illegible] | 0,102 | 565 | 0,098 | 570 | 0,094 | 575 | 0,090 |
| [illegible] | [illegible] | [illegible] | 0,082 | 590 | 0,078 | 595 | 0,071 | 600 | 0,070 |
| [illegible] | [illegible] | [illegible] | 0,072 | 615 | 0,073 | 620 | 0,071 | 625 | 0,075 |
| [illegible] | [illegible] | [illegible] | 0,077 | 640 | 0,078 | 645 | 0,079 | 650 | 0,080 |
| [illegible] | [illegible] | [illegible] | [illegible] | 665 | 0,130 | 670 | [illegible] | 675 | 0,137 |
| [illegible] | [illegible] | [illegible] | [illegible] | 690 | 0,177 | 695 | 0,190 | 700 | 0,203 |
| [illegible] | [illegible] | [illegible] | [illegible] | 715 | 0,213 | 720 | 0,257 | 725 | 0,270 |
| [illegible] | [illegible] | [illegible] | 0,297 | 740 | 0,310 | 745 | 0,323 | 750 | 0,337 |
| [illegible] | [illegible] | [illegible] | [illegible] | 765 | 0,277 | 770 | 0,390 | 775 | 0,403 |
| [illegible] | [illegible] | | | | | | | | |

Table A-11

SPECTRAL REFLECTANCE

Meadow with Abundant Bloom of Daisies

| Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| 380 | 0.023 | 385 | 0.030 | 390 | 0.037 | 395 | 0.043 | 400 | 0.050 |
| 405 | 0.057 | 410 | 0.063 | 415 | 0.070 | 420 | 0.077 | 425 | 0.085 |
| 430 | 0.090 | 435 | 0.090 | 440 | 0.090 | 445 | 0.090 | 450 | 0.090 |
| 455 | 0.090 | 460 | 0.090 | 465 | 0.090 | 470 | 0.090 | 475 | 0.090 |
| 480 | 0.090 | 485 | 0.090 | 490 | 0.090 | 495 | 0.096 | 500 | 0.102 |
| 505 | 0.109 | 510 | 0.115 | 515 | 0.121 | 520 | 0.127 | 525 | 0.134 |
| 530 | 0.140 | 535 | 0.140 | 540 | 0.139 | 545 | 0.139 | 550 | 0.139 |
| 555 | 0.138 | 560 | 0.138 | 565 | 0.138 | 570 | 0.137 | 575 | 0.137 |
| 580 | 0.137 | 585 | 0.136 | 590 | 0.136 | 595 | 0.136 | 600 | 0.135 |
| 605 | 0.135 | 610 | 0.134 | 615 | 0.134 | 620 | 0.134 | 625 | 0.133 |
| 630 | 0.133 | 635 | 0.133 | 640 | 0.132 | 645 | 0.132 | 650 | 0.132 |
| 655 | 0.131 | 660 | 0.131 | 665 | 0.131 | 670 | 0.130 | 675 | 0.130 |
| 680 | 0.155 | 685 | 0.181 | 690 | 0.206 | 695 | 0.232 | 700 | 0.257 |
| 705 | 0.282 | 710 | 0.308 | 715 | 0.333 | 720 | 0.358 | 725 | 0.384 |
| 730 | 0.409 | 735 | 0.435 | 740 | 0.460 | 745 | 0.467 | 750 | 0.475 |
| 755 | 0.482 | 760 | 0.490 | 765 | 0.498 | 770 | 0.505 | 775 | 0.512 |
| 780 | 0.520 | | | | | | | | |

Table A-12

**SPECTRAL REFLECTANCE**

International Orange

| Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) | Wavelength (mμ) | Reflectance (percent) |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | 0.024 | 465 | 0.028 | 550 | 0.080 | 635 | 0.632 | 720 | 0.620 |
| [illegible] | 0.024 | 470 | 0.028 | 555 | 0.128 | 640 | 0.637 | 725 | 0.615 |
| [illegible] | 0.024 | 475 | 0.029 | 560 | 0.176 | 645 | 0.641 | 730 | 0.610 |
| [illegible] | 0.025 | 480 | 0.029 | 565 | 0.224 | 650 | 0.645 | 735 | 0.605 |
| [illegible] | 0.025 | 485 | 0.029 | 570 | 0.272 | 655 | 0.644 | 740 | 0.600 |
| [illegible] | 0.025 | 490 | 0.029 | 575 | 0.320 | 660 | 0.644 | 745 | 0.597 |
| [illegible] | 0.025 | 495 | 0.030 | 580 | 0.368 | 665 | 0.643 | 750 | 0.593 |
| [illegible] | 0.026 | 500 | 0.030 | 585 | 0.416 | 670 | 0.643 | 755 | 0.590 |
| [illegible] | 0.026 | 505 | 0.035 | 590 | 0.464 | 675 | 0.642 | 760 | 0.587 |
| [illegible] | 0.026 | 510 | 0.040 | 595 | 0.512 | 680 | 0.642 | 765 | 0.583 |
| [illegible] | 0.026 | 515 | 0.045 | 600 | 0.560 | 685 | 0.641 | 770 | 0.580 |
| [illegible] | 0.027 | 520 | 0.050 | 605 | 0.575 | 690 | 0.641 | 775 | 0.577 |
| [illegible] | 0.027 | 525 | 0.055 | 610 | 0.590 | 695 | 0.640 | 780 | 0.573 |
| [illegible] | 0.027 | 530 | 0.060 | 615 | 0.605 | 700 | 0.640 | | |
| [illegible] | 0.027 | 535 | 0.065 | 620 | 0.620 | 705 | 0.635 | | |
| [illegible] | 0.028 | 540 | 0.070 | 625 | 0.624 | 710 | 0.630 | | |
| [illegible] | 0.028 | 545 | 0.075 | 630 | 0.628 | 715 | 0.625 | | |

Table A-13

PHYSICAL (RADIOMETRIC) CONCEPTS

| | c.g.s. Unit | m.k.s. Unit |
|---|---|---|
| Radiator (source of radiant energy) | | |
| Radiation (process) | | |
| Radiant energy | erg | joule |
| Radiant density | erg/$cm^3$ | joule/$m^3$ |
| Radiant flux | erg/s | watt |
| Radiant emittance | erg/(s × $cm^2$) | watt/$m^2$ |
| Radiant intensity | erg/(s × ω)* | watt/ω* |
| Radiance | erg/(s × ω × $cm^2$) | watt/(ω × $m^2$) |
| Irradiance | erg/(s × $cm^2$) | watt/$m^2$ |
| Spectral reflectance | | |
| Spectral transmittance | | |

*ω = unit solid angle. The unit is normally the steradian.

Table A-14

PSYCHOPHYSICAL (PHOTOMETRIC) CONCEPTS

| | c.g.s. Unit | m.k.s. Unit |
|---|---|---|
| Luminator (source of luminous energy) | | |
| Lumination (process) | | |
| Luminous energy | lumerg | talbot |
| Luminous density | lumerg/$cm^3$ | talbot/$m^3$ |
| Luminous flux | lumerg/s | lumen |
| Luminous emittance | lumerg/(s × $cm^2$) | lumen/$m^2$ |
| Luminous intensity | lumerg/(s × ω) | lumen/ω [candle] |
| Luminance | lumerg/(s × ω × $cm^2$) | lumen/(ω × $m^2$) [candle/$m^2$] |
| Illuminance | lumerg/(s × $cm^2$) | lumen/$m^2$ [lux] |
| *Luminous reflectance | | |
| *Luminous transmittance | | |

*The I.C.I. has adopted the collective term <u>luminance factor</u> for these.

Table A-15

PHOTOMETRIC CONCEPTS AND UNITS

| | Dimensional Formula | Defining Equation | Metric Units | English Units |
|---|---|---|---|---|
| Luminous flux | $L^2MT^{-3}$ | | lumen | lumen |
| Luminous intensity | $L^2MT^{-3}$ | $I = \frac{dF}{ds}$ | candle | candle |
| Luminous emittance | $MT^{-3}$ | $L = \frac{dF}{ds}$ | lumen/m$^2$<br>lumen/cm$^2$ etc. | lumen/ft$^2$<br>lumen/mile$^2$ etc. |
| Illuminance | $MT^{-3}$ | $E = \frac{dF}{ds}$ | lumen/m$^2$ (lux)<br>lumen/cm$^2$ (phot) etc. | lumen/ft$^{2}$*<br>lumen/mile$^2$ etc. |
| Luminance | $MT^{-3}$ | $B = \frac{d^2F}{d\omega\, ds \cos\theta}$ | candle/m$^2$<br>candle/cm$^2$ etc.+ | candle/ft$^2$<br>candle/mile$^2$ etc. |
| Luminous energy | $L^2MT^{-2}$ | $Q = F\,dt$ | talbot<br>lumen-hour etc. | lumen-hour<br>lumen-s etc. |
| Luminous density | $L^{-1}MT^{-2}$ | $q = \frac{dQ}{dv}$ | talbot/m$^3$ | |

*The lumen/ft$^2$ is frequently, though illogically, called the "foot-candle"; and the lumen/mile$^2$ the "mile-candle."

+The candle/cm$^2$ is also called the STILB.

## Annex B

## METHOD FOR THE DETERMINATION OF ATMOSPHERIC EXTINCTION COEFFICIENTS

Annex B

# METHOD FOR THE DETERMINATION OF ATMOSPHERIC EXTINCTION COEFFICIENTS

## 1. General

On passing through a medium, the energy contained in a beam of radiation may be scattered and/or absorbed by the particles comprising the medium. The quantity of energy that remains in the beam is dependent on the size, composition, and concentration of particles in the medium, and the path length of the radiation through the medium. Below are described the factors that affect attenuation and some methods for the determination of the degree of attenuations. The method that is given follows the treatment of Ref. 12.

## 2. The Extinction Coefficient and the Transmittance of Radiation

The change in the quantity of energy passing through a medium containing a homogeneous distribution of scattering bodies is proportional to the flux density of the radiation, and can be written

$$dE_\lambda = -\sigma_\lambda E_\lambda \, dr \quad , \tag{B-1}$$

where the scattering coefficient, $\sigma_\lambda$, is a proportionality constant and r is the path length through the medium. Integration over the range, R, yields

$$E_\lambda(R) = E_\lambda(0) \, e^{-\sigma_\lambda R} \tag{B-2}$$

where $E_\lambda(0)$ is the flux density at range zero. In the same manner, it is possible to define the absorption coefficient, $k_\lambda$, in terms of

$$E_\lambda(R) = E_\lambda(0) \, e^{-k_\lambda R} \quad . \tag{B-3}$$

If the medium contains both scattering and absorbing bodies, the two equations can be combined to yield

$$E_\lambda(R) = E_\lambda(0)\, e^{-(\sigma_\lambda + k_\lambda)R} = E_\lambda(0)\, e^{-\beta_\lambda R} \quad , \qquad \text{(B-4)}$$

where $\beta_\lambda$ is called the extinction coefficient. If the exponential is written as

$$e^{-\beta_\lambda} = \tau_\lambda \quad , \qquad \text{(B-5)}$$

the symbol $\tau_\lambda$ is called the transmissivity, and the transmittance of the medium is defined by

$$T_\lambda = \tau_\lambda^R \quad . \qquad \text{(B-6)}$$

3. The Determination of Scattering Coefficients

a. The Scattering Function

Let an elementary volume, dv, of a medium containing a cross section, ds, of absorbing and scattering bodies be illuminated by a beam of energy of flux density $E_\lambda$. At an angle $\theta$ with the direction of the incident beam, the intensity of scattered radiation, $I(\theta)$, is

$$I_\lambda(\theta) = E_\lambda b_\lambda(\theta)\, ds \quad , \qquad \text{(B-7)}$$

where $b_\lambda(\theta)$ is an angularly dependent function called the scattering function and is defined as the intensity of scattered radiation of wavelength $\lambda$ in the direction $\theta$ per unit of flux incident on the medium.

Where no absorption occurs, the total flux scattered into space is equal to the indident flux, so that

$$4\pi \int_0^\pi I_\lambda(\theta) \sin\theta\, d\theta = E_\lambda ds \qquad \text{(B-8)}$$

where 2 sin θ dθ is the solid angle subtended by an annular differential area at unit distance from the elementary volume. Substituting the value for $I_\lambda(\theta)$ from Eq. (B-7) yields

$$4\pi \int_0^\pi b_\lambda(\theta) \sin\theta \, d\theta = 1 \tag{B-9}$$

b. <u>The Volume Scattering Function</u>

When the nature of the attenuating bodies in the medium is unknown, it is expedient to define a volume scattering function,

$$I_\lambda(\theta) = E_\lambda b'(\theta) v \quad , \tag{B-10}$$

as the intensity of scattered radiation of wavelength λ in the direction θ per unit of flux incident on the volume, v, of medium. For a unit thickness of medium, integration over all space yields

$$4\pi \int_0^\pi E_\lambda b'(\theta) \sin\theta \, d\theta = \left(1 - e^{-\sigma_\lambda}\right) E_\lambda \quad , \tag{B-11}$$

where the right-hand term gives the difference between the incident and transmitted flux. Neglecting terms in $\sigma^2$, and higher powers, and dividing by $E_\lambda$, the fraction of flux scattered is

$$4\pi \int_0^\pi b_\lambda'(\theta) \sin\theta \, d\theta = \sigma_\lambda \quad . \tag{B-12}$$

c. <u>The Determination of Scattering Coefficients from the Scattering Function</u>

Let N be the number of attenuating particles per unit volume of medium, and $S'(\theta)$ the scattering function per particle. The volume scattering function is

$$b_\lambda'(\theta) = NS_\lambda'(\theta) \quad , \tag{B-13}$$

which upon substitution into Eq. (B-12) yields

$$\sigma_\lambda = 4\pi \int_0^\pi NS_\lambda'(\theta) \sin\theta \, d\theta \quad . \qquad \text{(B-14)}$$

Letting $\sigma_\lambda/N$ equal p and expressing $S'(\theta)$ as

$$S_\lambda'(\theta) = \frac{\lambda^2}{4\pi^2} S_\lambda''(\theta) \quad , \qquad \text{(B-15)}$$

there obtains

$$p = 4\pi \int_0^\pi \frac{\lambda^2}{4\pi^2} S_\lambda''(\theta) \sin\theta \, d\theta \quad ,$$

$$= \frac{\lambda^2}{\pi} \int_0^\pi S_\lambda''(\theta) \sin\theta \, d\theta \quad , \qquad \text{(B-16)}$$

which can be thought of as the radiation scattered per particle per unit of radiation. Dividing by the cross-sectional area of the particle, $\pi a^2$, yields

$$K' = \frac{\lambda^2}{\pi^2 a^2} \int_0^\pi S_\lambda''(\theta) \sin\theta \, d\theta \quad . \qquad \text{(B-17)}$$

The theories developing $S_\lambda''(\theta)$ include consideration of polarization phenomena. Since it is normally not necessary to consider polarization in the scattering of visible light,[5] the half sum, $S_\lambda'(\theta)/2$, can be used, and a scattering area ratio, $K_\lambda$, can be defined as

$$K_\lambda = \frac{2}{\alpha^2} \int_0^\pi S_\alpha(\theta) \sin\theta \, d\theta \quad . \qquad \text{(B-18)}$$

where

$$\alpha = 2\pi a/\lambda$$

$$S_\alpha(\theta) = S_\lambda''(\theta)/2 \quad .$$

Table B-1 summarizes the values $S_\alpha(\theta)$ for small water droplets (refractive index = 1.33) for various values of $\alpha$. For small values of $\alpha$ these table values can be used for the integration required in (B-18). From Eqs. (B-16) and (B-18), we have

$$\alpha_\lambda = NK_\lambda \pi a^2 \quad . \tag{B-19}$$

If it is assumed that there is no absorption, the extinction coefficient, $\beta_\lambda$, is also equal to $NK_\lambda \pi a^2$.

Equation (B-19) is valid only for homogeneous aerosols. For mediums containing particles of different sizes, Eq. (B-19) must be written

$$\sigma_\lambda = \sum_{i=1}^{n} N_i K_{i\lambda} \pi a_i^2 \quad , \tag{B-20}$$

where, the subscript i refers to the particle having the $i^{th}$ radius. For particle distributions that can be described by continuous functions, such as the normal or Rosin-Rammler distributions,[15] the summation may be replaced by an integral sign, and the equation becomes

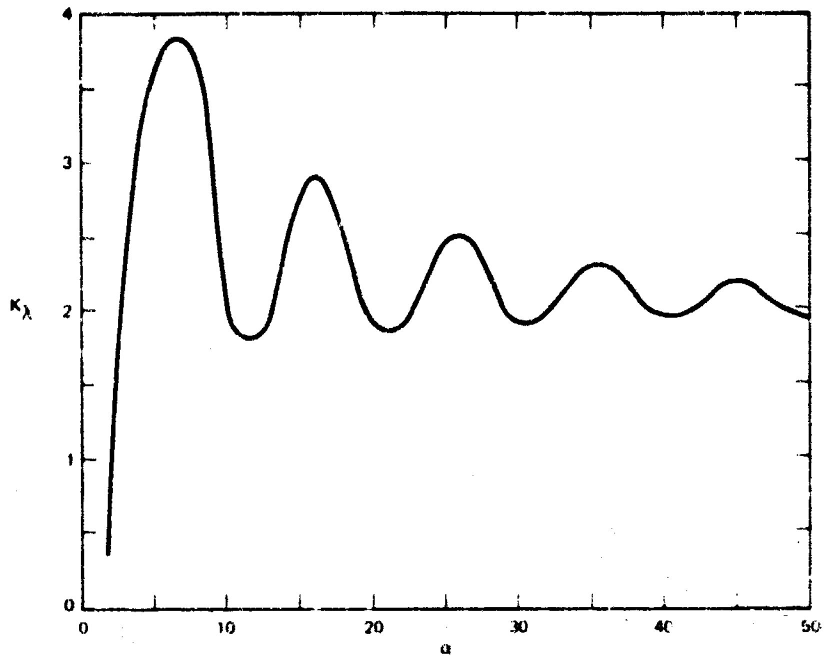
$$\sigma_\lambda = N \int_{a\text{-min}}^{a\text{-max}} f(a)\ k(a) \pi a^2\ da \quad , \tag{B-21}$$

where f(a) is the normalized distribution function, k(a) is the form of $K_\lambda$ as a function of a, and a-min and a-max are the smallest and largest radii in the system.

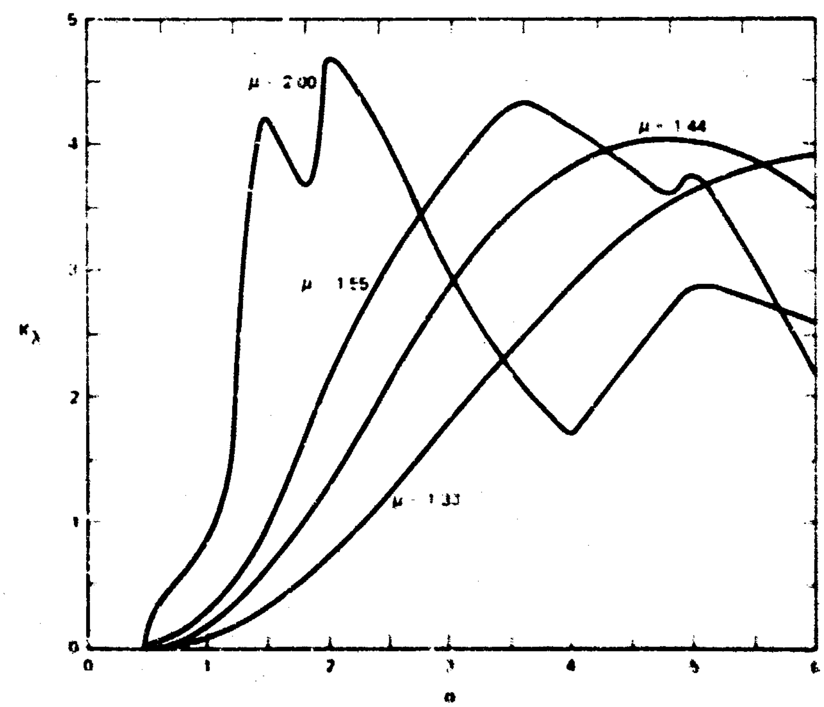
Values of $K_\lambda$ have been determined by Haughton and Chalker[15] for water droplets, and by LaMer and Sinclair[16] for materials having other reflective indices. Some of these values are summarized in Figure B-1.

d. The Determination of the Extinction Coefficient

For relatively short ranges (3-5 km), the absorption of radiation (380-780 mμ) by most atmospheric contaminants encountered on a battlefield--water vapor and droplets, dust, and smoke-screen agents--



(a) VALUES FOR $K_\lambda$ FOR WATER DROPLETS



(b) VALUES FOR $K_\lambda$ FOR VARIOUS REFRACTIVE INDICES, $\mu$

FIGURE 8-1 SCATTERING AREA RATIOS FOR VARIOUS MATERIALS

Table B-1

S(θ) FOR WATER DROPLETS (REFRACTIVE INDEX = 1.33) IN UNITS OF $\lambda^2 4\pi^2 cm^2$

| θ \ α | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 4.0 | 5.0 | 6.0 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.00071 | 0.05260 | 0.6465 | 3.937 | 14.20 | 41.69 | 197.7 | 585.8 | 1253. |
| 10 | 0.0069 | 0.05152 | 0.6288 | 3.790 | 13.45 | 38.68 | 173.7 | 478.0 | 927.1 |
| 20 | 0.0066 | 0.04846 | 0.5790 | 3.382 | 11.42 | 30.85 | 116.6 | 251.8 | 349.0 |
| 30 | 0.0061 | 0.04383 | 0.5054 | 2.800 | 8.705 | 21.00 | 57.71 | 76.70 | 56.58 |
| 40 | 0.0051 | 0.03827 | 0.4196 | 2.155 | 5.938 | 12.02 | 19.48 | 13.168 | 27.61 |
| 50 | 0.00048 | 0.03248 | 0.3331 | 1.546 | 3.626 | 5.646 | 4.333 | 9.441 | 28.16 |
| 60 | 0.00042 | 0.02706 | 0.2551 | 1.038 | 1.984 | 1.1549 | 2.064 | 10.234 | 9.396 |
| 70 | 0.00037 | 0.02253 | 0.19087 | 0.654 | 0.9808 | 0.6463 | 2.744 | 4.872 | 3.863 |
| 80 | 0.00033 | 0.01915 | 0.14213 | 0.3867 | 0.4519 | 0.3214 | 2.375 | 2.635 | 5.914 |
| 90 | 0.00032 | 0.01700 | 0.10765 | 0.21354 | 0.2149 | 0.3936 | 1.230 | 1.909 | 3.573 |
| 100 | 0.00032 | 0.01598 | 0.08472 | 0.10831 | 0.13202 | 0.4806 | 0.4746 | 2.390 | 1.5505 |
| 110 | 0.00034 | 0.01588 | 0.07025 | 0.1918 | 0.12225 | 0.4630 | 0.4771 | 1.354 | 3.052 |
| 120 | 0.00037 | 0.01645 | 0.06138 | 0.02028 | 0.14755 | 0.35880 | 0.8279 | 0.5854 | 2.730 |
| 130 | 0.00042 | 0.01741 | 0.05605 | 0.01096 | 0.19170 | 0.23317 | 1.0096 | 1.300 | 0.8624 |
| 140 | 0.00046 | 0.01951 | 0.05284 | 0.01370 | 0.2462 | 0.14452 | 0.8518 | 2.222 | 2.55[illegible] |
| 150 | 0.00050 | 0.01956 | 0.05088 | 0.02262 | 0.3034 | 0.1188 | 0.6302 | 2.065 | 4.647 |
| 160 | 0.00054 | 0.02042 | 0.04970 | 0.03288 | 0.3540 | 0.1446 | 0.6083 | 1.593 | 3.456 |
| 170 | 0.00056 | 0.02096 | 0.04906 | 0.04068 | 0.3888 | 0.1855 | 0.7196 | 1.829 | 2.880 |
| 180 | 0.00057 | 0.02115 | 0.04887 | 0.04358 | 0.4013 | 0.2042 | 0.8709 | 2.155 | 3.507 |

Source: From W. E. K. Middleton, Vision Through the Atmosphere, University of Toronto Press, 1952.

is small,[3] and the extinction coefficient, $\beta_\lambda$, can be set equal to the scattering coefficient, $\sigma_\lambda$. Moreover, in the particle size encountered in natural water droplet hazes and fogs (10-80 μ)[9] and in fog-oil smoke screens (0.6-0.7 μ),[12] the value of $K_\lambda$, assuming that the Haughton and Chalker data hold for values of $\alpha$ between 100 and 1000, is approximately equal to 2.0. Thus, if W and $\rho$ are the total weight concentration and density of the atmospheric contaminants, and $\gamma_i$ is the fraction of the weight of the contaminant with particle radius $a_i$, Eqs. (B-19) and (B-20) can be rewritten for all $\lambda$ as

$$\beta_m = \frac{3W}{d\rho} \quad \text{(homogeneous aerosols)} \quad , \tag{B-22}$$

$$\beta_m = \frac{3W}{\rho}\sum_i \frac{\gamma_i}{d_i} \quad \text{(heterogeneous aerosols)} \quad , \tag{B-23}$$

where d is the diameter of the particle in the attenuating medium.

The value of the extinction coefficient may also be determined from the meteorological visibility. Since the luminance of a black body is zero, the inherent contrast of a black body against the horizon is -1. If the meteorological visibility, $V_R$, is defined as the range at which the apparent contrast of a black body is -0.02, Eq. (52) yields

$$e^{-\beta R} = 0.02 \tag{B-24}$$

and

$$\beta = \frac{3.9}{V_R} \quad . \tag{B-25}$$

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13. ABSTRACT

Research was performed to (1) identify the essential elements and pertinent parameters for a visual model for surveillance of camouflaged personnel in various terrains, weathers, and combat environments, and (2) develop the mathematics and logic of the visual model.

A model was developed to account for the effects of luminance and color contrasts in the detection process. It accounts for intrinsic luminance and color contrasts at the target and the effects of the atmosphere and range between the observer and the object.

The state of knowledge concerning the effects of movement and form discrimination was found to be fairly primitive despite the extensive research that has been performed. It was not possible to develop a sufficiently detailed analytical model for the effects of either of these important parameters.

Since it is considered necessary to include a human's judgment in modeling the process of recognizing military objects, empirical data derived from human observers' performance of form recognition, in conjunction with a classification system for backgrounds, are required for developing a realistic empirical model of form discrimination.


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