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DESIGN GOALS FOR FUTURE

CAMOUFLAGE SYSTEMS

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The objective of this work is goals and specifications for a multi-purpose camouflage system suitable for use by units in a ground army. The principal steps in the methodology are:

- estimate the surveillance and target acquisition capabilities of battlefield sensor systems

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- characterize the vulnerability of ground target to surveillance and target acquisition,

- determine the level of countermeasures required to protect targets against surveillance and target acquisition,

- synthesize goals and specifications for a multi-purpose camouflage system to provide protection for most of the targets against most of the sensor systems under most operating conditions

Sensors operating in the visual and infrared spectra (including detectors of target thermal self-emission as well as detectors of scattered light), radars and laser measurement and target designator instruments were considered. Characteristics of sensor systems were used to generate criteria for discriminating among classes of targets. These criteria were used to divide the targets in the Camouflage Critical and Camouflage Sensitive lists into 9 categories. The vulnerability of targets in each category to sensor systems of each type was assessed, high-vulnerability high-importance combinations were noted, and characteristics required of multi-purpose camouflage systems to provide protection in these cases were synthesized.

TABLE OF CONTENTS

	Page
I. EXECUTIVE SUMMARY	I-1
II. TARGET ACQUISITION AND SURVEILLANCE SENSOR SYSTEMS	II-1
A. INTRODUCTION	II-1
B. DEFINITIONS	II-3
C. CHARACTERISTICS OF VISUAL AND VSWIR DETECTION AND TARGET ACQUISITION SYSTEMS	II-4
1. Visual	II-4
2. VSWIR	II-7
a. Photographic IR	II-7
b. Night Vision	II-9
3. Important Target Parameters	II-18
a. Visual (0.4 to 0.7 μm)	II-18
b. Very Short Wave IR (.75 to 1.0 μm)	II-19
4. Performance of Visual and Near Infrared (VSWIR) Sensors	II-20
a. Unaided Eye	II-20
b. Aided Eye	II-22
c. Passive Night Vision	II-24
d. Photographic Night Vision	II-24
e. Aerial Reconnaissance	II-24
5. Examples of Sensor System Performance	II-26
a. Camouflage for Unaided Eyes	II-28
b. Camouflage for Aided Eyes	II-31
c. Vision at Night	II-33
d. Aerial Reconnaissance	II-35
e. Synopsis of Contrast Data	II-35

TABLE OF CONTENTS

(continued)

	Page
D. CHARACTERISTICS OF LASER RANGE FINDERS, TARGET DESIGNATORS, BEAM RIDERS AND LIDARS	II-38
1. Types of Laser Systems	II-38
a. Laser Range Finders	II-39
b. Target Designators	II-41
c. Laser Beam Riders	II-42
d. Laser Radars (LIDARS)	II-42
2. Types of Lasers	II-42
a. Single Wavelength Lasers	II-42
b. Single, Fixed, Selectable Wavelength Lasers	II-44
c. Multiple, Fixed, and Selectable Wavelength Lasers	II-46
3. Recent Laser Threats	II-50
4. Target Parameters Affecting Laser System Performance	II-51
a. Effect of a Diffuse Surface at Irregular Aspect Angle	II-51
b. Effect of a Glossy Surface with Curvature	II-53
c. Comparison of Glossy to Matte Surface	II-55
d. The Attenuation Budget of Laser Range Finders and Designators	II-56
5. Important Target Parameters	II-58
6. Camouflage Implications	II-60

TABLE OF CONTENTS

(continued)

Page

E. CHARACTERISTICS OF SYSTEMS OPERATING IN THE MWIR AND LWIR SPECTRAL RANGES II-61

1. Introduction II-61

2. Surveillance and Target Acquisition in the MWIR and LWIR Spectral Regions II-63

a. Reconnaissance and Surveillance II-63

b. Target Acquisition II-64

c. Thermal Homing Weapons II-65

d. Range Finders II-66

3. Types of Sensors II-66

a. Principles of Infrared Scanners II-68

b. Imaging Optics II-72

c. Detectors II-72

4. Effects of Atmospheric Propagation II-74

a. Gaseous Attenuation II-74

b. Aerosol Attenuation II-74

c. Resulting Absorption Spectra and Transmission Windows II-74

d. Contrast Degradation II-76

5. Target Thermal Emission II-76

6. Target Parameters Affecting MWIR and LWIR System Performance II-82

TABLE OF CONTENTS

(continued)

	Page
F. PERFORMANCE OF RADAR SURVEILLANCE AND TARGET ACQUISITION SYSTEMS	II-90
1. How Much Can Radar Really Do?	II-90
2. Radar Surveillance and Target Acquisition Threats	II-93
a. Airborne Imaging Radars	II-93
b. Airborne MTI Radar with Data Link	II-97
c. Air-to-Surface Guided Semi-Active Missiles	II-98
d. Ground Surveillance MTI Radars	II-99
e. Mortar and Artillery Locating Radars	II-100
f. Millimeter Wave Radars	II-100
3. Operating Parameters of Particular Radars	II-102
4. The Radar Detection Process	II-102
5. Important Target Parameters	II-103
G. SEISMIC AND ACOUSTIC DETECTION SYSTEMS	II-105
H. SURVEILLANCE AND TARGET ACQUISITION SENSOR DEVELOPMENT TREND SUMMARY	II-108
1. The Human Eye	II-108
a. Unaided	II-108
b. Binoculars, Telescopes, etc.	II-108
c. Search Lights and Night Lights	II-109
d. Optical Range Finders	II-109
e. Overall Trend	II-109

TABLE OF CONTENTS

(continued)

		Page
2.	Electromagnetic Imagers with Visual Readout	II-109
	a. Combat Television	II-109
	b. Low-Light TV	II-109
	c. Image Intensifiers	II-110
	d. The Near IR	II-110
	e. Thermal IR	II-110
	f. Overall Assessment	II-110
3.	Photographic Systems	II-111
	a. Cameras, Optical Components and Film in General	II-111
	b. Camouflage Detection Film	II-111
	c. Thermal IR	II-112
	d. Multi-Spectral Narrow-Band IR	II-112
	e. Overall Assessment	II-112
4.	Lasers	
	a. Laser Illuminators	II-112
	b. Laser Target Designators and Beam-Riders	II-112
	c. Laser Range Finders and Lidars	II-113
	d. Overall Assessment	II-113
5.	Radar	II-113
6.	Acoustic and Seismic Detectors	II-114
I.	TARGET PARAMETERS THAT MOST AFFECT SENSOR SYSTEM PERFORMANCE	II-114

TABLE OF CONTENTS

(continued)

	Page
III. ABOUT THE TARGET	III-1
A. INTRODUCTION	III-1
B. CATEGORIZATION CRITERIA	III-10
1. General	III-10
2. Sensor-Specific	III-15
C. CATEGORIZATION	III-16
D. CAMOUFLAGE OPERATIONAL FLEXIBILITY	III-16
E. DESCRIPTION OF THE TARGET CLASSES	III-23
IV. TECHNOLOGY ASSESSMENT	IV-1
A. INTRODUCTION	IV-1
B. CAMOUFLAGE AGAINST SENSORS IN THE VISUAL, INFRARED AND LASER REGIONS	IV-4
1. Camouflage Applied to the Target	IV-5
2. Camouflage Applied Around and Near the Target	IV-8
3. Camouflage Applied Away from the Target	IV-9
C. CAMOUFLAGE IN THE IR THERMAL EMISSION SPECTRAL REGION	IV-10
1. The Significance of Thermal Self-Emission	IV-10
2. Thermal Suppression	IV-13
a. Ambient Air Considerations	IV-14
b. Thermal Blankets	IV-14
c. Coatings	IV-20
d. Porous Layer	IV-20
e. Cavity Effects	IV-20
f. Heat Pipes and Fluid Loops	IV-21

TABLE OF CONTENTS

(continued)

	Page
3. Elimination of Hot Exhaust Gases	IV-21
4. Other Countermeasures	IV-22
D. COUNTERMEASURES IN THE RADAR SPECTRUM	IV-23
1. General Categories of Radar Countermeasures	IV-23
2. Absorbing or Isolating Surfaces	IV-24
3. Materials with Less Undesirable Radar Scattering Properties	IV-29
4. Alteration of Shape	IV-29
5. Screens	IV-30
6. Tactical Siting	IV-31
7. Artificial Scatterers	IV-32
8. Radar Decoys	IV-34
E. ACOUSTIC AND SEISMIC CAMOUFLAGE	IV-35
V. CAMOUFLAGE SYSTEM SPECIFICATIONS	
A. INTRODUCTION	V-1
B. OBSERVATIONS, ISSUES AND LONG-RANGE GOALS	V-3
1. Paints and Coatings against Imaging Devices in the Visual and Infrared (VSWIR, SWIR, MWIR and LWIR) Spectrum	V-3
2. Paints and Coatings against Laser Sensors	V-6
3. Coatings and Surface Treatments at Radar Frequencies	V-7
4. Nets	V-8
5. Countermeasures against Sensors Operating in the Thermal Infrared Spectrum	V-10
6. Scatterers and Absorbers Suspended in the Atmosphere	V-12

TABLE OF CONTENTS

(continued)

		Page
7.	Build Up the Energy Level of the Background (Clutter Enhancement, etc.)	V-13
8.	Decoys	V-14
9.	Information and Sensory Feedback	V-15
10.	Compatibility	V-17
C.	CAMOUFLAGE DEVELOPMENT FOR THE NEAR, INTERMEDIATE AND REMOTE FUTURE	V-17
1.	Nets and Screens	V-18
2.	Paints and Thin Coatings	V-23
3.	Heat Suppressors and Dissipators and Thermal Redesign	V-25
4.	Artificial Augmentation of Background Noise (Clutter)	V-27
5.	Blankets and Thick Coatings	V-29
6.	Decoys	V-29
7.	Mechanical, Thermal, and Electrical Redesign and the Control of Shape and Texture	V-29
8.	Tactical Siting	V-30
9.	Sensory Feedback	V-31
D.	ALTERNATIVE EXPOSITION OF CAMOUFLAGE SYSTEM SPECIFICATIONS	V-32
1.	Introduction	V-32
2.	Camouflage Equipment and Material Specifications	V-34
a.	Net System	V-34
b.	Pattern Paints and Thin Coatings	V-36
c.	Heat Suppressors and Dissipators and Thermal Redesign	V-37

TABLE OF CONTENTS

(continued)

		Page
d.	Artificial Augmentation of Radar Clutter	V-39
e.	Mechanical, Electrical and Thermal Redesign	V-40
f.	Control of Shape and Texture	V-41
3.	Methodology Specifications	V-42
4.	Information Specifications	V-42
a.	Information Specifications before 1986	V-43
b.	Information Specifications between 1986 and 1991, and after 1991	V-44
VI.	REFERENCES	VI-1

LIST OF TABLES

Table No.		Page
II-1	DEFINITIONS OF WAVELENGTH REGIMES	II-3
II-2	CONTRASTS REQUIRED FOR UNAIDED EYE TO SEE (AT A PROBABILITY OF DETECTION OF 0.95) 0.1 SQ. M. TARGET AT 1 KM AND A 10 SQ. M. TARGET AT 1 KM	II-28
II-3	CONTRASTS REQUIRED TO SEE (AT A PROBABILITY OF DETECTION OF 0.95) VARIOUS SIZED TARGETS AT VARIOUS RANGES IN A CLEAR DESERT	II-29
II-4	CONTRAST REQUIRED TO SEE A 0.3-MRAD TARGET IN A CLEAR DESERT - S/G = 1.4; VISIBILITY = 30 MILES	II-30
II-5	CONTRASTS REQUIRED TO SEE (AT A PROBABILITY OF DETECTION OF 0.95) VARIOUS SIZE TARGETS AT VARIOUS RANGES IN GRASSLAND	II-31
II-6	CONTRASTS REQUIRED TO JUST SEE (AT A PROBABILITY OF DETECTION OF 95%) VARIOUS SIZED TARGETS AT VARIOUS RANGES IN GRASSLANDS WITH 10X BINOCULARS	II-32
II-7	CONTRASTS REQUIRED TO JUST SEE (AT A PROBABILITY OF DETECTION OF 95%) VARIOUS SIZED TARGETS AT VARIOUS RANGES IN GRASSLANDS WITH A 20X TELESCOPE	II-33
II-8	LASER DETECTION SYSTEM SCENARIOS	II-49
II-9	DF CHEMICAL LASER	II-50
II-10	LASER SYSTEMS	II-51
II-11	RANGE IN METERS AT WHICH THE SIGNAL DROPS TO ZERO	II-81
II-12	CAPABILITIES OF AIRBORNE IMAGING RADARS AGAINST STATIONARY TARGETS	II-96
II-13	TARGET PARAMETERS THAT MOST AFFECT SENSOR SYSTEM PERFORMANCE	II-115
III-1	CATEGORIES OF MATERIEL ITEMS AND SYSTEMS DESIGNATED CAMOUFLAGE CRITICAL	III-2
III-2	CATEGORIES OF MATERIEL ITEMS AND SYSTEMS DESIGNATED CAMOUFLAGE SENSITIVE	III-5

LIST OF TABLES

(continued)

Table No.		Page
III-3	TARGET CATEGORIZATION CRITERIA	III-11
III-4	TARGET CLASSES FOR CAMOUFLAGE PURPOSES	III-17
III-5	CHARACTERISTICS OF VARIOUS TARGET CLASSES RELATING TO DETERMINATION OF VULNERABILITY TO DETECTION BY VARIOUS SENSOR SYSTEMS	III-20
III-6	SUSCEPTIBILITY OF NINE TARGET CLASSES TO VARIOUS SENSOR SYSTEM TYPES	III-21
III-7	CAMOUFLAGE OPERATIONAL FLEXIBILITY INDEX	III-22
IV-1	COMPARISON OF CANDIDATE THERMAL SUPPRESSION TECHNIQUES	IV-15
IV-2	GENERAL CATEGORIES OF RADAR CAMOUFLAGE TECHNIQUES AND HOW THEY DEGRADE RADAR PERFORMANCE	IV-25
V-1	COUNTERMEASURES FOR PERIOD BEFORE 1986	V-19
V-2	COUNTERMEASURES FOR PERIOD 1986-1991	V-20
V-3	COUNTERMEASURES FOR PERIOD AFTER 1991	V-21

LIST OF FIGURES

Figure No.		Page
II-1	SCHEMATIC SYSTEM FOR VISUAL, INFRARED AND LASER SURVEILLANCE AND TARGET ACQUISITION	II-6
II-2	INTENSITY OF SCATTERED LIGHT AS A FUNCTION OF WAVELENGTH FOR VARIOUS ANGLES OF INCLINATION OF AN AERIAL CAMERA	II-8
II-3	SPECTRAL SENSITIVITY CURVES OF KODAK EKTACHROME INFRARED FILM	II-10
II-4	NORMALIED SPECTRAL DISTRIBUTION OF A 2860°K BLACK BODY RADIATOR COMPARED TO STARLIGHT AND MOONLIGHT	II-12
II-5	NORMALIZED SPECTRAL PRODUCT OF STARLIGHT AND 2850°K WITH AN S25 PHOTOCATHODE	II-13
II-6	TYPICAL REFLECTIVITY OF GREEN VEGETATION	II-14
II-7	SPECTRAL PRODUCTS OF STARLIGHT AND MOONLIGHT WITH S20 ER RESPONSE AND GREEN VEGETATION REFLECTIVITY	II-15
II-8	FOREST GREEN SPECTRAL REFLECTANCE	II-16
II-9	AIRCRAFT GREEN SPECTRAL REFLECTANCE	II-17
II-10	VISIBILITY CURVES FOR A NORMAL EYE - "A", AT ORDINARY BRIGHTNESS ACCORDING TO GIBSON AND TYNDALL; "B", AT THE THRESHOLD OF VISION ACCORDING TO KONIG	II-21
II-11	ANGULAR RESOLUTION FOR HAND-HELD OPTICS (10 to 20 POWER), WITH AND WITHOUT STABILIZATION	II-23
II-12	DETECTION RANGE OF CAMOUFLAGED M60A1 TANK	II-27
II-13	VARIATION OF CONTRAST SENSITIVITY WITH FIELD BRIGHTNESS FROM DATA OBTAINED BY KONIG AND BRODHUN	II-34
II-14	RESOLUTION PREDICTION BY THE INTERSECTION OF A SYSTEM MTF AND AIM CURVE	II-36
II-15	COMPARISON OF VARIOUS TM CURVES FOR 3404 FILM MEASURED BY DIFFERENT TECHNIQUES	II-37

LIST OF FIGURES

(continued)

Figure No.		Page
II-16	LINE-OF-SIGHT GUIDANCE (OPTICAL BEAMRIDER)	II-43
II-17	WAVELENGTH RANGE OF OPERATION OF SOME IMPORTANT GAS LASERS	II-45
II-18	WAVELENGTH RANGE OF OPERATION OF (LOW-POWER) SEMICONDUCTOR DIODE LASERS	II-47
II-19	TUNING RANGE OF HIGH-PRESSURE (HIGHER-POWER) LASERS	II-48
II-20	LASER BEAM STRIKING A DIFFUSE REFLECTOR	II-52
II-21	LASER BEAM STRIKING A CURVED GLOSSY SURFACE	II-54
II-22	PROFILE OF ATMOSPHERIC TRANSMITTANCE	II-75
II-23	TARGET RADIANCE DUE TO EMITTED THERMAL AND REFLECTED SOLAR RADIATION	II-78
II-24	FOG SITUATION VALID AT A 500-m RANGE ON NOVEMBER 24, 1977 AT OPAQUE STATION "BIRKHOF"	II-83
II-25	VISUAL AND IR TRANSMISSION (3.4 to 5.0 μm) RECORDINGS OF A 500-m RANGE DURING JANUARY, 1977, FROM OPAQUE STATION "BIRKHOF"	II-84
II-26	COMPARISON OF MEASURED IR TRANSMISSION (8.25 to 13.2 μm) AND CALCULATION AFTER LOWTRAN 3B FOR A 500-m RANGE DURING OCTOBER 27-30, 1977	II-85
II-27	FACTORS TO BE CONSIDERED IN THERMAL MODELING OF A SCENE OBJECT	II-87
II-29	TEMPERATURE DIFFERENCE BETWEEN A TANK AND AIR AS A FUNCTION OF THE TIME OF DAY FOR VARIOUS VIEWING DIRECTIONS	II-88
II-29	EFFECTIVE RADIANT CONTRAST BETWEEN THE TANK AND THE GRASS BACKGROUND AS A FUNCTION OF TIME OF DAY FOR VARIOUS VIEWING DIRECTIONS IN THE 8- to 12-μm SPECTRAL BAND	II-89

LIST OF FIGURES

(continued)

Figure No.		Page
II-30	DETECTION PROBABILITY AS A FUNCTION OF DISTANCE FOR A RADAR WHERE SIGNAL IS PROPORTIONAL TO THE FOURTH POWER OF DISTANCE AND SIGNAL-TO-NOISE RATIO IS NORMALLY DISTRIBUTED WITH A STANDARD DEVIATION OF 12.5 dB	II-104
III-1	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS I	III-25
III-2	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS II	III-27
III-3	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS III	III-28
III-4	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS IV	III-30
III-5	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS VII	III-32
III-6	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS VIII	III-34
III-7	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS IX	III-35
III-8	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS X	III-37
III-9	CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS "SPECIAL"	III-38
IV-1	CLASSIFICATION OF CAMOUFLAGE METHODS	IV-2

I. EXECUTIVE SUMMARY

The purpose of this study is to develop specifications for a multipurpose camouflage system for use by units of a mobile army in the field. The multipurpose system will be used to protect many different kinds of mobile army units against many different surveillance and target acquisition sensor systems in several different environments. Some combinations of sensor, target and environment are more likely and have more important military consequences than others, and each variety of camouflage technology is more effective against some combinations than against others. To understand what kind of a system will achieve results of the greatest military value that can be achieved with the camouflage resources that can be allocated, it is necessary to study certain aspects of threat sensors and targets as well as camouflage technology and the environment. The approach comprises the following steps:

- the threat
  - list the generic surveillance and target acquisition system threats against items of equipment in a mobile field army, particularly items on the 'Camouflage Critical' and 'Camouflage Sensitive' lists
  - describe how each type of surveillance or target acquisition system works and what the information it generates is used for, in terms that can support inferences about the importance and effectiveness of various camouflage measures
- the target
  - state the qualities of targets that determine how vulnerable they are to surveillance and target acquisition sensor systems
  - classify targets into a small number of homogeneous classes according to their vulnerability to surveillance and target acquisition sensor systems

- camouflage needs--for each combination of threat sensor type and target class, determine the level of camouflage needed to alleviate the threat
- camouflage system goals
  - describe the various kinds of camouflage technology available
  - state where technological or developmental improvements in camouflage might be possible
  - synthesize a description of a multi-threat general purpose camouflage system to meet the needs in a time-phased approach with three phases: before 1986, 1986 to 1991, and after 1991

Chapter II reviews the following types of sensor systems and how they work:

- the human eye, both unaided and aided with binoculars, telescopes, periscopes, etc.
- imaging systems and cameras operating in the visible and near infrared, including infra-red cameras, low-light-level television, image intensifiers, etc.
- systems operating in that part of the more remote infrared often called thermal infrared, that are sensitive both to scattered illumination and to self-emission from the target, including both heat-seekers and imaging systems
- laser range finders, target designators, beam riders, and lidars
- radars, including moving target indicator, synthetic aperture, millimeter wave, and other special adaptations
- seismic and acoustic detectors

When the characteristics of surveillance and target acquisition sensor systems are used as criteria for grouping targets and discriminating between groups, the natural groupings are considerably different from the groupings in the Camouflage Sensitive and Camouflage Critical lists. This is not surprising, for the CC/CS lists reflect the need to perserve critical assets, and do not account for differing characteristics, vulnerabilities, missions, battlefield locations, etc. that bear on the solution to the camouflage problem. We finally grouped the targets into the following classes:

- Target Class I - Motorized, Air Mobile or Airborne Forward Area Combat Units, Controlling Headquarters and Auxiliary Support
- Target Class II - Armored and/or Mechanized Forward Area Combat Units, Controlling Headquarters and Auxiliary Support
- Target Class III - Self-Propelled and/or Towed Cannon and Rocket Artillery and Anti-Aircraft Combat Support Units and Associated Fire Control and Target Acquisition Support
- Target Class IV - Tactical Bridges
- Target Class VII - Aircraft Operating Bases
- Target Class VIII - Surface-to-Surface Missile Units
- Target Class IX - Large Rear Area Command Control Communications and Support Installation Heavily Dependent on Electrical Power
- Target Class X - Large Rear Area Ammunition POL, Supply and Combat Service Support installations With Low-to-Moderate Electrical Power Requirements
- Special Class - Missile, Cannon, Rocket, and Mortar Units Vulnerable to Counterfire Radar

The qualities of a target that determine its vulnerability to surveillance and target acquisition are listed in Table III-3, Target Categorization Criteria. We also defined one additional criterion, "camouflage operational flexibility index", an indicator of the amount of operational constraints that could be tolerated, resources that could be allocated, and effort that could be spent for camouflage without unduly inhibiting that target from carrying out its mission. Although the camouflage operational flexibility index is not related to target vulnerability, it does help to segregate those types of targets for which a particular type or level of camouflage might be suitable. The "special" class is so designated because all the items it contains are also contained in one of the other classes as well, and are regarded as belonging to the "special" class only during the particular phase of their operation when a shell or missile is in flight. Two classes, V and VI, were initially defined but then excluded because they are not within the camouflage mission area of MERADCOM.

The relation between these designated target classes and the classes and sub-classes listed in the Camouflage Sensitive and Camouflage Critical lists is given in Table III-4.

For each combination of sensor type and target class, the susceptibility of the target class to detection or acquisition by the sensor systems is rated high, moderate or low. These ratings are tabulated in Table III-6, which shows 19 combinations where the susceptibility is high, 21 of moderate susceptibility and 32 of low susceptibility. This classification into three vulnerability categories, together with the rationale for the classification found in Section D of Chapter III, constitute a qualitative statement of camouflage needs.

Countermeasures against visible and IR light, laser, radar, acoustic and seismic sensors and instruments to hide, blend, disguise, and decoy fall naturally into three groups:

- camouflage applied to the target itself
    - paints, surface treatments, and coatings
    - replacement of materials in the target by others with less undesirable scattering, reflecting, and radiation characteristics
    - spoiling, disguise, or altering the signature by
        - superficial changes
        - changing underlying structure and materials
        - changing the pattern of deployment
- camouflage applied near the target
    - blankets, screens, and nets
    - natural cover, defilade, tactical siting, etc.

- camouflage removed from the target
  - aerosols, smoke, and chaff
  - artificial scatterers to increase the background clutter and interference
  - decoys and deliberate creation of credible fake or misleading targets

Chapter IV reviews the technology available for camouflage of each of these types against sensor systems of each generic type, and indicates where further technological or developmental improvements might be possible.

A synthesis of these findings into a description of a general-purpose multi-threat camouflage system is found in Chapter VI. The system includes:

- a light-weight modular net system
- a heavy-duty modular net system
- a pattern-painting with paints and thin coatings
- heat-suppressors and dissipators
- artificial augmentation of radar clutter
- mechanical, thermal and electrical redesign of many types of equipment
- control of shape and texture
- certain essential auxiliary measurement equipment

II. TARGET ACQUISITION AND SURVEILLANCE SENSOR SYSTEMS

A. INTRODUCTION

The enemy needs information about our military units before he can use his forces effectively against them. He uses this information to decide when and where to engage in battle and how to deploy his forces before engaging ours (strategic surveillance), how to operate and maneuver his forces in the most favorable relation to ours during combat (tactical surveillance), to select and localize targets for his weapons to fire on (target acquisition), and to aim and provide homing guidance for weapons (fire control). He uses information about the presence, identity, location, and operations of our units in various proportions, depending on the application, and his tolerance for incompleteness, inaccuracy, unreliability, and false alarm depend on the application, also. Much of this information is gathered with remote sensing systems.

All remote sensors depend on detecting some sort of perturbation created by or modulated by the target, and distinguishing it from the background. Propagating electromagnetic fields, like those used in vision and radar, are particularly useful because they travel fast, carry a considerable amount of information, and are often only slightly distorted or impeded by the atmosphere. Acoustic and seismic radiating fields, electrostatic and magnetostatic phenomena, and spoor of various kinds also can contribute valuable information. Camouflage works by preventing the sensor from detecting or correctly identifying the perturbation. Contrast and comparison among camouflage alternatives are helped by an understanding of how various kinds of remote sensor surveillance and target acquisition systems work.

We have, therefore, gathered in this chapter some information about sensor systems, the disturbances they detect, the physical principles their operations depend on, and, by inference, the target and environmental parameters that most affect their performance. The classes of sensors are reviewed in the following sequence:

- visual and very short wave IR(VSWIR)--the eye, aided and unaided, photographic cameras and television, and analogous low-light-level and night-vision devices operating in the near infrared;
- laser--devices in all bands from visible to long wave IR(LWIR) depending on laser light;
- medium and long wave IR(MWIR and LWIR)--devices influenced (or potentially influenced) by thermal self-emission radiation from the target as well as reflected and scattered radiation;
- radar; and
- acoustic and seismic.

Direct intercept of and ranging on radio and radar emissions is within the province of electronic warfare, and is excluded from this project. Within each class, the following issues are addressed:

- the energy field and the physics of its generation (if significant) and propagation;
- how the target interacts with or modulates the field;
- how the sensor detects the field;
- resolving and discriminating powers of sensor systems relating to target characteristics;
- how camouflage degrades sensor system performance; and
- what kind of progress is anticipated in the next decade or so in this area of sensor technology.

This is followed by a summary of development trends, identifying those types of sensors that are expected to pose a greater threat in the future than they do now, and a tabular presentation of target parameters that most affect sensor system performance, by sensor type.

B. DEFINITIONS

For some purposes the terms visible, infrared, radar, acoustic and seismic are sufficient descriptions of parts of the STANO spectrum. At other times, a distinction between far or thermal infrared and near or non-thermal infrared is necessary, or a distinction between millimeter waves and (more conventional) radar. When even more distinctions are necessary, and in general adherence to standard practice, the definitions of Table II-1 have been followed:

TABLE II-1

DEFINITIONS OF WAVELENGTH REGIMES

λ (microns)	f (GHz)	Name	Abbreviation
.4 - .72		visible	--
.72- 1.0		very short wavelength IR	VSWIR
1.0 - 2.9		short wavelength IR	SWIR
2.9 - 5.5		medium wavelength IR	MWIR
7.5 - 14		long wavelength IR	LWIR
10.0 -500	30000-600	(unexplored for military applications)	--
500.0 -10000	600-30	millimeter waves	--
10000.0 →	30→	radar	--

The cutoff for VSWIR at 1.0 μ is somewhat aebitrary and was influenced by the importance of the 1.06μ laser. There are numerous atmospheric absorption bands in the SWIR regime. The 2.9μ cutoff was selected because there is a major atmospheric transmission window at 2.9-5.5μ. The region 5.5-7.5μ is omitted because of atmospheric absorption. In the absence of any qualification, radar is often construed to include millimeter wave as well.

In all cases there are overlaps between the various wavelength regimes. There are also wide differences in terminology. The above terms and definitions regimes were selected because they represent a sort of consensus and are consistent with usage in the MERADCOM projects.

C. CHARACTERISTICS OF VISUAL AND VSWIR DETECTION AND TARGET ACQUISITION SYSTEMS

1. Visual

In the visual region of the spectrum (and also the near IR) sensors form images of targets which are eventually presented to the eyeballs of human observers. The observers use their eye-brain combination to detect, recognize, identify, and locate targets and then to decide whether to take action and, if so, what action to take. The practice of observing targets with human operators is an old art, and therefore many aids exist for assisting with the task. Familiar devices such as binoculars, telescopes, periscopes, low light level systems, and aerial platforms are commonly used to help in target identification and location. Since optical systems invariably have high resolution and good contrast performance (relative to the size of objects being searched in tactical Army scenarios), the job of comouflaging these targets for all situations is difficult. However, with human need for survival being what it is, solutions to the problem have been created that are quite successful for many applications. In general, these solutions tend to hide targets in natural terrain or blend them with the background by using techniques such as pattern paints, nets, mirrors, screens, cloths, shape disrupters, decoys, and smoke screens. At night dark colors are used to blend targets into the background.

A generalized schematic diagram of a visual, infrared and laser surveillance and target acquisition sensor system is shown in Figure II-1. The interaction of countermeasures with the system is also shown.

In general, the target in the figure is illuminated by direct sunlight or scattered skylight in the visible spectrum, and light scattered by the target is transmitted through the atmosphere and collected by an imaging sensor of some sort (eye, TV, or photographic system).
The image is shown to a human observer who makes some decisions

regarding the presence or absence of a target. Since most of the targets of interest to the tactical Army are quite large, they can be viewed from a long distance and still be detected. The observer must be within line of sight of the target, but the use of both airborne and ground observation by the enemy forces makes the job of hiding large targets extremely difficult. Also, visual sensors present data in the form of an easily recognized image (unlike the range/reflectivity/motion signatures offered by most radars) and this makes camouflage even more difficult. Techniques for camouflaging or obscuring the target are also indicated in Figure II-1. These include: smokes or other obscurants placed between the target and the senor, nets or screens placed over the target and colored to blend into the background; mirrors at the target location positioned to project an image of the background into the sensor; cloths to remove specular reflections; alterations of surface reflectances with paints or other textures; pattern painting to blend the target into the background, and judicious use of the natural terrain to hide targets and their shadows. All of these techniques are used to reduce the amount of energy from the target that reaches the sensor, alter the character of the energy from the target so it is harder to discriminate from energy from other sources, reduce the contrast between target and background, or increase the magnitude and fluctuation of the background energy so it masks the target. However, optical imaging systems in this frequency range have very high resolution, and the eye and photographic film have a low threshold of detectability of contrast (and color) differences. The cloak of invisibility that completely eliminates energy from the target or blends it chameleon-like with all background is not available, so we must be content with merely reducing target detection and identification using whatever means are available.

One of the biggest threats in the visual and near infrared spectrum is sensors in aircraft and satellites. Ground resolution of less than 30 cm is possible, and the USSR is known to have many orbiting cameras. The projected capability with such sensors is expected to improve over

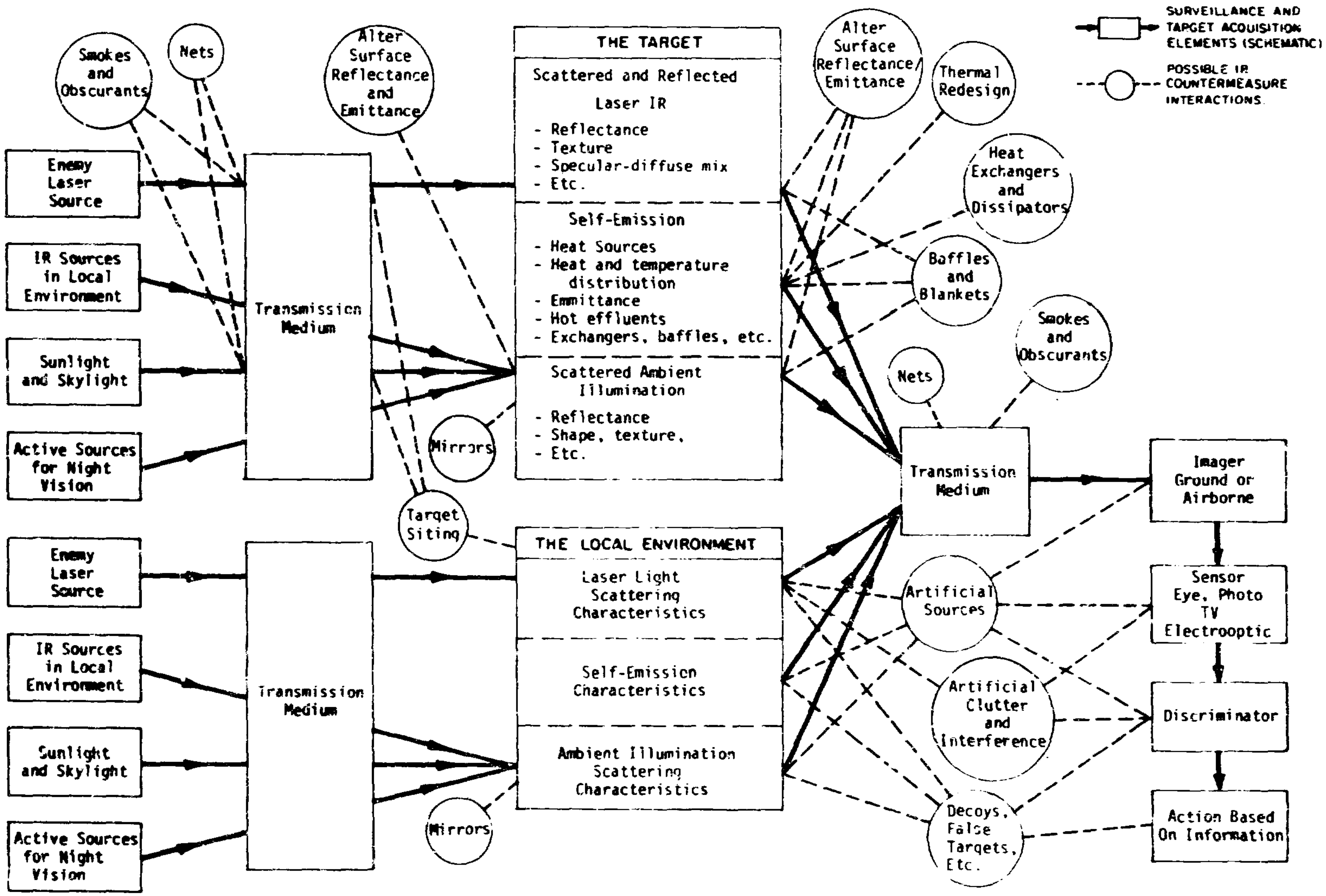

FIGURE II-1. SCHEMATIC SYSTEM FOR VISUAL, INFRARED AND LASER SURVEILLANCE AND TARGET ACQUISITION the next decade. These current photo systems will probably be supplemented with imaging arrays and down-link capability so that "real time" interaction with the FEBA imagery will become possible.

2. VSWIR

a. Photographic IR

Very short wave IR (0.75 to 1.2 μm) is useful in photographic applications for detecting differences in foliage and vegetation and for penetrating haze. Green foliage contains chlorophyll which has high reflectance in the near IR. The high reflectance makes leaves and grass appear to be intensity lit against the sky background that is normally black in this part of the spectrum. Photographs of distant objects are also clearer in the IR than the visible because of the greater penetration of atmospheric haze by near IR radiation. A plot showing the increased atmospheric transmission through haze* as a function of wavelength for a camera pointed vertically downward and one at an angle of 60 degrees to the horizontal is shown in Figure II-2. It has also been observed that as the particulates in the atmosphere become bigger (fogs ≈ 5 to 50 μm), the increased penetration of IR radiation rapidly diminishes (Ref. 2, 3).

Photographic films were developed prior to World War II to capitalize upon these reflectance differences in the near IR and have been very successful. The emulsions of the films are specially sensitized with dyes to extend the sensitivity to about 1 μm. Hypersensitizing by immersion in weak solutions of ammonia before use is often done to increase film speed. Color films are also commercially available to

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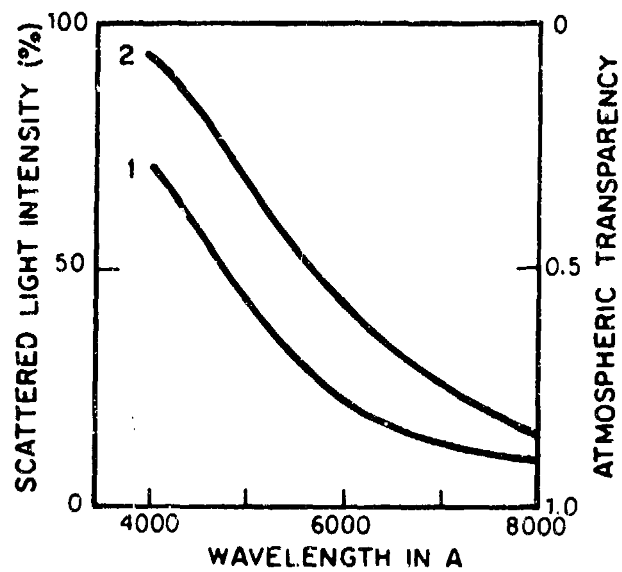
*In the visible and near IR regions (wavelength: 0.4 to 1.0 μm) haze is defined as an atmosphere containing dust and smoke particles in the size range 0.00 to 0.1 μm so that Rayleigh scattering predominates.



Note: Curve 1 is for the camera pointing vertically downward; Curve 2 is an angle of 60 degrees to the horizontal.

Source: Reference 2.

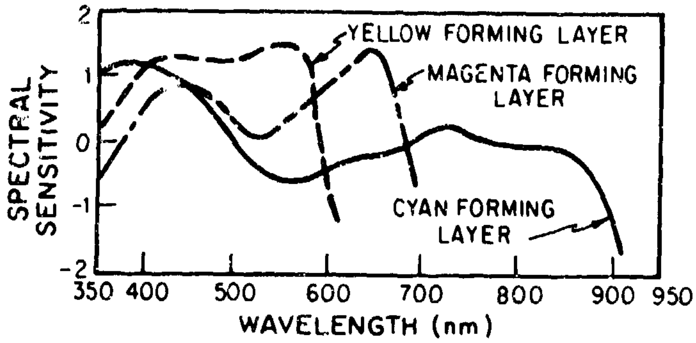
FIGURE II-2. INTENSITY OF SCATTERED LIGHT AS A FUNCTION OF WAVELENGTH FOR VARIOUS ANGLES OF INCLINATION OF AN AERIAL CAMER accentuate these differences in IR reflectivity further and are used by the military. In general, these films have three layers of emulsion, the near IR radiation develops to a red image, red portions of the scene develop to a green image, and green portions of the scene develop to a blue image. Blue portions of the scene are negated by using a yellow (minus blue) filter over the camera lens (Ref. 4). A spectral sensitivity curve of Ektachrome infrared film (Kodak) is shown in Figure II-3. The false color images require a learning curve for interpretation, but they have proven to be extremely effective against camouflage and hence put an additional requirement on the development of CS-86.

Multi-spectral narrow-band photography or electroptic imaging in the near-infrared and visible spectrum adds an additional degree of precision and specificity by limiting detection to narrow non-overlapping bands. Precise quantitative estimates are made of the ratio of the brightness of the image in one band to the brightness in another. The bands are carefully chosen in regions where the background (e.g., chlorophyll in the case of green vegetation) has particularly high or particularly low reflectance, and the brightness ratio estimates discriminate the background from all but the most carefully matched targets.

b. Night Vision

(1) Passive Illumination. Passive night vision devices use scattered natural starlight or moonlight, and oversized imaging optics (to collect maximum amounts of energy) and image intensifiers (low-light-level TV sensors) to enable operators to see subjects of interest up to ranges of several kilometers at night. In general, a night vision device is used whenever the ambient light is so low that the normal visual observation techniques are not effective.

In an image intensifier tube, the optical image on a photocathode induces emission of electrons. The energy of the electrons is electrically increased and the electrons are refocussed on a display screen (usually

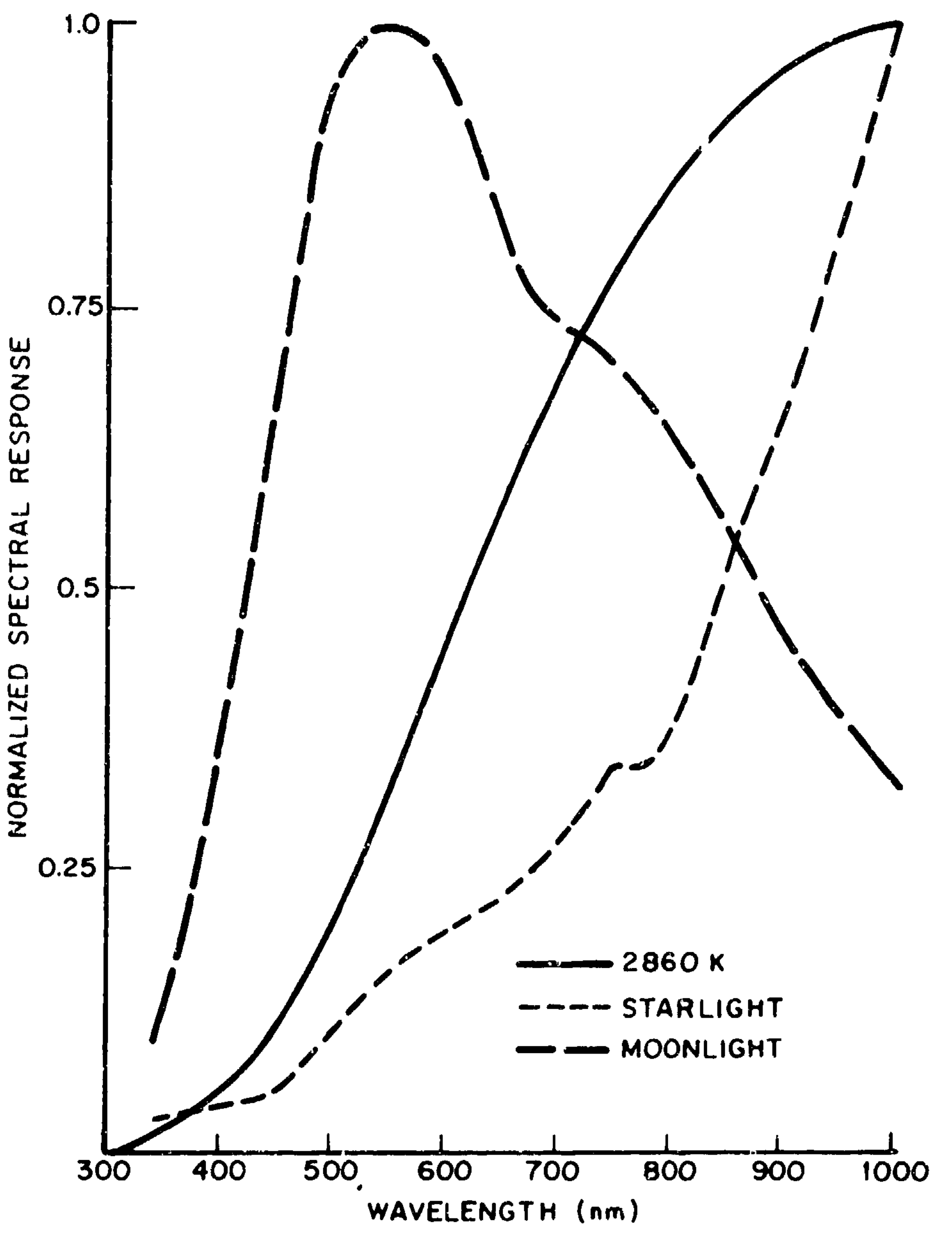


Source: Reference 4.

FIGURE II-3. SPECTRAL SENSITIVITY CURVES OF KODAK EKTACHROME INFRARED FILM phosphor) so that the viewer sees a visual image of the low light level scene. The tubes are sensitive to the green and red regions of the visual spectrum and the near IR out to 0.9 or 1.0 μm. The more recent tubes utilize microchannel plates to extend the infrared dynamic range and permit good operation in the presence of bright light sources. The spectral response of the system depends on the spectral distribution of the radiation (usually starlight or moonlight, see Figure II-4, and the spectral response of the photocathode. An example of the system spectral response of an S25 photocathode with starlight illumination is shown in Figure II-5. Some natural substances such as green vegetation, loams, and coniferous forests have enhanced reflectivities in the far red and near IR portions of the spectrum, which further complicates the situation (see Figure II-6). When these effects are combined with the illumination and photocathode responses, spectra are produced as seen in Figure II-7.

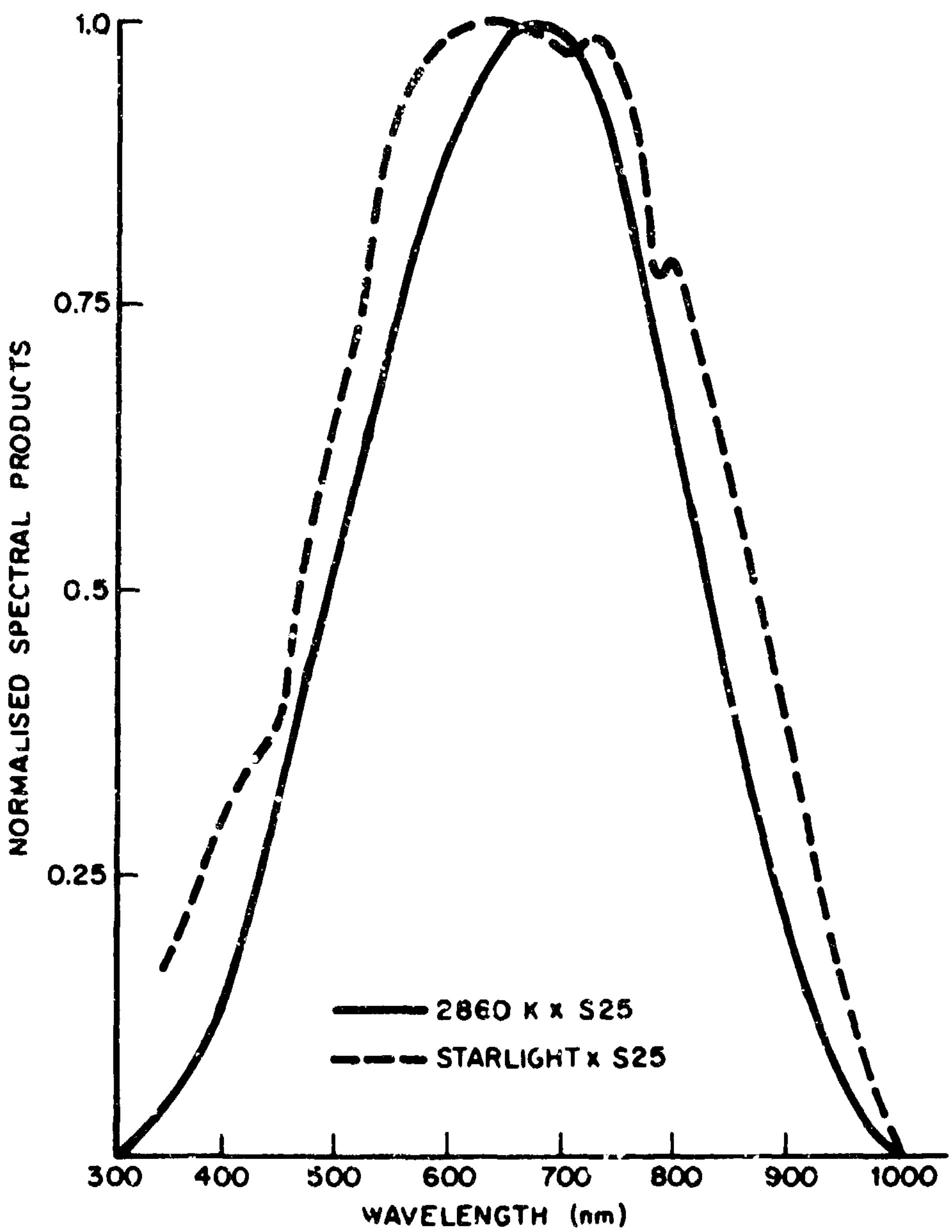
Since man-made objects, concretes, etc., have fairly uniform reflectivities in the spectral region of night vision devices, large contrast differences are possible. Some camouflage paints have spectral characteristics in the near IR which are similar to green vegetation (Figure II-8) whereas others (Figure II-9) have quite flat spectral characteristics. A vehicle painted with the paint of Figure II-9 would be "more readily seen" with a night vision instrument against a background of green vegetation than the same vehicle painted with the camouflage forest green paint of Figure II-8.

Examples of passive night vision devices include starlight scopes, weapon sights, night observation devices, night vision goggles and binoculars, night vision periscopes, night vision pocketscopes, drivers' viewers, and metascopes which are used to detect IR sources being used by the enemy. These devices offer varying magnifications up to 4x and weigh as little as 1.5 lbs.



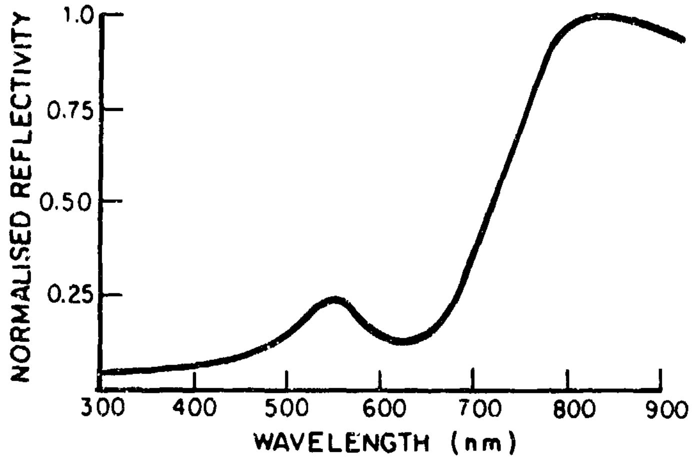
Source: Reference 5.

FIGURE II-4. NORMALIZED SPECTRAL DISTRIBUTION OF A 2860°K BLACK BODY RADIATOR COMPARED TO STARLIGHT AND MOONLIGHT



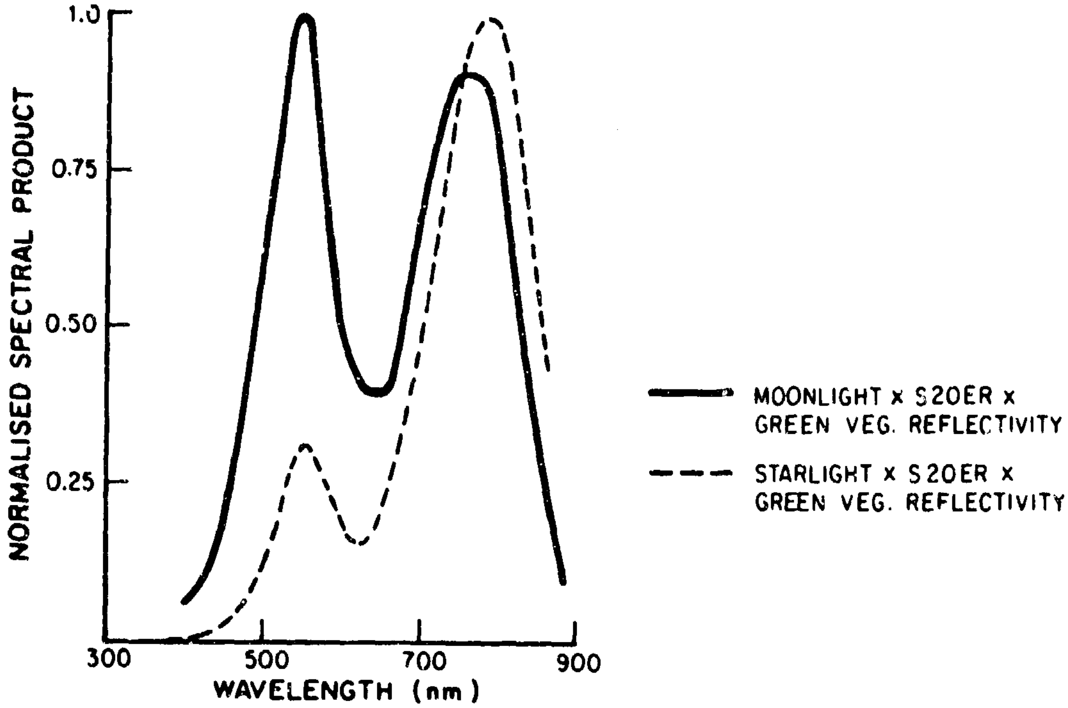
Source: Reference 5.

FIGURE II-5. NORMALIZED SPECTRAL PRODUCT OF STARLIGHT AND 2860°K WITH AN S25 PHOTOCATHODE



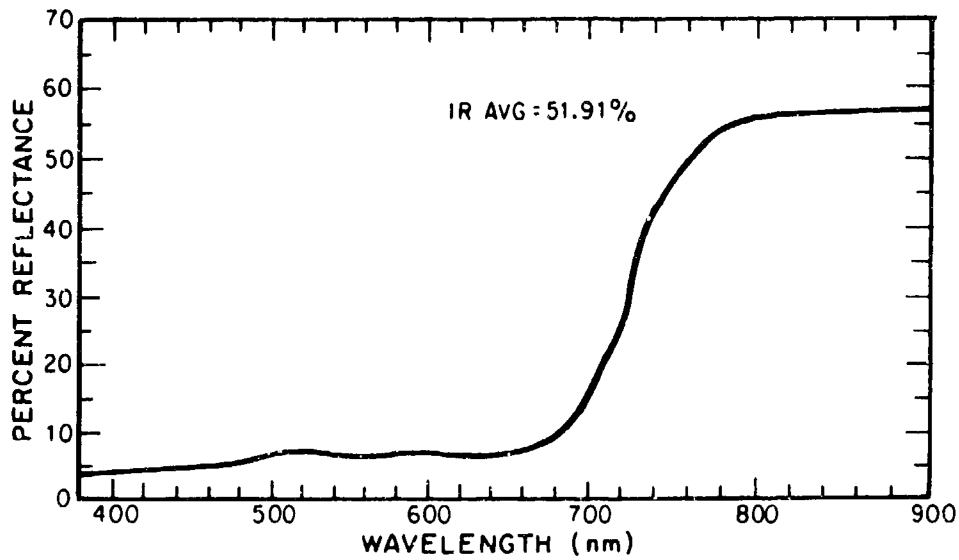
Source: Reference 5.

FIGURE II-6. TYPICAL REFLECTIVITY OF GREEN VEGETATION



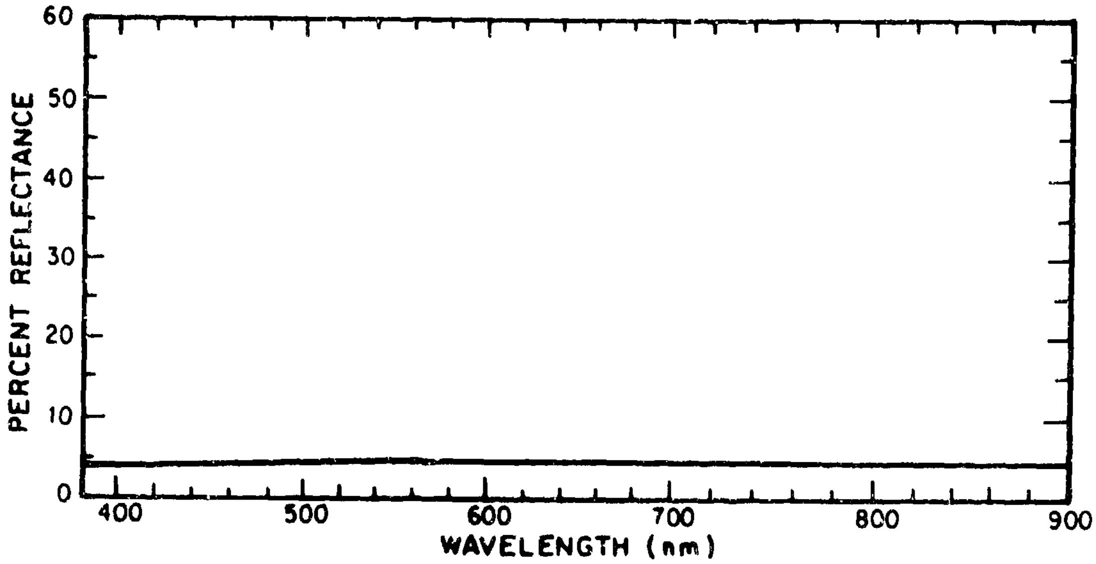
Source: Reference 5.

FIGURE II-7. SPECTRAL PRODUCTS OF STARLIGHT AND MOONLIGHT WITH S20 ER RESPONSE AND GREEN VEGETATION REFLECTIVITY



Source: Reference 1.

FIGURE II-8. FOREST GREEN SPECTRAL REFLECTANCE



Source: Reference 1.

FIGURE II-9. AIRCRAFT GREEN SPECTRAL REFLECTANCE

(2) Active Illumination. Night vision devices using active invisible VSWIR radiation and image intensifier tubes are also used in military applications. Such devices use active illuminants to increase range to 5-10 km in aerial reconnaissance (Ref. 6) or to perform precise targeting (Ref. 7) with weapon sights. Snooper-scopes with active IR illumination, popular in World War II, have been replaced with passive devices such as starlight scopes because the enemy's IR detectors easily detect systems using active sources. In aerial reconnaissance systems, active illumination systems in the near IR (flares and searchlights) are combined with photographic aerial cameras having image intensifiers between the focal plane and the film plane to decrease exposing time for the film. This creates a nighttime aerial reconnaissance capability for the tactical military forces and is one more threat that must be considered to an all-purpose camouflage system.

3. Important Target Parameters

a. Visual (0.4 to 0.7 μm)

The following target characteristics influence the detection and recognition of targets by sensors in the visual spectrum:

Size	Color
Shape	Texture
Shadows	Position and Associated Movement
Reflectance	Range
Apparent Contrast	Terrain
Illumination Level	Weather

Of these, the following are most critical for analyzing camouflage performance:

- Size, range and subtended angle (relative to sensor resolution)
- Reflectance and contrast with background
- Location with respect to FEBA
- Shape
- Color
- Motion

b. Very Short Wave IR (.75 to 1.0 μm)

The target parameters of interest to photographic detectors* in the VSWIR region are:

- Size and range
- Contrast
- Near-IR reflectance
- Dead foliage
- Color (blues not detected)

The target parameters of interest to passive night vision devices in the VSWIR region are:

- Size and range
- Shape
- Near-IR reflectance
- Location with respect to FEBA
- Light level

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*Since data with this detector are primarily acquired by aerial photography, the location with respect to FEBA is not as important a parameter.

The target parameters of interest to active night vision devices* in the VSWIR region are:

- Size and range
- Shape
- Near-IR reflectance

4. Performance of Visual and Near Infrared (VSWIR) Sensors

In this section, the performance of various types of sensor systems normally used against camouflated targets in the visual and very shortwave IR (VSWIR) spectrum will be explored.

a. Unaided Eye

The unaided eye is a well-known sophisticated sensor with response in the visual region of the electromagnetic spectrum (0.4 to 0.7 μm) and having a peak response in the green region. (See Figure II-10.) At the threshold of vision the peak of the curve shifts from 0.51 to 0.55 μm as seen in the figure.

The normal eye is a good color sensor, and it has a resolution capability of 0.3 to 0.9 mrad (1 to 3 minutes of arc)** a field of view of approximately 120° (7° for the high resolution afforded by the macula), a dynamic range of nearly nine decades (10^{-6} to 10^{3} candles per square meter), a contrast threshold between 2 and 3 percent, and a flicker sensitivity of 10 to 20 Hz. The performance of the eye is affected by atmospheric absorption and the surrounding environment (e.g., deserts or forest) as well as by physiological and psychological responses of the observer. However, the above values can be taken as average for determining camouflage specifications as illustrated in the next section. The subject of human vision is quite complex and has been the subject of numerous investigations (Ref. 8-11) for the purpose of evaluating visual camouflage.

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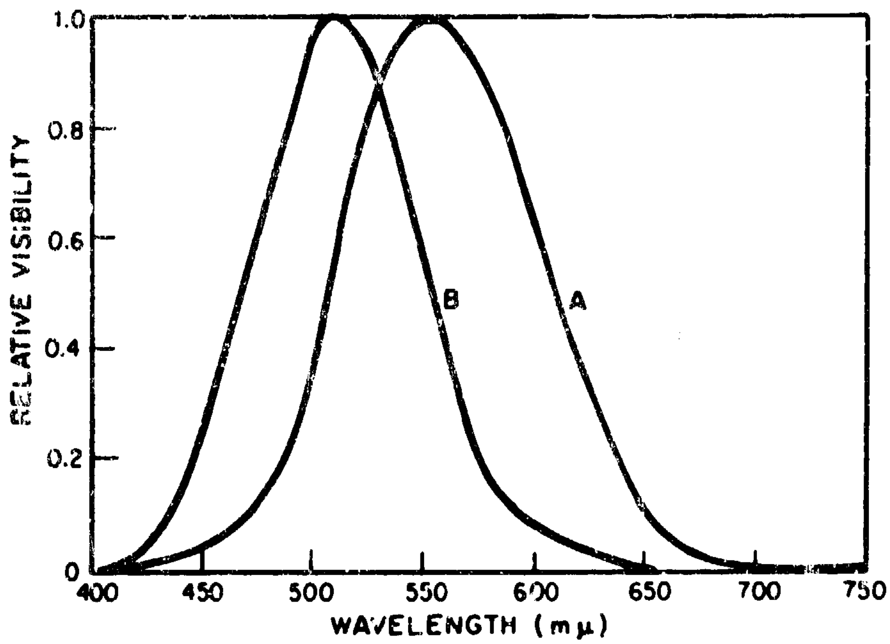
* Since data with this detector are primarily acquired by aerial photography, the location with respect to FEBA is not as important a parameter.

**1 mrad angular resolution is the ability to resolve 1 m at a range of 1 km.



Note: Both curves are plotted for an arbitrary maximum of unity.

Source: Reference 12.

FIGURE II-10. VISIBILITY CURVES FOR A NORMAL EYE - "A", AT ORDINARY BRIGHTNESS ACCORDING TO GIBSON AND TYNDALL; "B", AT THE THRESHOLD OF VISION ACCORDING TO KONIG

b. Aided Eye

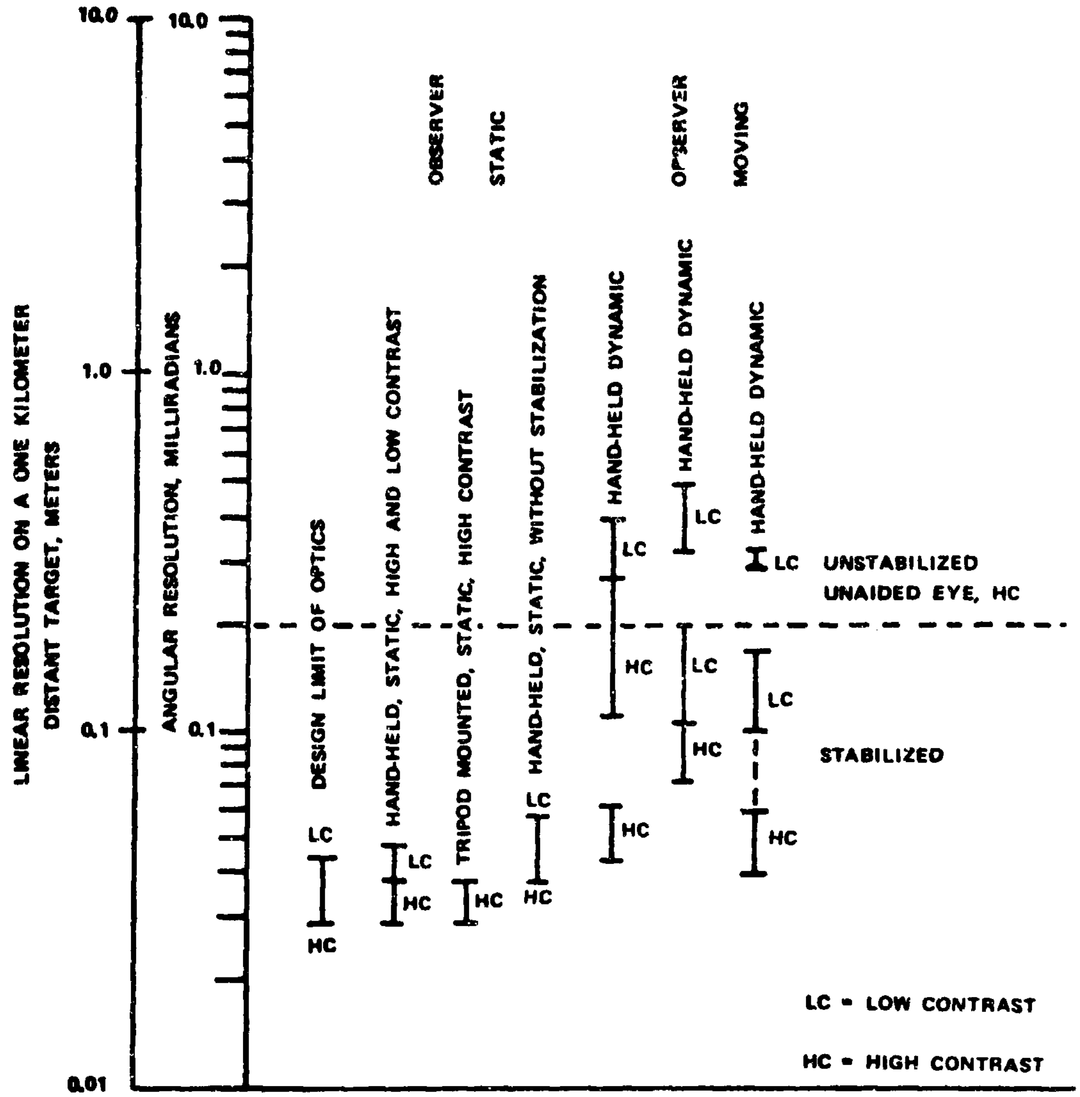
A number of devices exist for aiding the eye in observing distant objects. These include binoculars, periscopes, and telescopes in the visual, image intensifier and low-light-level TV systems in the near IR, starlight scopes, weapon sights, night observation devices, night vision goggles and binoculars, night vision periscopes, night vision pocket-scopes, drivers' viewers, IR stereo rangefinders, IR theodolites, and metascopes.

The direct visual devices usually have magnification less than 10 or 20, resolutions of a few arc seconds, and fields of view of 4 to 8°. They tend to increase the range by a factor of 2 to 4 times over that obtained by the unaided eye (Ref. 1). The improvements possible with such devices (Figure II-11) are made possible primarily by (1) using anti-reflection coatings on the optical surfaces, and (2) using hand stabilization devices.

In Figure II-11 the dashed horizontal line represents the resolution limit for the unaided eye on a clear bright day. The vertical bar at the extreme left of the diagram represents the "design limit" of improvement to be expected from 10-20 power optical devices for high and low contrast targets. The next three vertical bars represent measured resolution data for typical static instruments and the next three vertical bars represent measured resolution data for moving observers.

The upper set of bars are measurements without image stabilization, and the lower set of bars represent performances achieved with the use of image stabilization devices.

Unfortunately, range does not increase directly with resolution because of complicating effects introduced by the atmosphere, illumination level, target contrast, and the physiological and phychological factors associated with a given observer. As an example, the increased detection



Source: Reference 1.

FIGURE II-11. ANGULAR RESOLUTION FOR HAND-HELD OPTICS (10 to 20 POWER), WITH AND WITHOUT STABILIZATION range afforded by binocular-aided vision for viewing a camouflaged M60A1 tank in a simulated European scenario is shown in Figure II-12 (Refs. 1 and 13). As seen from this data, the range is increased between a factor of 2 or 3 and not by a factor directly proportional to angular resolution as Figure II-11 might suggest.

c. Passive Night Vision

Typical passive night vision devices in the VSWIR have magnifying powers up to 4x, ranges from 1 to 3 km, resolutions < 0.1 mrad, and fields of view of a few degrees. For low target contrasts (i.e., targets well camouflaged against near IR reflectivity from starlight and/or moonlight), ranges less than 1 km are more typical (Ref. 7).

d. Photographic Night Vision

Photographic night vision devices operating in the VSWIR with active illumination have ranges from 3 to 10 km, achieve resolutions of 18 lines per millimeter on the film at altitudes of 1 km, and have typical fields of views of 30-40° (Ref. 6).

e. Aerial Reconnaissance

A vast technology for performing surveillance from aircraft and satellites in the visual and near IR regions exists in both the United States and the Soviet Union. In general, tactical systems (operating at heights up to 20 km) achieve resolutions of 30 to 50 lines per millimeter on the film with cameras operating at speeds of approximately f/2. Such systems achieve ground resolutions less than 30 cm. The factor limiting resolution in these systems is usually V/H, the ratio of aircraft speed (V) to height above the ground (H).

While these aerial systems are capable of performing with both black and white and color film, black and white film is usually used because: it is easier to handle in the field (i.e., simpler chemical processing requirements), it yields higher resolutions at comparable speeds, and it costs less than one-third as much when both film and processing costs are considered. The exceptions to this rule are camouflage-detection pseudocolor and narrow band multi-spectral film which utilize the marked differences in reflectance in the near IR between man-made objects and vegetation, as discussed in Section B. The recent introduction of real time sensors into aerial cameras without appreciable sacrifice of resolution or noise performance gives these systems even more capability and increases the threat of detection, location, and recognition for camouflaged targets.

In general, the threat from aerial photography is different from the threat of observation from the ground, for remote, high resolution sensing can be achieved with airborne devices. Many sites that hide a target from ground-based sensors do not protect it from aerial cameras. Vulnerability depends less on position with respect to FEBA because photographs miles behind FEBA can be obtained from high-flying aircraft. Low contrast targets are less vulnerable because the contrast in most aerial photography is degraded by the atmosphere and haze that must be penetrated. Stereoscopic pairs of photographs that detect and exaggerate depth provide another parameter to distinguish targets from the environment.

Targets that blend into the background in the vertical or oblique directions still have less chance of being detected than uncamouflaged targets because of the low contrast response of most aerial photographic systems. For example, if an aerial camera has a contrast value of 2:1 (modulation of 0.33, a fairly typical stiuation) at the film plane, and if the target blends into the background with a difference of 10%, then the contrast of the image would be 0.0333, i.e., barely detectable visually. Because of the ranges involved, camouflage protection from aerial cameras may not be as stringent as that required from ground-based observing sensors.

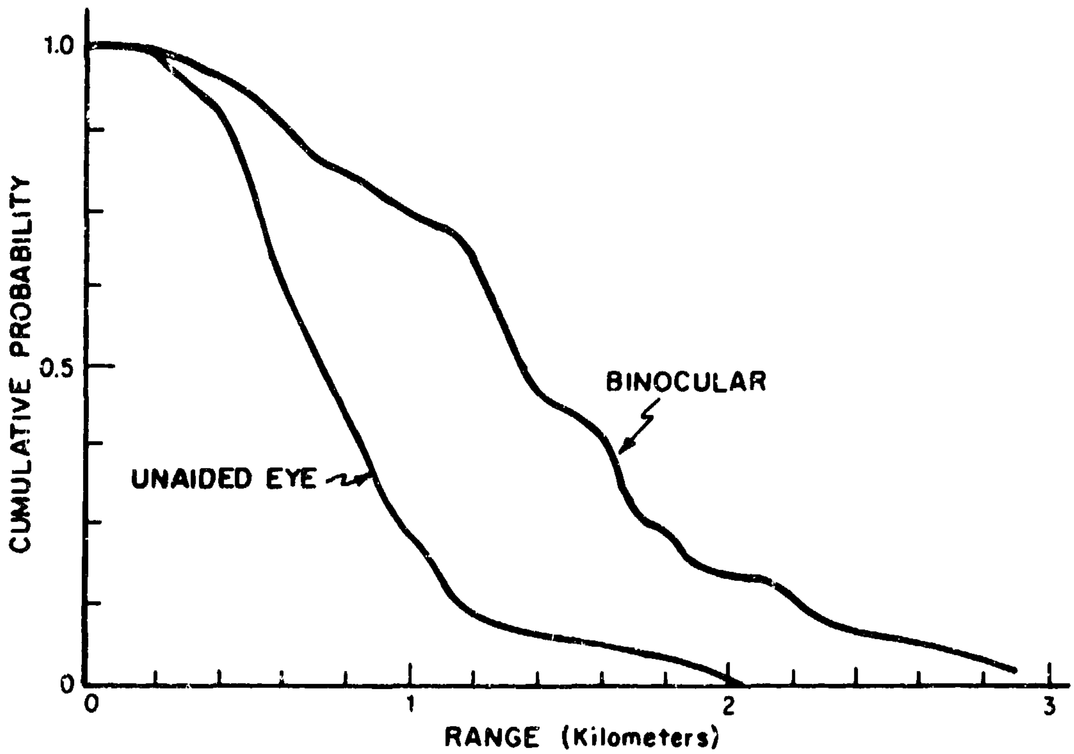
5. Examples of Sensor System Performance

The images of most targets on the Camouflage Critical/Camouflage Sensitive (CC/CS) lists (Chapter III, Tables III-1 and III-2) are easily resolved by optical sensors in the visual region of the spectrum, providing usable signatures for detection, recognition, identification, and location. When the image is large enough so that size does not limit its detectability, the parameter that does limit detectability is contrast. A series of examples are given below for the reader to gain an appreciation for this target parameter. In these examples, other parameters are optimized (e.g., good weather, 30-mile visibility, desert and grassy terrains, and a bright sunlit day) so that worst-case estimates of camouflage requirements for various enemy sensors in a variety of scenarios can be exhibited. If camouflage is successful under the conditions given in the example, it will be even more successful under most other conditions.

The techniques developed by Duntley (Refs. 8 and 9) (which were based upon Blackwell's Tiffany Data (Ref. 10)) and modified by Middleton (Ref. 11) will be used to perform this analysis. In particular, the nomogram presented in Middleton (Ref. 11) for a 95% probability of detection and discussed in Reference 1 is used to determine the contrasts required to hide various sized targets at different ranges in various terrains under good seeing conditions. Contrast is usually defined as

$$C = \frac{B_T - B_B}{B_B}$$

where B_T = Brightness of target and
B_B = Brightness of background.



Source: Reference 1.

FIGURE II-12. DETECTION RANGE OF CAMOUFLAGED M60A1 TANK

With this definition, contrasts range from −1 to ∞ with contrasts greater than 5 being unusual in the presence of an atmosphere.

a. Camouflage for Unaided Eyes

The initial conditions selected include: an unaided eye, a clear sky with a visibility of 30 miles, and a target size of 100 square feet (10 sq. m.) at a range of 1 km. For the other extreme a target size of 1 square foot (0.1 sq. m.) was also investigated. The required contrasts are shown in Table II-2.

TABLE II-2

CONTRASTS REQUIRED FOR UNAIDED EYE TO SEE (AT A PROBABILITY OF DETECTION OF 0.95) 0.1 SQ. M. TARGET AT 1 KM AND A 10 SQ. M. TARGET AT 1 KM

Sky Cond.	Ground Cond.	S/G	Visibility (km)	Range (km)	Contrast for 1 sq. ft. (0.1 sq. m.) tgt.	Contrast for 100 sq. ft. (10 sq. m.) tgt.
clear	snow	0.2	50	1	0.04	0.0015
clear	desert	1.4	50	1	0.3	0.011
clear	forest	5	50	1	1.0	0.04
over-cast	desert	7	50	1	2.4	0.048

The contrast of the 10 sq. m. target has to be reduced to the visual threshold (0.02) in snow and clear deserts, not quite so much in forests and overcast deserts, in order to avoid detection by the eye at a range of 1 km. On the other hand, the contrast requirements for the 0.1 sq. m. target at this range are much less stringent, as would be expected.

Table II-3 presents the camouflage contrasts required to hide various sized targets at different ranges in a clear desert.

TABLE II-3

CONTRASTS REQUIRED TO SEE (AT A PROBABILITY OF DETECTION OF 0.95)

VARIOUS SIZED TARGETS AT VARIOUS RANGES IN A CLEAR DESERT

Sky Cond.	Ground Cond.	S/G	Visibility (km)	Range (km)	C(0.1 sq. m.)	C(1 sq. m.)	C(10 sq. m.)
clear	desert	1.4	50	1	0.3 (0.3)*	0.36 (0.9)	0.013 (3)
clear	desert	1.4	50	4	0.6 (0.07)	0.6 (0.2)	0.072 (0.7)
clear	desert	1.4	50	6	18 (0.05)	1.6 (0.16)	0.18 (0.65)

*The numbers in parentheses refer to the angular resolutions (in mrads) of the target at these ranges. The examples below the dotted line represent targets non-resolvable by the unaided human eye (angular resolution ∿ 0.3 - 0.9 mrad).

From Table II-3, we conclude that the contrast sufficient to camouflage the 10-sq. m. target at 1 km is sufficient to protect smaller targets. Literal applications of formulas, tables and nomograms call for contrasts below 0.02, the threshold of human perception. However, whenever a number less than 0.02 appears, 0.02 is sufficient.

Table II-4 presents the contrasts required to see targets of 0.3-mrad angular resolutions at various ranges in a clear desert.

TABLE II-4

CONTRAST REQUIRED TO SEE A 0.3-MRAD TARGET IN A CLEAR DESERT

S/G = 1.4; VISIBILITY = 30 MILES

Linear Diameter of Target		Area			
Feet	Meters	Sq. Ft.	Sq. M.	Range (km)	Contrast
1	0.3	1	0.7	1	0.3
3.9	1.2	15.5	1.4	4	0.42
5.9	1.8	34.8	3.1	6	0.48
7.9	2.4	61.9	5.6	8	0.54
14.8	4.4	217.7	19.6	15	0.94

Again, a level of contrast sufficient to camouflage the 0.1-sq. m. target at a range of 1 km is more than sufficient to camouflage the other four examples, for higher target contrasts are required at the longer ranges to overcome losses of contrast due to the atmosphere. These tables also show that it is relatively easy to camouflage small targets from the unaided eye.

The contrasts required to camouflage targets at various ranges on a clear day in grasslands are presented in Table II-5. Data from pages 73 and 216 of Reference 11 were combined to show that the sky-ground ratio for grasslands is greater than 1 and probably less than 3 on a clear day. To get the results in the table, a compromise sky-ground ratio of 2.5 was selected and target contrasts were estimated from the revised Duntley Nomographs (Ref. 1 and 11).

TABLE II-5

CONTRASTS REQUIRED TO SEE (AT A PROBABILITY OF DETECTION OF 0.95)

VARIOUS SIZE TARGETS AT VARIOUS RANGES IN GRASSLAND

Sky Cond.	Ground Cond.	S/G	Visibility (km)	Range (km)	C(.1 sq. m.)	C(1 sq. m.)	C(10 sq. m.)
clear	grass	2.5	50	1	0.53	0.065	0.022
clear	grass	2.5	50	4	-	-	0.12
clear	grass	2.5	50	6	-	-	0.3

The blank spaces in Table II-5 represent non-resolvable targets, and hence, required target contrasts are not presented. The worst case is the 10-sq. m. target at 1 km range which requires a contrast difference of less than 2.2% to render it non-detectable. This is the best resolved target of all cases considered in Table II-5.

b. Camouflage for Aided Eyes

Since foot soldiers often use eye aids, it is also necessary to determine the target contrasts necessary to camouflage targets from these devices. Typical examples of camouflage contrasts to hide various targets from such devices are considered below.

(1) Binoculars. Coatings reduce veiling glare and enable one to work at higher luminance levels which lowers the contrast threshold of the eye. The just-visible contrasts at different ranges with magnifying optics can be estimated by multiplying the areas in the nomograph by M^2, where M is the magnifying power of the optical system (Ref. 9). Table II-6 is a repeat of Table II-5 for 10x binoculars having a 6 arc-sec resolution limit (28.8 μrad).

TABLE II-6

CONTRASTS REQUIRED TO JUST SEE (AT A PROBABILITY OF DETECTION OF 95%)

VARIOUS SIZED TARGETS AT VARIOUS RANGES IN GRASSLANDS WITH 10X BINOCULARS

Sky Cond.	Ground Cond.	S/G	Visibility (km)	Range (km)	C(0.1 sq. m.)	C(1 sq. m.)	C(10 sq. m.)
clear	grass	2.5	50	1	0.022 (3)*	0.017 (9)	0.014 (30)
clear	grass	2.5	50	4	0.12 (0.7)	0.022 (2)	0.018 (7)
clear	grass	2.5	50	6	0.3 (0.5)	0.05 (1.6)	0.022 (5)

*The numbers in parentheses refer to ideal angular resolutions (in mrads) at these ranges with 10x binoculars.

Thus, the biggest target at the closest range, 10 sq. m. at 1 km, must be camouflaged to a contrast of 0.014 (actually 0.02, since that is the threshold of the eye) to be invisible. Without binoculars, a camouflage contrast of 0.022 was required for the unaided eye. (See Table II-5.)

(2) Periscope. A 10x periscope behaves the same as the 10x binoculars described above in Table II-6.

(3) Telescopes. A 20x telescope having 4 seconds of arc resolution will perform as shown in Table II-7.

TABLE II-7

CONTRASTS REQUIRED TO JUST SEE (AT A PROBABILITY OF DETECTION OF 95%) VARIOUS SIZED TARGETS AT VARIOUS RANGES IN GRASSLANDS WITH A 20X TELESCOPE

Sky Cond.	Ground Cond.	S/G	Visibility (km)	Range (km)	C(0.1 sq. m.)	C(1 sq. m.)	C(10 sq. m.)
clear	grass	2.5	50	1	0.016	0.014	0.0135
clear	grass	2.5	50	4	0.045	0.021	0.02
clear	grass	2.5	50	6	0.091	0.038	0.026

In all of the cases in Table II-7, the contrast of the camouflage on the target must be at or near the visual threshold; otherwise, the target will be seen with a probability of detection of 95%.

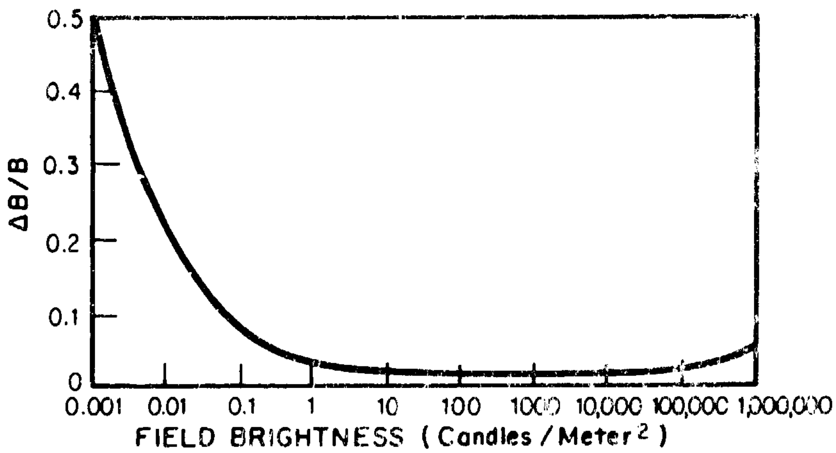
c. Vision at Night

At night the camouflage contrasts for the unaided eye can be relaxed because the contrast sensitivity of the eye is poorer under low brightness conditions than it is under normal daylight, as shown in Figure II-13. Representative values of brightness for day and night observation (Ref. 12) are:

Outdoors in daylight	10^4 candles/m^2
Outdoors at night	0.01 candles/m^2
Inside in daylight	100 candles/m^2

Comparing these values with Figure II-13, we see that the camouflage contrast requirements relax by an order of magnitude for the unaided eye as we go from day to night.

In general, night vision devices, because of their inherent gains, have approximately the same contrast threshold as the unaided eye during the day (Ref. 14). Inasmuch as they are routinely used by armies at night,



Note: These investigators used an artificial pupil one square millimeter in area and expressed the field brightness in photons, one photon being by definition the retinal illumination produced by viewing a surface having a brightness of one candle per square meter through such a pupil. The curve in this figure has been adjusted for the size of the natural pupil.

FIGURE II-13. VARIATION OF CONTRAST SENSITIVITY WITH FIELD BRIGHTNESS FROM DATA OBTAINED BY KONIG AND BRODHUN camouflage must be designed to protect against them. However, whereas every soldier is using his eyes most of the time, not everyone on the battlefield has a night vision device or a pair of binoculars, and even if he does, using them requires some effort and may be incompatible with or divert him from some other task.

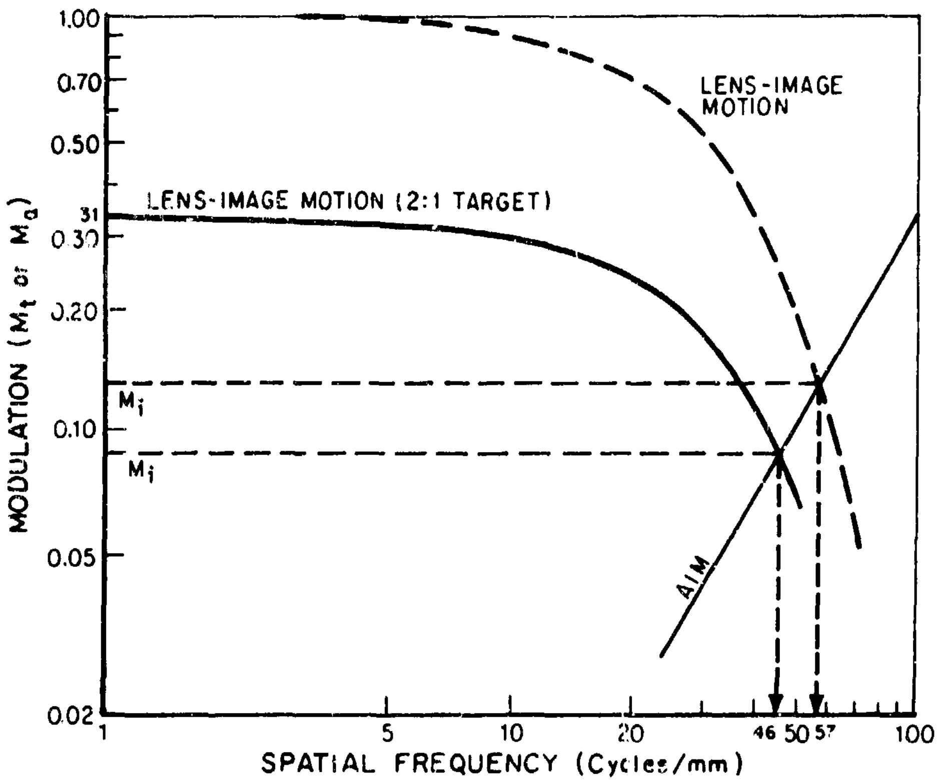
d. Aerial Reconnaissance

The contrast threshold of aerial cameras is determined by the Aerial Image Modulation (AIM) noise threshold of the film. The AIM curve varies with spatial frequence; i.e., smaller targets are harder to see. The limiting resolution (50% probability of detection) of the system is determined by the crossing point of the lens transfer function with that of the AIM curve. For low-contrast imagery, the low-contrast transfer function of the lens is commonly used (Ref. 15). This method of system performance prediction is illustrated in Figure II-14. Since the film threshold curve is a statistical measure, its variability changes are described by various probabilities of detection which give rise to a range of limiting resolutions rather than a single number (Ref. 16).

The AIM curve and its one sigma variability for a typical aerial film (Kodak 3404 aerial film) is shown in Figure II-15. From Figure II-15, we see that limiting film contrasts vary between 2 and 8% and depend on the spatial frequency content (size) of the image in the film plane.

e. Synopsis of Contrast Data

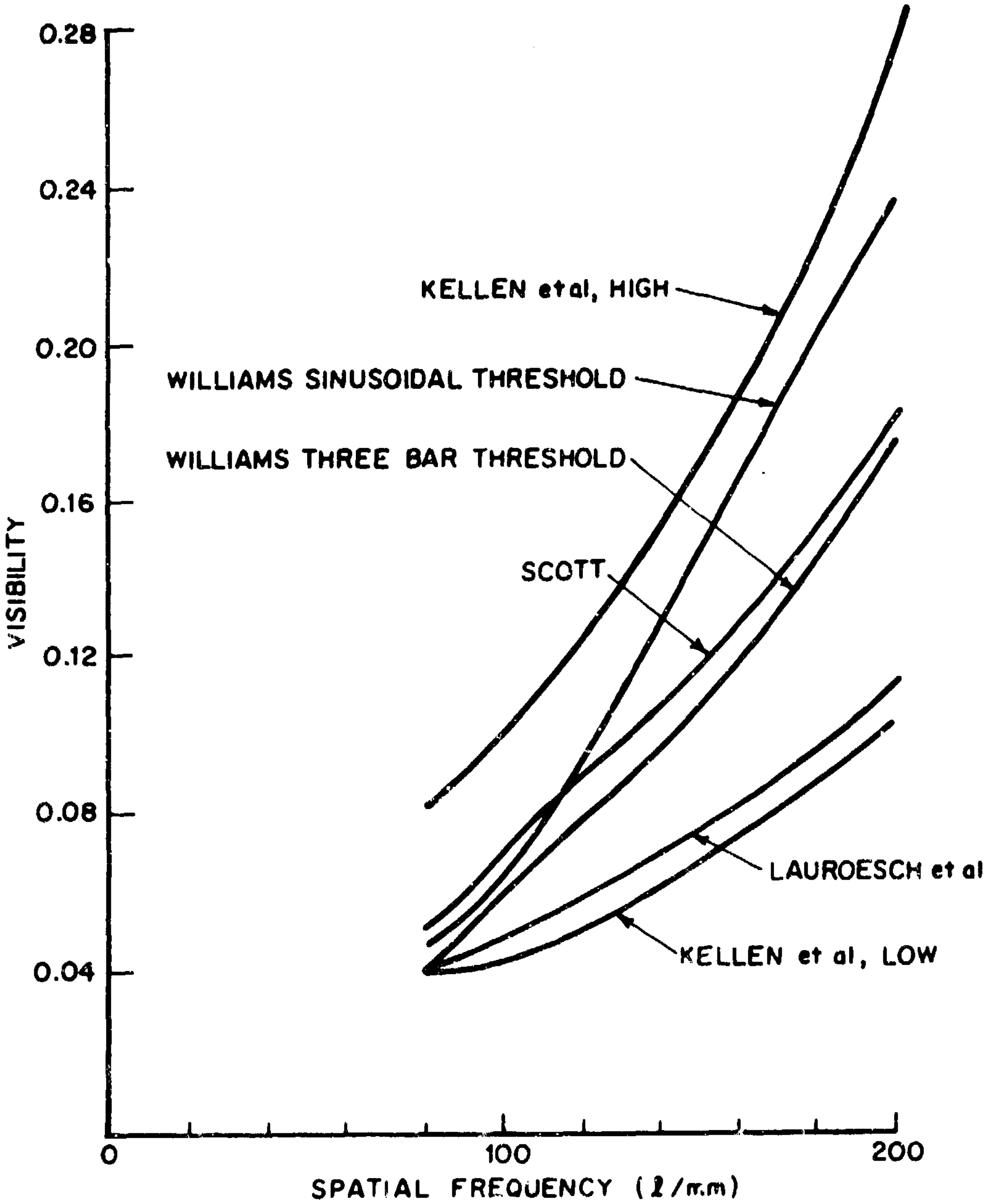
All sensors have limiting performance determined by the target contrast at the sensor after propagating through the atmosphere. What, then, can the camouflage designer/user do, knowing these facts? Obviously, if he camouflages his target so well that the contrast difference between the background and the target is below the thresholds of the detectors to be used against the target, then the target has a high probability of going undetected. However, as we have just seen, these detector contrast



Note: Modulation of the target on the ground (M_t) or in aerial image at camera lens (M_a) is shown by vertical axis; modulation required for resolution is given by M_i, also read from vertical axis.

Source: Reference 15.

FIGURE II-14. RESOLUTION PREDICTION BY THE INTERSECTION OF A SYSTEM MTF AND AIM CURVE



Source: Reference 16.

FIGURE II-15. COMPARISON OF VARIOUS TM CURVES FOR 3404 FILM MEASURED BY DIFFERENT TECHNIQUES thresholds are a few percent or less and, therefore, it is highly improbable that a general purpose camouflage can be built which will work this well against the variety of backgrounds and broad wavelength ranges about which today's Army is concerned.

Why, then, is camouflage successful? The military worth of camouflage is determined not only by the contrast of the target, but also by the time that it takes an observer to see the target. If the background is quite noisy (a lot of trees, shrubbery, etc.), then it will take an observer longer to find a medium-contrast camouflaged target than it will to find a high-contrast uncamouflaged target.

In measuring camouflage performance, the time it takes to detect a target is factored into the analysis to determine the probability of detecting the target. This is a fairly complex process, and sophisticated computer programs for performing these analyses exist (Ref. 17 and 18). A good discussion of the factors involved in these analyses is given in Chapter 6 of Reference 14, and in References 19 and 20

D. CHARACTERISTICS OF LASER RANGE FINDERS, TARGET DESIGNATORS, BEAM RIDERS AND LIDARS

1. Types of Laser Systems

The maturation of laser-related military applications, both in the U.S. arsenal and in foreign systems, has forced a parallel need for laser detection and countermeasure systems. To quote the Hon. William J. Perry, Undersecretary of Defense for Research and Engineering, in his FY 1980 report to Congress, February 1979 (p. 1-13):

> "We have a substantial lead in the technology critical to precision guided weapons, and since we give this technology highest priority in our R&D program, we expect that lead to continue. Nevertheless, the Soviet Union is working hard

on this technology. We are beginning to see significant progress in weapons now under test, and we expect to see precision guided weapons entering Soviet forces in quantity in the early 1980's. Even these first-generation weapons will present us with a significant problem. Our response to this emerging problem will be threefold:

- we will strive to keep one generation ahead of the Soviets in these weapons;
- we will pursue a vigorous countermeasure program; and
- we will evolve different force mixes and tactics with a strong emphasis on mobility and stealth features."

A number of current military devices use active laser sources at various wavelengths in the visible and near IR to range on and/or designate (locate) targets. Such devices of interest to ground defense include:

- laser range finders,
- laser target designators,
- laser beam riders, and
- laser radars (lidars)

a. Laser Range Finders

These pulsed devices are pointed by the gunner at a target of interest. The laser spot on the target is usually small relative to the size of the target, and the return is not diluted or marked by unwanted returns from neighboring objects and the environment. The return signals are detected with a receiver located at the source position, and the time of travel of a pulse is measured. From the round-trip travel time, the range to the target is determined. Lasers used for this application include ruby (0.69 μm), Nd:YAG (1.06 μm), and CO_2 (10.6 μm).

Laser range finders are used chiefly with tank main guns to increase first-round kill probability. In the important engagements tank-vs-tank, three basic types of projectiles would be used: (1) the high-velocity kinetic energy round, which consists essentially of a slug of tungsten carbide driven by a sabot to a muzzle velocity of a few thousand meters per second; (2) the slower shaped charge to penetrate the armor, or (3) plastic explosive that produces spalling from the inside of the hull. The kinetic energy round (APDS) is perhaps the most effective antitank round. Because its high density and extreme velocity give it a very flat trajectory, range-finding would probably be important only at ranges beyond 1000 meters. The range at which one would engage a tank in European terrain would probably not go beyond 3000 meters. The slower, shaped charge round (HEAT) or plastic explosive round (HEP) would need range data perhaps down to a few hundred meters for an accurate hit on a vulnerable part of the tank.

We assume, therefore, a most important range of 500 to 3000 meters for a laser range rinder. From this range, the signal must be returned in retroreflection to the transmitter.

The beam emitted by the range finder would be designed to be smaller than the expected target. This assures a return from the target and not from its surroundings, the ground, and the foreground, even when the target is only partially exposed.

More important yet, no energy is lost geometrically on the way to the target. Instead of a $1/r^4$ relationship between transmitted and returned energy, as in radar, a $1/r^2$ relationship governs the return signal strength of the range finder.

b. Target Designators

In these systems an operator illuminates the target of interest with a laser beam (line-of-sight), and the detector located on the missile, bomb, or projectile uses this reflected laser beam as a homing beacon. The target must be diffusely reflecting for the laser beam to be detected by the other projectile at all angles of view. The most commonly used laser for this application is Nd:YAG (1.06 μm). In newer versions of this concept, the laser and the receiver are located in the head of the munition so that longer ranges can be realized.

Target designators can operate over a wide range. An infantryman can guide a Copperhead artillery shell onto a target as close as a few hundred meters, or a pilot can guide a bomb from several thousand meters.

Target designators differ from retroreflection range finders in that both the range and the direction from target to designator and from target to missile will differ grossly. Ranges from a few hundred to a few thousand meters will occur, and the angle between the designator beam and the direction to the incoming missile may exceed 90 degrees.

The beam size of a designator would probably be advantageously made smaller than the expected target. One wants to cover only the target with the pulse-coded designator beam, and not the ground or the trees in the foreground. Perhaps more important, all the energy from the designator can thus be (geometrically) transferred to the target, and the range from designator to target then does not enter the calculation of the strength of the scattered signal. It is the same reasoning as with the range finder.

A laser (in contrast to an incoherent source) can emit its energy in a beam as narrow as diffraction allows. For, say, a 1/2-mrad beam divergence at a wavelength of 1.06 μm from an Nd:YAG laser, an aperture of less than 1 cm would theoretically suffice to provide the required collimation of the entire laser power. Also, the Nd:YAG laser is capable of extremely short high-power pulses, albeit of modest energy.

c. Laser Beam Riders

In these systems an operator points the laser beam at the target. A sensor in the aft end of the missile centers on the laser beam, and hence, on the target. (See Figure II-16.) In essence, the missile rides the laser beam to the target.

Lasers being considered for these systems include Nd:YAG (1.06 μm) and CO_2 (10.6 μm). Target reflectivity is not a factor with these systems.

d. Laser Radars (LIDARS)

These devices are similar to radar except they are more precise at target location. They will be used in future systems for fire control (i.e., using the laser to obtain and update range and angle information regarding a specific target), on hybrid systems with microwave radars to give precision information about targets, for detecting motions of targets, and for precision tracking and pointing in long-range weapons applications.

2. Types of Lasers

There are a number of classes of laser threats, as described below.

a. Single Wavelength Lasers

Countermeasures must be created to defeat single wavelengths that have a high probability of occurring. The Nd:YAG laser operating at 1.06 μm has the combination of high peak power and low laser threshold, along with good optical, thermal, and mechanical properties. These qualities have made Nd:YAG the favored emitter for range finders and target designators

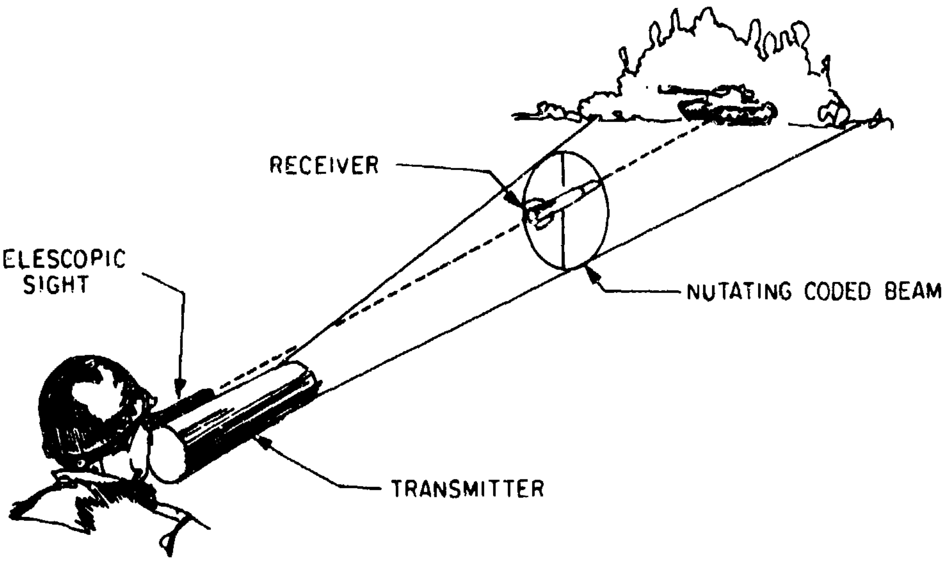


FIGURE II-16. LINE-OF-SIGHT GUIDANCE (OPTICAL BEAMRIDER) in Western forces. It has virtually displaced ruby in the range finder role.

The USSR has published on numerous neodymium-doped crystals and glasses, with wavelengths shorter, in the fluorides (~1.047 μm) and longer in other oxides (1.079 μm) and has also invested heavily in YAG growth. The Bagdasarov technique, using molybdenum crucibles, was developed at the Institute of Crystallography and commercialized at the Yerevan manufacturing plants in Armenia.

We do not expect to see "wavelength agile" Nd:YAG-based target designators and range finders in the near future. For the total system to operate at different wavelengths, parallel changes must be made in the sensor system on the designated bombs and/or missiles. Also, their narrow band optical filters and/or even detectors would require costly changes.

b. Single, Fixed, Selectable Wavelength Lasers

Systems are conceivable that would operate on any one line chosen from a group of laser lines in a given situation. However, we do not know which one of the set of discrete wavelengths will be used in a given threat system. Since these lasers conceivably could be used on range finders and/or target designators, an effective countermeasure (camouflage) system may be needed to suppress reflected energy of these wavelengths. Figure II-17 shows the infra-red range of operation of some important gas lasers. The CO_2 laser (even when not operated in the high-pressure mode) can be operated at various lines in the 9- to 11-μm region. For a radar or a communication system, to utilize such a laser effectively, a single wavelength and a narrow band filter must be used to reduce the background radiation noise.

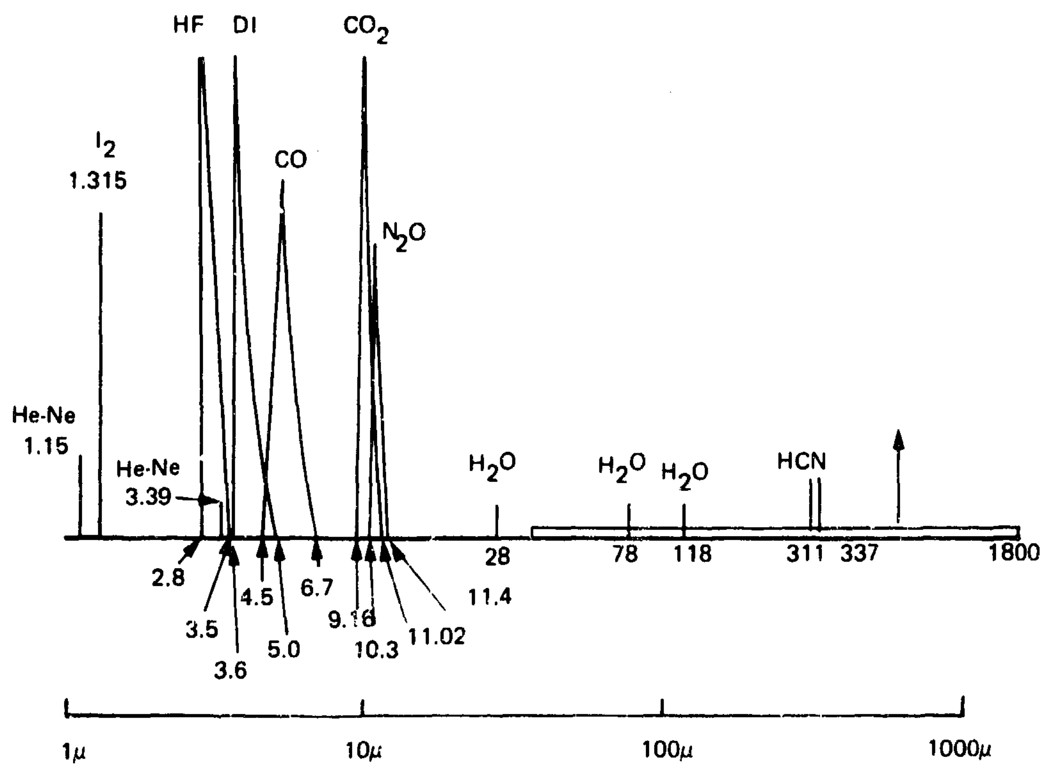


FIGURE II-17. WAVELENGTH RANGE OF OPERATION OF SOME IMPORTANT GAS LASERS

c. Multiple, Fixed, and Selectable Wavelength Lasers

In some applications, it may be possible to use laser radiation from any of a set of lines indiscriminately or from several lines simultaneously. Consider, for instance, infrared missiles which operate in the 2.7- to 5-μm region. They "home-in" on IR radiation from the hot exhausts of the engines. Their sensors have IR transmitting filters to reject as much sun and earth background as possible, but they are broadly open in the 3- to 5-μm atmospheric window where the exhaust emission provides signal. At least two military uses related to such IR missiles may be envisaged utilizing the multiplicity of laser lines, such as in the DF laser, from 3 to 5 μm. These are (1) IR countermeasures when such lasers are used as decoys or jammers, and (2) target augmentation. In this latter use, a laser whose wavelength is in the band of the thermal signature of a target is used whenever a mobile target provides too low a thermal profile to the guidance system of an IR missile. This case is more likely against aircraft targets than ground-based targets.

One can imagine other variations that use CW or pulsed lasers in the band of the missile's sensor. Multiple laser lines make it more difficult to counteract than a single-frequency laser. Anti-sensor warfare provides another example.

d. Multiple, Tunable Wavelength Lasers

As shown in Figures II-18 and II-19, many lasers operate over a broad band and are continuously (or stepwise continuously) tunable. Semiconductor lasers, for example, are both "settable" (by their compensation mix) and tunable (by temperature and pressure).

As we have seen in the previous case, a number of situations exist in which a narrow-band filter over a cooperative sensor is not needed and multi-line operation is an advantage. Other military scenarios can also exist in which a fixed filter is used on the cooperative receiver--but a tunable wavelength can still be used.

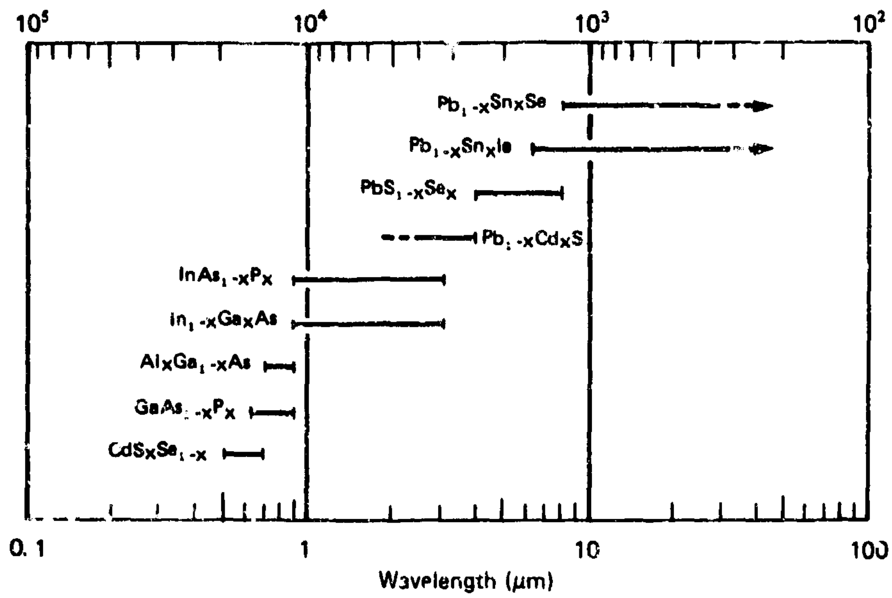


FIGURE II-18. WAVELENGTH RANGE OF OPERATION OF (LOW-POWER) SEMICONDUCTOR DIODE LASERS

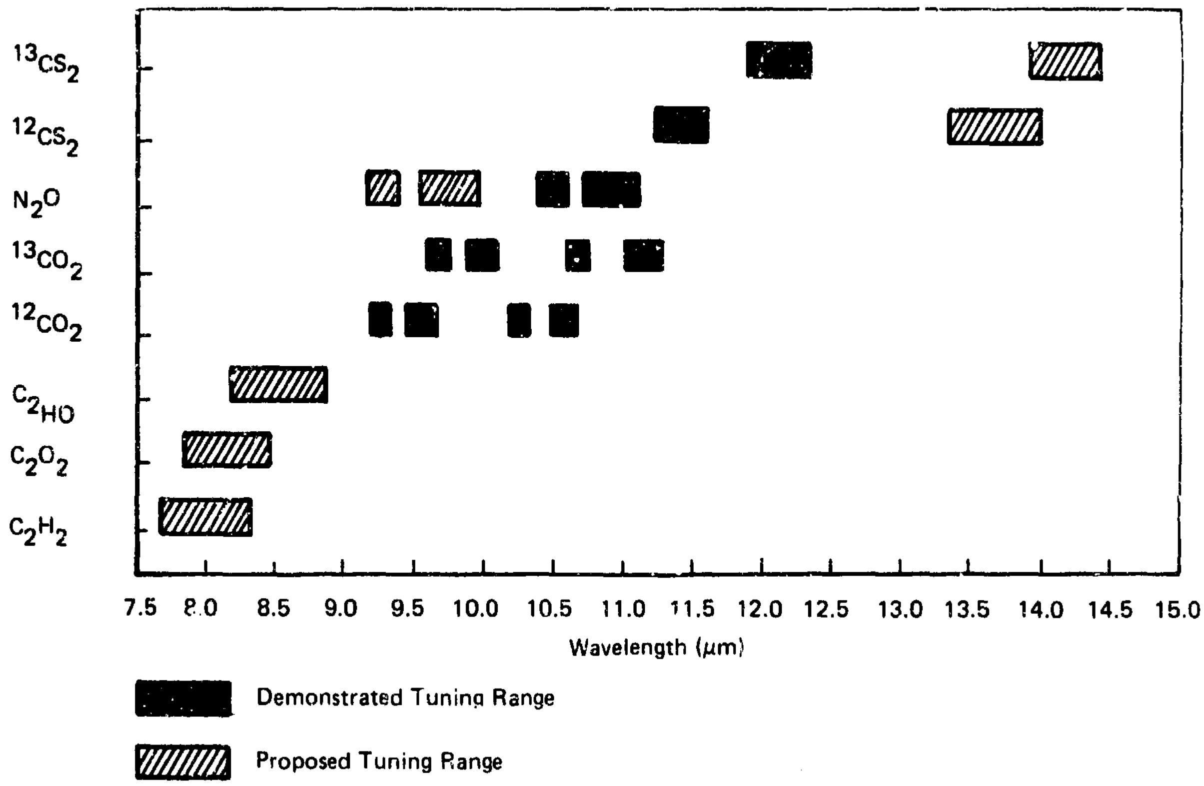


FIGURE II-19. TUNING RANGE OF HIGH-PRESSURE (HIGHER-POWER) LASERS

One such case that utilizes semiconductor lasers is the hard-to-counter laser beam rider (LBR) missile. (See Figure II-16.) The GaAs laser diode emits in the 0.84- to 0.91-μm region, depending on composition. (See Figure II-18.) Additionally, as the laser material heats up, and/or as pressure is applied, the laser's wavelength can be shifted. In LBR missiles, the sensing detector, usually silicon for GaAlAs-type laser sources, must be filtered to eliminate sun background noise. However, the backward-looking field-of-view of the sensor (see Figure II-16) need not be very wide.

These four cases discussed above are summarized in Table II-8.

TABLE II-8

LASER DETECTION SYSTEM SCENARIOS

Spectral Characteristics	Example
Single, fixed, highly-probable wavelength	Nd:YAG at 1.064 μm for range finders and target designators
Single, fixed, selectable wavelengths (but which one is not known *a priori*)	CO_2 between 9.6 and 10.6 μm, or DF between 3 and 5 μm, for laser radar
Multiple, fixed, selectable wavelengths (but which *set* of wavelengths is not known *a priori*)	DF chemical laser operating in the 3- to 5-μm region as an IR countermeasure
Single or multiple, tunable wavelength	A semiconductor laser operating in the 0.84- to 0.91-μm region for a laser beam rider missile.

3. Recent Laser Threats

Some characteristics of DF chemical lasers are discussed in Table II-9, and some laser systems characteristics are given in Table II-10. Most applications of DF laser systems are classified and are not discussed further here.

TABLE II-9

DF CHEMICAL LASER

(∿3.8 μm)

Average Power	1 to 4 kW - continuous
Size	
- Laser Head	30 to 60 cm, in diameter by 1 m long
- Pump and Fuel	depends on operating time for the laser
- Output Beam Diameter	2-4 cm (with a "hole" in center)
Laser Efficiency	10-15 kW (kilo/sec) (including ejectors) 60 kW (kilo/sec) (not including ejectors)
Auxiliary Equipment Necessary	fuel supply vacuum pump ejector
Ejector Efficiency	100-250 gr/sec of fuel

TABLE II-10

LASER SYSTEMS

Laser/λ(μm)	Avg. Power (MW)	Divergence (mrad)	Tracking Accuracy (mrad)	Nominal Range (km)
DF/(3.8)	5	0.01	0.01	1-4
CO_2/(10.6)	5	0.02	0.01	1-4

4. Target Parameters Affecting Laser System Performance

The most important target factors are those that directly affect the magnitude of the return signal. These consist of large-scale geometric factors, such as size of the target, curvature and aspect angle; small-scale roughness, such as matte vs. glossy surfaces, and, finally, the reflectivity of the surface material. Contrast is of secondary importance here. The target has already been detected and identified when it is being aimed at with a designator or range finder that is boresighted with visual (or IR) weapon sights. The laser itself does not form the image seen by the gunner.

a. Effect of a Diffuse Surface at Irregular Aspect Angle

Suppose a beam of diameter D and power P_t strikes an extended surface at an angle of incidence i and is then scattered perfectly diffusely into the hemisphere as in Figure II-20. A range finder of collector aperture A_c at range S will then collect a return power P. It will be a small fraction of the transmitted power P_t and can be shown to be given by:*

$$P/P_t = \frac{R\, A_c \cos i}{\pi\, S^2} \qquad (1)$$

*The cos i term distinguishes this expression as a brightness caused by reflection of a collimated beam. In self-emission, the brightness is independent of aspect angle and the sun thus appears as a uniformly bright disk. The full moon, on the other hand, should show limb darkening according to cos i, assuming it to be a diffuse reflector. The cosine is, however, a rather slow function of angle and the effect is thus not very pronounced until one looks very near the moon's limb.

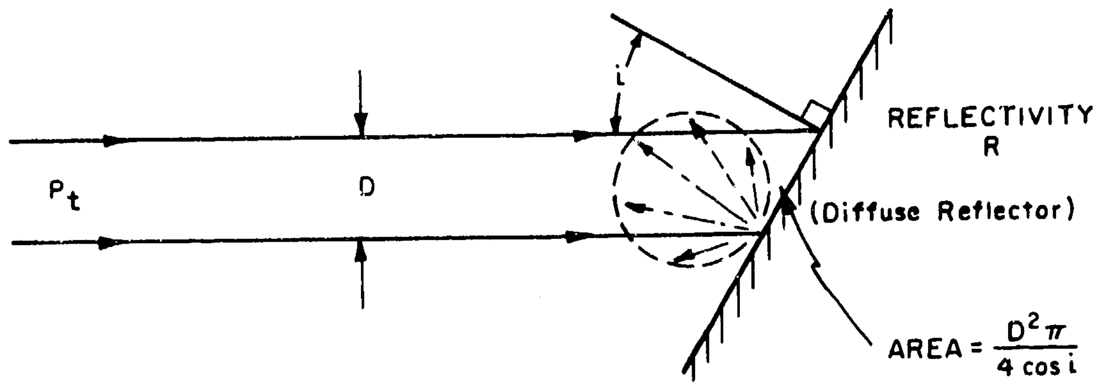


FIGURE II-20. LASER BEAM STRIKING A DIFFUSE REFLECTOR

For ranges from 500 to 3000 meters, and some reasonable assumptions about the collector aperture A_c, the reflectivity R, and the angle of incidence I, one could obtain the following numerical values:

A_c = 5×10^{-3} m^2 (≈ 3 inch dia.)

R = 0.5

i = 45°

S = 500 to 3000 m

P/P_t = 2×10^{-9} to 6×10^{-11} (2)

b. Effect of a Glossy Surface with Curvature

A glossy specular surface will produce no returns unless at least some surface element is aligned normal to the beam. Armored vehicle designers already try to avoid surfaces that might be square on to the enemy, in order to reduce the effect or armor piercing rounds. Normally, one would expect at best to see a curved surface such as from a turret or glints from edges, but not specular returns from appreciably large, flat surfaces.

To obtain some estimate as to the results, we assume a spherically curved surface as shown in Figure II-21.

The incoming power P_t in a beam of diameter D is returned as if it came from a point source located at a distance F ≈ r/2 behind the apex of the reflecting surface. The power is spread into the large solid angle after being attenuated by the reflectivity R. The range finder or the missile homing on the designator spot sees, therefore, a point source and a collector of area A_c provides at range S a ratio of returned power to transmitted power:

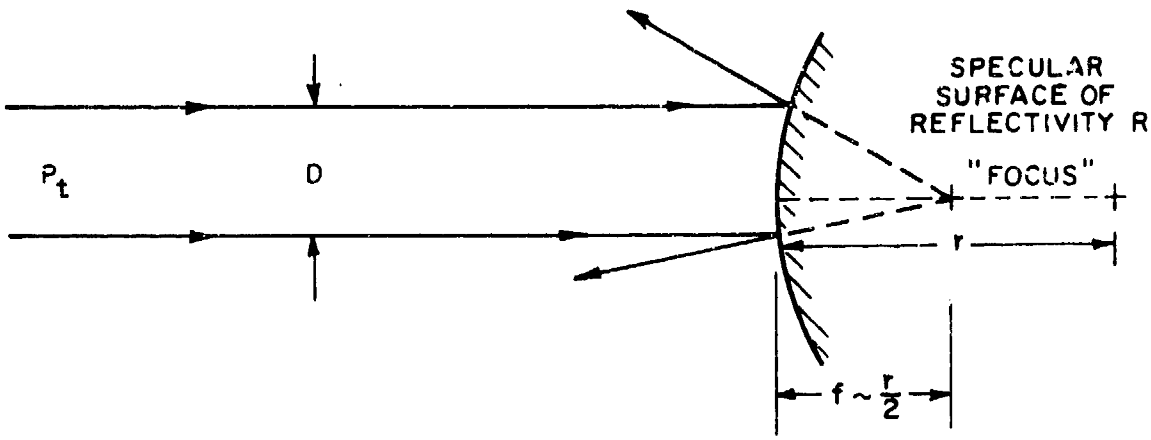


FIGURE II-21. LASER BEAM STRIKING A CURVED GLOSSY SURFACE

$$\frac{P}{P_t} = \frac{R\, r^2 A_c}{D^2 \pi S^2} \qquad (3)$$

For instance, if

$D = 1$ meter

$R = 0.5$

$r = 1$ meter

$A_c = 0.005\ m^2$

$S = 1000$ m

then

$$\frac{P}{P_t} = 7.97 \cdot 10^{-10}$$

The ratio would be reduced by another order of magnitude at a range of 3000 meters.

c. Comparison of Glossy to Matte Surface

Comparing the attenuation of glint (3) from a spherical specular surface to the attenuation of the return from a diffusely reflecting surface (1) of equal reflectivity, we find

$$\text{glint/diffuse return} \approx (r/D)^2. \qquad (4)$$

For clarity, we have neglected the small effect of aspect angle. It reduces diffuse returns proportional to cos i, but does not affect glint, to comparatively large angles, as clearly seen in Figure II-21.

Equation (4) shows that, when the radius of spherical curvature r of the glint surface is much smaller than the beam diameter, a glossy surface with glint will return much less power than a diffuse one. This may be the reason why the Warsaw Pact vehicles have glossy paint. While it is still glossy, it is optically superior, and when it becomes dirty, it is no more diffuse than can be helped.

One of the reasons the U.S. Army is also considering a different paint is the ease of decontamination. A glossy surface is easier to clean than a matte one, and the new polyurethane binders are chemically much more resistant to violent cleaning than alkyd and other binders they replace.

Perhaps far more important and not as evident is the fact that a matte paint, unless very cleverly constructed of a matte base and a clear transparent cover, has a very much larger specific surface than a smooth one. Therefore, it will absorb or accumulate a much larger amount of nuclear fallout or of chemical agents. Not only would it then be more difficult to clean, but also it would present a very much larger hazard while it is still contaminated.

d. The Attenuation Budget of Laser Range Finders and Designators

The typical Nd:YAG laser range finder or designator sends out a pulse of an energy around 10^{-2} joule, a peak power around 10^{6} watt and a duration between 5 and 10 nanoseconds (about 2 m at the speed of light). The transmitted beam is narrow, around 0.5 mrad, so that all the laser power will be scattered by the target. In this respect, laser range finders and designators are different from radar, and the round trip attenuation is therefore proportional to R^{-2}, not R^{-4}.

Range Finder

Paragraphs 4a and 4b give estimates of the round trip attenuation. The worst case estimates for ranges that would occur in tank engagements lead to return fractions of:

$$\frac{P}{P_t} \sim 10^{-10}$$

In addition to this geometric effect, practical losses will occur because the windows are dirty, there is scattering in the atmosphere, the aim is imperfect, etc. A very pessimistic assumption for these is another factor of 1/100 and this then yields the estimate of power available for the detector:

$$P_D \sim 10^{-6} \text{ W}$$

A typical silicon avalanche photodiode will have a noise equivalent power (NEP) around:

$$\text{NEP} \sim 10^{-13} \text{ W}/\sqrt{\text{Hz}}$$

A matched filter for 7ns pulses has a bandwidth near 70 MHz. The resulting signal to noise ratio is:

$$S/N = P_D/\text{NEP}\sqrt{\Delta f} \sim 1000$$

The margin of performance of the range finder is evidently so large that reduction of target reflectance alone could not defeat it.

Target Designator

Here the situation is different. The range may be longer and atmospheric effects enter more strongly. The detector and its optics are on the smart bomb or missile and therefore cannot be as expensive as they might be in the range finder. The chief difference, however, is that the detector has to search its field of view for the target rather than being boresighted to it from the beginning. This will lead to a much worse signal to noise ratio than in the range finder. Finally, the detection circuit in the smart bomb or missile is not adjustable by an intelligent operator as it is in a range finder.

All this will easily cause a reduction in effective signal to noise ratio to a point where the homing performance becomes noise limited. At that stage, any reduction in available signal will reduce the performance of the system noticeably.

We conclude:

- against range finders in tank vs. tank engagements a reduction in reflectance of the tank's surface is ineffectual. It should never be obtained at the cost of other protection. in particular not at the expense of visual camouflage.

- against laser designators (in particular, at long ranges), reducing reflectance is likely to be effective.

5. Important Target Parameters

From the discussion above, we can infer that certain target parameters will influence the performance of laser range finders, target designators, beam riders, and lidars more than others. A very important one is the size of the target relative to the laser beam. Laser light is coherent, the beam is usually well collimated, and in many cases all of the beam energy falls upon the target.

A second important group of target characteristics are those relating to reflectivity. The proportion of the beam energy that is reflected depends on the composition of the target, for instance, whether it is metallic, dielectric, or coated, and also on the roughness of the surface. One can distinguish between specular reflection from the surface that is smooth on a scale relative to the incident wavelength and diffuse reflection from the surface that is rough on a scale relative to the incident wavelength; but most actual surfaces are neither perfectly specular nor perfectly diffuse. Both the reflectance of the material itself and the effects of roughness are wavelength dependent. In fact, in the visual and VSWIR region, man-made targets are often diffuse reflectors, whereas in the 10.6-μm region, the reflection from man-made targets is more specular.

The gross target shape also affects reflectivity: convex curves tend to scatter incident energy widely, flat surfaces produce strong reflection in certain directions, and re-entrant angles and corners can produce strong retro-reflections or strong absorption. Because of this, the aspect angle, that is, the angle of incidence of the laser beam on the target, is also significant. In some instances, the effectiveness of the laser could be altered by controlled polarizers on the target. The slope of a dielectric (i.e., paint) reflecting surface affects reflectivity to polarized radiations and many lasers are strongly polarized.

Some other characteristics are not purely qualities of the target, for the defender has partial control over them and can sometimes make a choice. First among these are atmospheric conditions. Atmospheric absorption reduces the energy in the laser signal, and atmospheric scattering reduces contrast at the receiving sensor. Sometimes the target has a choice of location with respect to haze and fog. Also, contrast between the target and the background is important in some instances as well as simply the target reflectance.

To summarize, the important target-related characteristics influencing laser system performance are:

- target size relative to laser beam cross-section,
- target reflectance and the factors that contribute to it,
- atmospheric conditions, and
- laser beam polarization.

6. Camouflage Implications

The use of laser range finders and various types of target designators poses major problems for the camouflage designer since these systems operate throughout the various IR bands. These systems operate by line-of-sight and are usually operator assisted. When a laser beam illuminates and dwells on a target, it can only mean that the operator has already detected and acquired the target. The calculations in the previous section show a ratio of received to transmitted power in excess of $6 \cdot 10^{-11}$ in both examples. Laser powers of megawatts are feasible, and absolute detector sensitivities of microwatts are possible. To reduce the return signal below the threshold of detectability would require reducing the reflectivity R nearly two orders of magnitude. This is hopelessly far beyond the realm of plausibility. The most that can be hoped for is to reduce the extreme range, and degrade performance under poor environmental conditions such as haze.

In general, passive countermeasures against laser weapons include shaping of surfaces to avoid retroreflections, use of active jammers, and use of specialized coatings (paints) to minimize reflection. Dirt and dust are common problems associated with the latter technique since they tend to change the reflectivity and therefore require that surfaces be kept clean. This is a very difficult requirement in many operational theaters.

The relative vulnerability of targets to laser devices can be ranked roughly as follows:

Low - Surface composition is chosen to minimize strength of return, or specular returns (targets) are positioned so that specular reflection goes away from detector. Decoys are used.

Medium - Surface composition reduces reflectivities at particular wavelengths.

High - The surface is such that a significant amount of energy is reflected toward detector, i.e., no protective laser coatings are applied or no other precautions are taken. Decoys are not used.

E. CHARACTERISTICS OF SYSTEMS OPERATING IN THE MWIR AND LWIR SPECTRAL RANGES

1. Introduction

Systems operating in the visible and near IR and systems using lasers depend entirely on light scattered by the target. In the MWIR and LWIR ranges, most targets radiate a significant amount of electromagnetic energy as well. All matter radiates thermally induced electromagnetic waves. A red hot poker or an incandescent filament is a visible expression of this phenomenon. At lower temperatures, the radiation is predominantly at longer (infrared) wavelengths. At room temperature (20°C), the power radiated near 5 μm by an efficient radiator is as great as the power received from direct sunlight at the same wavelength on the same area; at longer wavelengths, the thermal radiation is greater than that of incident sunlight. In the infrared, we have not only light scattered and reflected from the sun and sky and laser sources but also the universal infrared "glow" emitted by targets and backgrounds alike. Also, the atmosphere is not uniformly and consistently transparent to infrared as it normally is to visible light.

Figure II-1 is a generalized schematic diagram of a system to accomplish surveillance and target acquisition in spectral regions including MWIR and LWIR, showing the role of target thermal emission and the way some conceivable countermeasures might interact with it.

We can distinguish conceptually among scattered and reflected artificial IR light, scattered ambient (sun- and sky-) light, and thermal emission. However, when the energy from these three sources leaves the target, it is indiscriminately mixed as it propagates toward an observer. It passes through a transmission medium--the atmosphere--to a collector of IR energy, often in the form of an imager. The imager serves two purposes:

(1) increasing the effective sensitivity and discrimination of the device (by segregating the energy received from one small solid angle from the energy received from other directions), and

(2) at the same time inferring additional information about the geometric relations among sources of infrared.

The IR energy is detected by the sensor--analogous to the retina of the eye, the image plane of a television camera, or the film in a photographic system. The sensor may be designed to measure energy intensity, spectral distribution, temporal characteristics, and other qualities of the radiation. The sensor generates some pattern of signals that has a consistent relation to the IR energy distribution in the field of view of the imager. These signals are subjected to some processing to help the operator discriminate targets from other sources of IR radiation.

Because of self-emission, the local environment from which target signals must be picked out is somewhat richer and more varied at MWIR and LWIR than at shorter wavelengths. It includes, obviously, natural sources such as sunlight and artificial light scattered from the trees and ground, thermal IR radiated by natural objects at ambient temperatures, such as the intensely radiating cone of Mount St. Helens, a sunlit southern slope, or desert sand, and other naturally hot features of the panorama. It also includes IR radiation and reradiation from any source that the observer decides, for reasons of his own, is not of primary interest. Just as any plant growing in a garden where you don't want it is a weed, any object in the field of view of a sensor system that you don't want to look at is local environment. If it makes it harder to see your target, it is properly described as "interference" or "clutter."

2. Surveillance and Target Acquisition in the MWIR and LWIR Spectral Regions

The IR threat to the U.S. Army is threefold:

(1) long-range reconnaissance and surveillance sensor systems

(2) comparatively short-range target acquisition and fire control equipment

(3) thermal homing weapons

Where specific information is lacking, we will assume that hostile IR technology development is at least parallel to that of the United States.

a. Reconnaissance and Surveillance

Reconnaissance and surveillance are typically accomplished by line scanners in aircraft, although long-focal-length, two-dimensional scanning images or staring focal plane imagers may also be used. In the near future, Remote Piloted Vehicles (RPV's) may also be employed for such missions. Equipment of that kind, operating at long slant ranges, first demonstrated the strong IR signatures of much of the Army's present equipment. In particular sets of engine generators that are typically deployed around otherwise well-camouflaged headquarters, missile batteries, etc., were quite conspicuous.

Thermal IR reconnaissance and surveillance equipment typically looks down or sideways from the aircraft. A line scanner is probably the most effective implementation of such a reconnaissance imager, where a mechanical-optical scanner sweeps the image of a detector or group of detectors across the track of the aircraft for full strip coverage. The optics of such a scanner are comparatively straightforward, and their operation is simple and automatic. The output of the line scanner can be stored on filmstrips or, more practically, on videotape. In other applications, the output of the line scanner could be instantaneously transmitted to a ground station for immediate evaluation. The operation of scanners is discussed in more detail in Section 3.a. below.

Evidently, reconnaissance and surveillance are also possible with two-dimensional scanner imagers or with staring arrays. However, these would require carefully aimed and stabilized platforms and would be more suitable for operation by an observer rather than in the automatic collection of imagery.

b. Target Acquisition

Target acquisition occurs in combat, where Forward Looking Infrared Systems (FLIR's), thermal weapon sights, hand-held viewers, or other imagers are used to detect opposing targets, recognize them by type, classify them by importance, identify them as friend or foe, and finally, control direct-fire weapons against them. A typical adjunct to such a system is a laser range finder.

Important examples of such target acquisition systems are the FLIR pod of an attack helicopter, the thermal sight of a launcher of wire-guided anti-tank missiles, or the thermal sight of a tank main gun. Imagers for this task are typically based on mechanically or optically scanned detector arrays that form two-dimensional images in an electro-optic display. The quality of the images varies according to their bulk and cost. The best FLIR's can deliver spatial resolution comparable to first-class TV images with minimum resolvable temperature differences (MRT) of small fractions of a degree. The comparatively simply hand-held imager of an infantryman will, at a range of 100 meters, yield an image of a tank good enough to identify its type.

c. Thermal Homing Weapons

Infrared emission by the target is a practical signal for comparatively inexpensive homing missiles. These were first introduced against aircraft, because the high temperature of engine exhausts and the clutter-free cold sky background made it possible to use simple uncooled (or moderately cooled) short-wave infrared detectors.

Ground targets, on the other hand, rarely have a very high temperature signature and have to be detected against the highly cluttered thermal background of the surrounding terrain and combat environment. Therefore, detection typically depends on shape or pattern of deployment. A hot spot detector alone will not do. Missiles with an infrared imaging tracker are being planned and developed at present, because they are so extraordinarily promising. In theory they could be given much image processing and discrimination capability. However, at present this appears still to be extraordinarily expensive and the mass production of the required high sensitivity infrared imaging systems extraordinarily difficult. Such a threat to the U.S. Army, therefore, does not have to be expected for many years.

Alternatively, a relatively simple and readily manufacturable missile could be designed to home on hot ground targets, i.e., a "hot spot." It could employ simpler detectors and optics, probably in the 3-5 micrometer band. Ambient background clutter could be suppressed by a simple threshold circuit. Targets that are not vulnerable to such missiles would include personnel, vehicles at rest, command posts, storage depots, and any other whose temperature contrast would be inherently (or by camouflage) low. Vulnerable targets would be tanks and vehicles with hot exhausts, engine generators, hot gun barrels, radar sets with large dissipation, etc.

d. Range Finders

The laser range finder is not covert and must be used with care in training and field exercises to avoid damaging the eye. A potentially useful alternative type of range finder could be based on optical correlation methods operating in the infrared. Akin to some present autofocus cameras, this could be automated and provide a fast and entirely passive method of ranging. It would be both eye-safe and covert, yet have the haze penetration potential of thermal IR devices. Camouflage, by disrupting and blurring the sharp outline of a target, would be particularly effective against such range-finding methods.

3. Types of Sensors

Because the Warsaw Pact forces apparently have no substantial numbers of thermal imagers fielded or in the present inventory, we cannot base any analysis on actual threat performance. However, it is publicly known that the threat forces have long deployed simple but effective IR homing missiles. According to the open literature, IR imagers have also been used in medical applications, and obviously they have access to at least some commercial thermal IR imagers; publications on the development of detector materials have also appeared. From the established technical competence and success in past R&D efforts of the Warsaw Pact forces and from the above-mentioned specific indications, we assume their technology to be potentially as close to the fundamental limits set by the laws of physics and the general state of present-day engineering as NATO's technology is.

What they will actually deploy is another matter. In the past, the USSR has often led the development of specific highly effective military equipment. Tanks are the most notable example. In other fields, the USSR has often taken advantage of its relative security against surprise attack to observe and follow foreign developments that are often openly conducted. When the USSR's military doctrine convinces them that these developments will lead to significant military advantages, they step in with simple, straightforward, and effective technical implementations. Night vision equipment and laser range finders are examples, and appear to be universally employed in their tank force. If the USSR should feel that the additional capability of a thermal viewer is worthwhile, it can likewise employ them. We may therefore assume that the USSR could field roughly the following equipment:

- State-of-the-art 8- to 14-μm IR scanners for long-range reconnaissance and surveillance. Comparatively small numbers are needed to be an effective threat.
- Target acquisition and fire control equipment--operating in the 3- to 5-μm (InSb) range, which would be easier to implement than those for operation at 8-14 μm.
- Inexpensive and simple thermal viewers in larger quantities, perhaps even based on uncooled (pyroelectric) detectors.
- Infrared homing munitions using simple detectors effective against fairly high temperature signatures only.

In the long term, we must assume that the threat can always match our technology, and possibly surpass our equipment in specific fields where the adversary feels it is warranted.

It is physically possible to measure thermal radiation differences to a fraction of a degree Celsius. However, the background radiation variations against which targets must be observed make this sensitivity useless. It is generally agreed that differences in emission corresponding to temperature differences of less than ±4° are significant. One may also assume that the Warsaw Pact forces have an IR common module program equal to that of the U.S. Army Night Vision Laboratory. Further, one may assume that the USSR has a lesser number of very high-performance reconnaissance scanners and FLIR's equal to the best available here and in the United Kingdom. Predictions on possible future performance improvements should be based on ongoing developments in the state-of-the-art in the United States and on the fundamental limits set by the laws of physics.

a. Principles of Infrared Scanners

Most present IR imaging systems use single detectors, or linear arrays, in mechanical-optical scanners which perform a full two-dimensional scan as in a FLIR, or a line scan from a moving vehicle. "Staring" focal plane arrays are attractive in principle, because they observe all spatial resolution elements continuously and avoid mechanical scanning. However, they are more difficult to build, because the average thermal photon flux from ambient temperature objects is large compared to typical contrasts between the objects in that scene. This puts large demands on the linearity and dynamic range of the detectors and, in a staring array, requires close uniformity between elements. In a scanner, the problem is avoided, because one or relatively few detectors are used to scan the whole scene, and "AC coupling" can easily reject the thermal average background and only reproduce the scene contrast. This is one of the reasons that mechanical-optical scanners are easier to implement than are staring focal plane arrays.

The resolution in a well-designed IR imager is limited by the number of lines per picture and the video bandwidth during scan. The minimum resolvable temperature (MRT) is determined by the noise in the video and the derivative of target radiance with respect to temperature. The temperature noise limit is set either by the quality of the detector and preamplifier, or by the statistical fluctuations in the photon stream incident upon the detector. Practical systems can quite closely approach this ideal limit (called background noise-limited (BLIP) operation) and are then no longer limited by the quality of the detectors. The remaining engineering measures to improve the signal-to-noise ratio are therefore: to employ a fast optical system to maximize both target and background signals; to use a detector with high quantum efficiency; and to arrange the patterns and detector geometries so that as many photons as possible are usefully collected during each frame.

In addition, the spatial field of view of the detector is carefully limited by cooled baffles. The spectral bandpass of the detector is limited by the detector's response curve on the long wavelength side and by a cooled filter on the short wavelength side. These measures reduce the background photon noise in the detector current to the limit set by the scene alone.

Most scanners use arrays of detectors rather than a single detector. Linear arrays can be arranged in the direction of the scan, and the output of these detectors can then be integrated, with suitable time delays, to produce a net increase in the signal-to-noise ratio by the square root of the number of the detectors employed. This also smoothes the variations between detectors in the array. Linear arrays can also be arranged in parallel to sweep a wider swath across the field of view, which reduces the required mechanical scanning speed for equal coverage. This approach has the disadvantage of a systematic bias due to the variations between the individual detectors. These variations are one of the more serious engineering problems in the manufacture of detectors, and a definite limit on the performance of detector arrays. However, the "art" of making infrared detectors is continuously improving, as is the cost-effectiveness of the associated complex electronics. It is thus possible to re-standardize each detector channel with respect to gain and zero level as frequently as every line or frame. Such schemes lead to a considerably more uniform and accurate representation of the scene than the simple AC coupling mentioned above, in the presence of strong overall background radiation from the scene.

Mechanical scanning imagers are the basis of most present thermal IR viewing technology. Typically, they use arrays of detectors in series and/or parallel to improve the signal-to-noise ratio and reduce scanner speed. The detector performance can be near the fundamental limit set by the fluctuation in the photon stream from the scene.

The performance of a thermal imager can be described without having to specify its foreoptics. A given relative resolution (measured, for example, in horizontal and vertical lines per frame) can be mapped either by long focal length optics on a small field of view or by wide-angle optics on a large one. Assuming the foreoptics to be of approximately equal quality and F/number, the relative spatial resolution and the minimum resolvable temperature difference will be the same in both cases. The angular resolution measured in the field of view will, of course, differ. The optimum thermal imager for a given task is the one that provides the required angular resolution, resolvable temperature difference and field of view, but without overloading the perceptual capabilities of the observer.

The following data would be typical of a simple thermal imager and of a more recent foreign FLIR.

A typical handheld thermal viewer is the U.S. Army AN/PAS-7 which works in the three to five micrometer band using a thermoelectrically cooled array of detectors. Its commercial version (AGA, Sweden) has these specifications:

Field of View	6° by 12°
Resolution	2 mrad
Frame Rate	30 Hz
Detector Elements	48
Detectable Temperature Differences	0.1°C

Its recognition range for a man is stated as 200 meters. A device such as the AN/PAS-7 could be readily manufactured in the Eastern Bloc.

A more sophisticated foreign FLIR (Siemens, W. Germany) works in the 8-12 micrometer range and has these specifications:

Field of View	4.3 x 2.8 or	8.6 x 5.5
Target Detection Range (1 cycle per target)	9 km	5 km
Target Recognition Range (4 cycles)	2.8 km	1.5 km
Target Identification Range (6.4 cycles)	1.4	0.8 km
Detector Elements	55, HgCdTe, closed cycle cooled	55, HgCdTe, closed cycle cooled
Detectable Temperature Difference	0.08°C	0.08°C

Performance data taken at: 70° humidity; 5 kilometer visual range; 20° centigrade. The output is CCTV Compatible.

b. Imaging Optics

The thermal imager itself must be matched optically to the observation task. A certain minimum numerical aperture or F/number ("speed") of the optics is required to produce near background limited performance. When high magnification is required for long-range reconnaissance or surveillance, long focal lengths and large apertures result. This can easily lead to practical limitations. For example, in the turret of a tank, the size of the aperture is limited by the size of the permissible opening in the armor, or by parts one can attach to the outside. In the case of an airplane, the permissible drag and weight set upper limits on these dimensions.

c. Detectors

Detectors fall into two categories: quantum detectors and thermal detectors. The former are photovoltaic or photoconductive devices that deliver, for each incoming photon, on the order of 1 electron in their output current. (The quantum efficiency of most practical IR detectors is around unity.) Thermal detectors, on the other hand, react to minute temperature fluctuations by changing resistance in the case of bolometers, or by the appearance of an electric potential at their terminals, as in the case of thermocouples or pyroelectric detectors.

In practical detector systems, the noise comes from five sources: detector thermal (Johnson) noise, amplifier noise, statistical noise in the input photon stream, statistical noise in the process of generating carriers, and excess noise in the detector and preamplifier. The last is typically present in all devices that require a bias current, such as photoconductive devices and transistors, but not in detectors such as photovoltaic diodes that generate an electrical signal directly from the photon input. In the absence of an input, these cannot generate more than their inherent thermodynamic noise power $P = kT \Delta f$, which is uniformly distributed over frequency. This is the so-called Johnson noise. Excess noise, on the other hand, typically increases rapidly toward low frequencies in the audio range and is often called 1/f, or modulation noise.

The pyroelectric detector is an unusual device, a room-temperature thermal detector without a built-in thermal (Johnson) noise source. Its active element is a capacitor, rather than a resistive source, as in the case of a thermocouple. In theory, it contains no dissipative element (if the pyroelectric dielectric were lossless) and thus delivers no Johnson noise. However, its very high source reactance and its bias requirements lead to noise contributions from preamplifier and bias circuitry. The pyroelectric detector has the further advantages of being simple and cheap and having a relatively small thermal mass. Compared to other thermal detectors it is fast, although not nearly as fast as quantum detectors. Because of the combination of these properties, it is the only room-temperature detector which presently offers even a remote possibility of adequately performing thermal imaging with staring focal plane arrays. Both pyroelectric vidicons and solid-state arrays have been built successfully.

The most commonly used IR quantum detectors for thermal imagers are HgCdTe, PbSe, and InSb. The chief requirements are low noise and speed of response for scanners. InSb is operated typically at 77°K; i.e., at the temperature of liquid nitrogen, and performs exceedingly well in the wavelength range from 3 to 5 μm. It is typically photon noise-limited. PbSe can be operated above 200°K, and is adequate for hand-held viewers. HgCdTe can be tailored either for operation in the 8- to 14-μm band, where it is operated at 77°K, or for operation in the 3- to 5-μm band, where it can be operated at temperatures up to 195°K. This permits operation from multi-stage thermoelectric coolers, thus avoiding the mechanical complications of providing either a reciprocating cooler, a stored gas Joule-Thompson system, or a liquid nitrogen-filled dewar. HgCdTe is probably the most important detector material for thermal imaging.

4. Effects of Atmospheric Propagation

a. Gaseous Attenuation

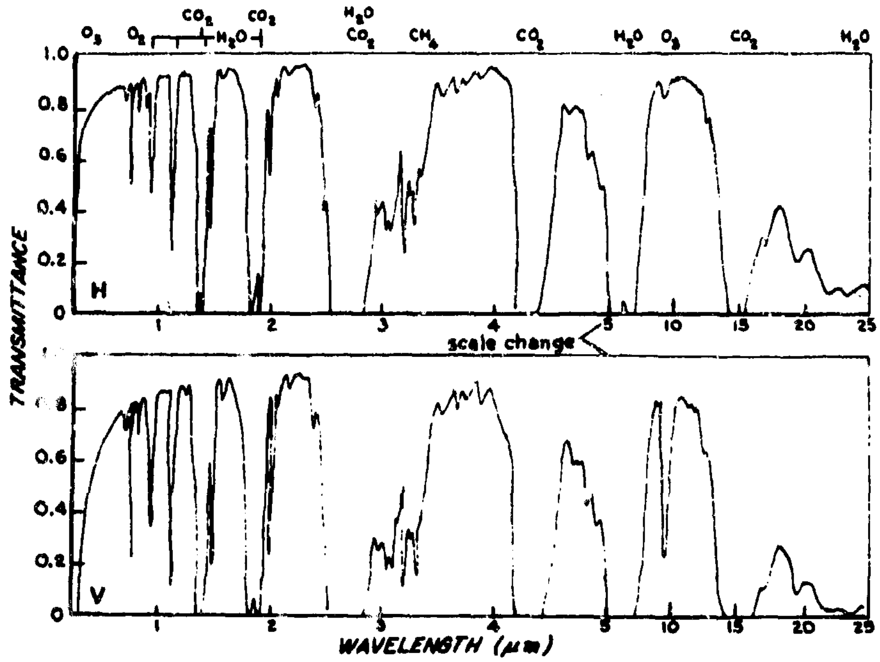
A typical spectrum of the earth's atmospheric opacity is shown in Figure II-22. The principal atmospheric absorbers are water vapor and CO_2, although small amounts of N_2O, CH_4, and CO can often be seen. In addition to the absorption bands of these atmospheric IR active gases, there are continua due to dimers and polymers of water vapor and to collision-induced absorption by nitrogen. An important point to be considered when using Figure II-22 is that the precise shape of spectral transmission of the atmosphere depends not only on the path length and direction (slant) and atmospheric humidity, but also on the spectral resolution employed by the sensor. That is, a low-resolution sensor may record a region as being spectrally opaque, whereas a high-resolution sensor may be able to look through gaps between the lines of the atmospheric molecular spectra. The individual lines of atmospheric gases tend to be a few tenths of a wavenumber broad, and as a consequence many gaps will occur (depending on the path length) that do not appear in a low-resolution spectrum like Figure II-22.

b. Aerosol Attenuation

The other atmospheric attenuator consists of the natural aerosol which tends to have a quite broad attenuation that is a function of the particle size distribution present as well as of the chemistry of the aerosol constituents. Reference 21, for example, goes into considerable detail in this matter, but further discussion is not warranted here.

c. Resulting Absorption Spectra and Transmission Windows

The net result of the absorption by the lines and bands of the atmospheric gases, the continuum absorption by atmospheric gases, and the broad band of atmospheric aerosols is that the principal spectral



a. Atmospheric transmittance for 1 km ho. :ontal (H) path at sea level (top)

b. Atmospheric transmittance for the vertical (V) path between space and sea level :ottom)

FIGURE II-22. PROFILE OF ATMOSPHERIC TRANSMITTANCE regions for concern in the thermal infrared are regions that fall roughly between 7.5 and 14 μm and 3 and 5 μm (although the region between 4.2 and 4.4 μm is blocked by an atmospheric band of CO_2). In addition, at shorter wavelengths there are window regions between approximately 2 to 2.5 μm, 1.45 to 1.8 μm, 1.15 to 1.35 μm, and so on, into the visible region. These do not comprise all potential threat regions, because the atmospheric absorption spectrum varies slightly with atmospheric humidity. However, the windows described above are the principal threat regions. Any excess heat that can be dissipated without giving enhanced signatures in these spectral regions is satisfactory for present purposes.

d. Contrast Degradation

The contrast of the scene at the sensor plane is determined by a combination of varying absorption of the atmosphere as a function of wavelength, the path length (range and direction) involved in a given infrared observation, atmospheric scattering caused by extraneous particles such as dust, etc., and the individual signatures of the different targets of interest. If this contrast can be lowered below the ambient fluctuation, then an effective countermeasure has been realized.

5. Target Thermal Emission

All targets at temperatures above absolute zero emit thermal IR radiation. The wavelength dependence of the IR emission for a perfect emitter is described by the Planck function:

$$B = 2\pi c^2 h \lambda^{-5} \left(e^{(hc/k\lambda T)} - 1\right)^{-1} \qquad (1)$$

where h and k are Planck's constant and Boltzmann's constant, c is the velocity of light, and λ and T are the radiation wavelength and the absolute temperature. Equation (1) needs only the modifying factor ε_λ, the emittance, to completely describe the spectral radiance, N_λ, characteristic of any target. The emittance is a function of wavelength which depends upon the chemical and physical properties of the target or its coating. The simple equation

$$N_{\lambda} = \varepsilon_{\lambda} B \tag{2}$$

describes the naturally occurring radiation from any target. Figure II-23 shows a typical blackbody curve (for a 400°K target) as modified by a spectrally uniform emittance of 0.6 (graybody).

In practice, however, a number of complicating factors must be considered, along with the temperature of the object and the emittance of its skin, to fully describe the signature of an IR target. The first of these is the solar radiance curve (solar irradiance multiplied by target reflectance) which is also drawn in Figure II-23. In practice, it would also be diminished by the earth's atmospheric opacity (Figure II-22). It can be seen that for targets of reflectance R = 0.4, the two curves cross in the region between 3 and 4 µm. At any wavelength:

$$R_{\lambda} = 1-\varepsilon_{\lambda}, \tag{3}$$

providing the substance is opaque and the proper angular complements are used.

The reference to angular complements in the previous discussion refers to the fact that Kirchhoff's Law, as described in Equation (3), holds only for pairs of emittances and reflectances measured at the equivalent angles. For reflectance, we must append two subscripts $R_{\theta,\phi}$, one having to do with the angle of the incident radiation θ and one having to do with the angle of reflected radiation, ϕ. Either of these angles may be replaced by a spread of angles. For diffuse measurements, we may substitute the subscript, D, for either θ or ϕ. For emittance, an angular effect is also important, but this time only one angle, ϕ,

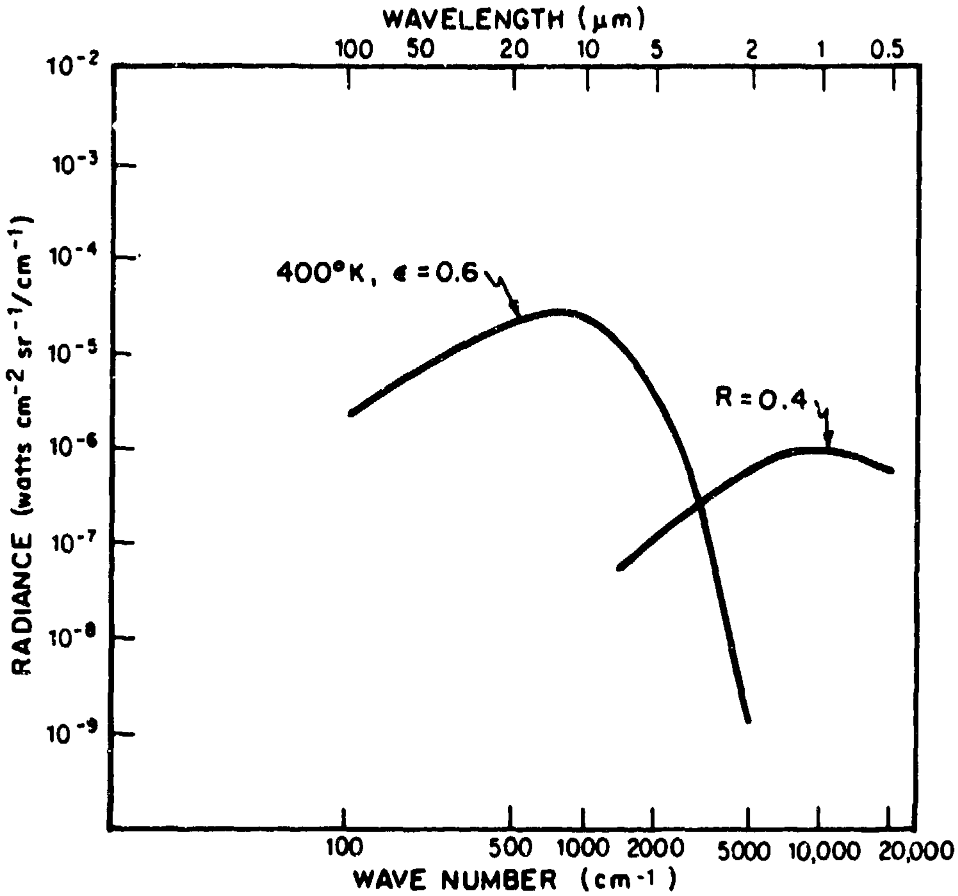


FIGURE II-23. TARGET RADIANCE DUE TO EMITTED THERMAL AND REFLECTED SOLAR RADIATION that of the emitted radiation, need be specified, as the other angle is diffuse. For the special case of specular reflection, the angles of incidence and reflectance are equal.

We referred above to the fact that all bodies at temperatures above absolute zero radiate. The high sensitivity of IR detectors is such that very small temperature differences of the order of tenths of a degree can be detected, even by commercial instrumentation. However, the real problem is not the detection of such small temperature differences, because the practical situation involves the detection of target signatures in the presence of a background having natural fluctuations of many degrees.

It is, in fact, erroneous to discuss the problem of thermal IR detection as one relating exclusively to temperature. The actual measurements are always ones of radiance (watts/cm^2-ster-μm, or watts/cm^2-ster/cm^{-1}). The point of importance here is the significance of the emittance of the target surface (Equation (2)).

For example, the 4°K permissible target variation from ambient is equivalent to a small emittance variation. However, the corresponding emittance variation is a function of both the spectral band of interest and the absolute temperature of the target.

A few simple calculations suffice to demonstrate the effect. If one assumes that the radiating target is at 300°K, then a decrease by 4 degrees will result in a radiance decrease of 16% in the 3- to 5-μm band and 6-1/2% in the 8- to 14-μm band. Because of the obvious linearity of the effect of a change in the emittance, the same result could be accomplished by a decrease in the emittance from unity to 0.84 in the 3- to 5-μm band and from unity to 0.935 in the 8- to 14-μm band. Thus, the 4°K tolerance is equivalent to an approximately 10% emittance drop. For purposes of comparison, the same calculations made for a 700°K object indicate that 100 degrees in temperature is equivalent to an emittance change of 80% for the 3- to 5-μm band and 33% for the 8- to 14-μm band.

Such emittance changes are possible, but they are, of course, difficult to specify because of their variation with the temperature of the target and the wavelength of interest. Nonetheless, the 4° tolerance is likely to have been derived from measurements which in truth involved the emittance willy nilly and only represent some average value of the radiance.

It is important to distinguish in the thermal IR region between the 3- to 5-μm and 8- to 14-μm atmospheric windows. Both of these wavelength ranges are only approximate and a reference to Figures II-18, II-19 and II-22 will make this clear. Historically, the first threat region was the 3- to 5-μm region because of the earlier development in InSb detectors, but recent developments in HgCdTe detectors have made the 8- to 14-μm region of equal or higher importance.

Planck's Law shows that the 8- to 14-μm band contains more radiant power than the 3- to 5-μm band for near room temperature objects. Nonetheless, the rate of change of radiance with temperature from a blackbody source varies more rapidly in the 3- to 5-μm range than it does in the 8- to 14-μm range. That is, the radiance on the long wavelength side of the peak of the Planck function varies with temperature approximately in a linear fashion, while on the short wavelength side of the peak it goes with a much higher power of temperature.

On clear days of high absolute humidity, IR systems of equivalent sensitivity usually operate better in the 3- to 5-μm region while hazy conditions favor 8- to 12-μm window. However, such considerations are only the beginning if one attempts to define the relative qualities of the two spectral regions for target sensing.

Table II-11 from the current literature presents the range in meters at which signal radiance difference at the sensor approaches zero* for different wavelength bands and under varying atmospheric conditions.

TABLE II-11

RANGE IN METERS AT WHICH THE SIGNAL DROPS TO ZERO*

Propagation Conditions	Spectral Intervals (μm) 3.5-4.1	3.5	9.5-10.1	9.5-11.5	8-12	8-14
High alt. clear	283,180	29,983	16,876	30,075	28,233	12,616
Clear channel	16,731	462	820	777	697	352
NVL 1 fog	283	84	194	198	180	117
NVL 11 fog	270	84	205	195	178	122
EOTF fog	178	47	211	234	197	141

*Somewhat implausibly, the source states "drops to zero." We have examined the source to find out more precisely what this means. No precise explanation is given, and we infer that it means "approaches zero."

SOURCE: Reference 22.

NVL refers to previous Night Vision Laboratory models for fog. As can be seen from the table, under clear atmospheric conditions the 3- to 5-μm band is clearly superior to the 8- to 14-μm band, but both bands can be improved by using different wavelength limits within the band. Under these conditions the 3.5- to 4.1-μm band is considerably superior to all bands examined under clear atmospheric conditions. However, while this band is a fairly good choice even in foggy conditions, it is no longer the best band, as the 9.5- to 11.5-μm band data are somewhat superior. The authors conclude that when fog is present it is often impossible to use the so-called high sensitivity 3- to 5-μm band. However, it is apparent from the table that all bands are significantly degraded under foggy conditions. So, depending on the weather conditions (likelihood of a particular kind of fog or haze) the comparative advantages or disadvantages of the various bands or subbands are uncertain. In principle, one would have to protect for all conditions. However, in practice, in one region and season, certain weather is highly improbable and can be safely ignored.

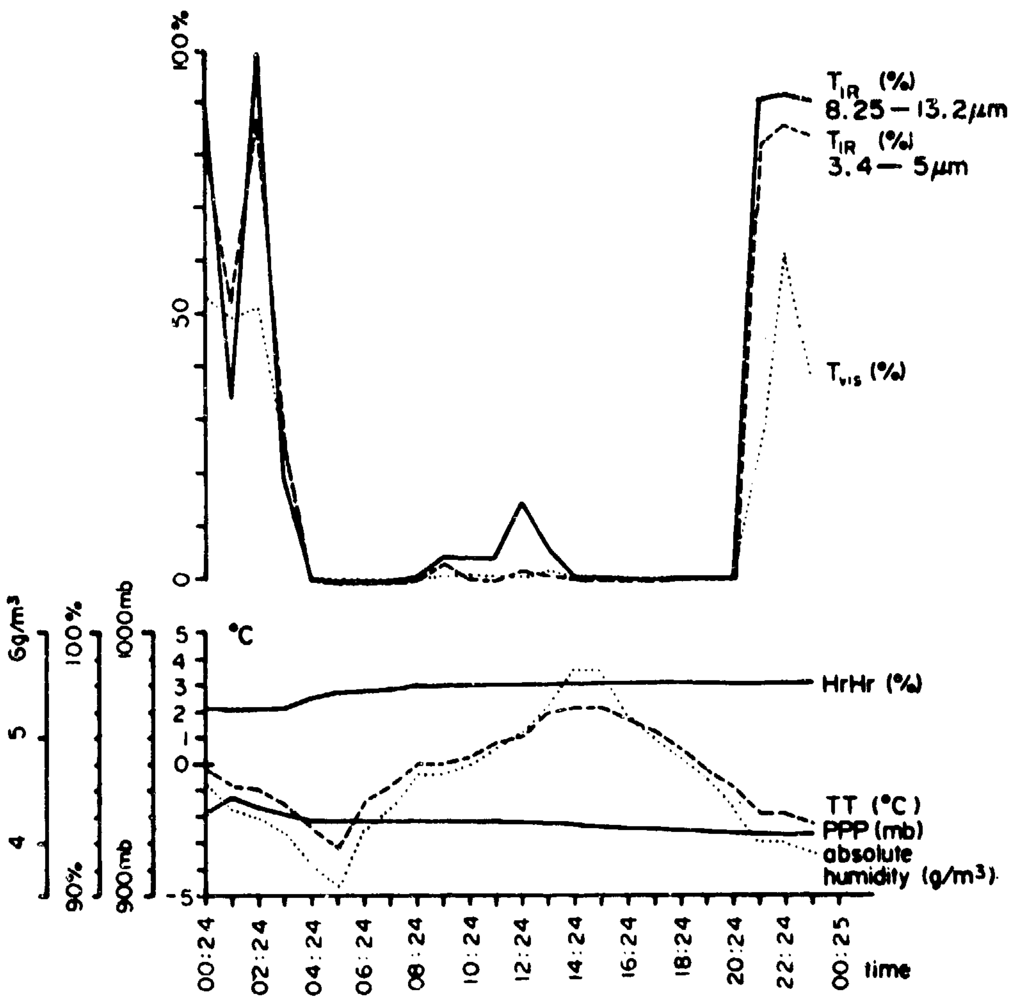
Another recent paper gives experimental measurements versus Lowtran 3B model data for differing atmospheric conditions and 500-meter range. It can be seen (Figure II-24) that for both the 3.4- to 5-μm region and for the 8.25- to 13.2-μm region, the IR transmission varies between approximately 0 and 0.9, depending on atmospheric conditions.

One can infer that visual transmission during rainfall is generally higher than IR transmission but that the relationship is highly complex, even for rain.

Figures II-25 and II-26 show a comparison of the atmospheric transmission in the two IR bands and visual for 500-m range. It is apparent that the bands have differences which are somewhat variable depending on fog conditions with the 8.25- to 13.2-μm band generally having the better transmission as might be expected from its greater wavelength. The important consequence is that the adversary's decision with respect to the best bands to use for thermal detection must be known in order to optimize the camouflage chosen.

6. Target Parameters Affecting MWIR and LWIR System Performance

The important parameters peculiar to this spectral region of thermal emission vulnerability are any combination of internal heat generation, thermal inertia, surface emittance, and size that gives a large signature.



T_{IR} - Infrared Transmission

T_{VIS} - Visual Transmission

TT - Temperature

HrHr - Relative Humidity

PPP - Pressure

FIGURE II-24. FOG SITUATION VALID AT A 500-m RANGE ON NOVEMBER 24, 1977 AT OPAQUE STATION "BIRKHOF"

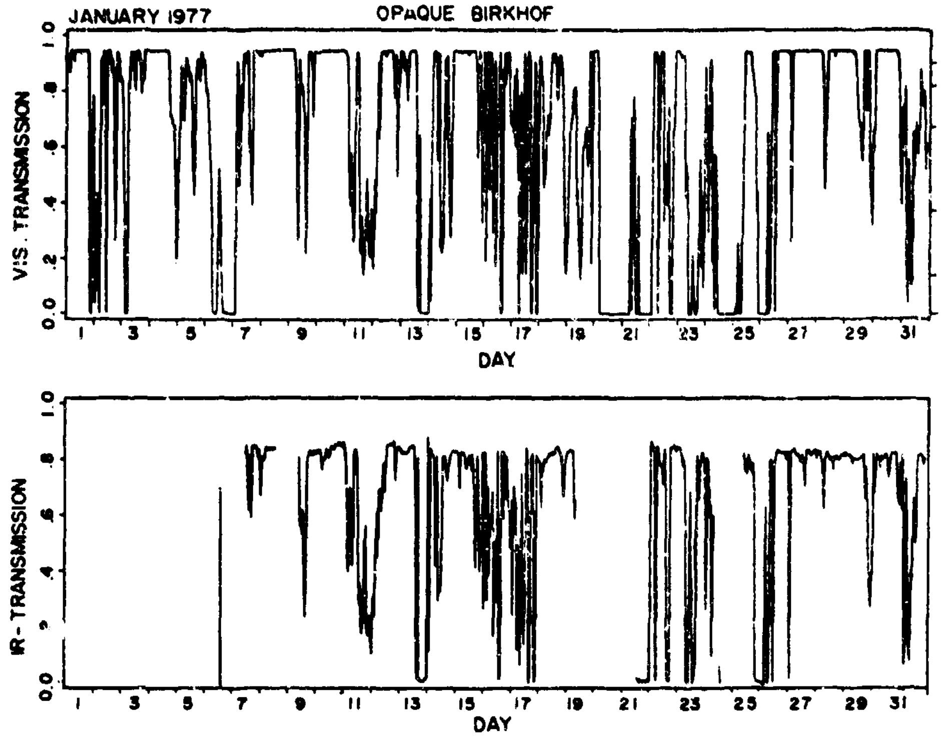


FIGURE II-25. VISUAL AND IR TRANSMISSION (3.4 to 5.0 μm) RECORDINGS OF A 500-m RANGE DURING JANUARY, 1977, FROM OPAQUE STATION "BIRKHOF"

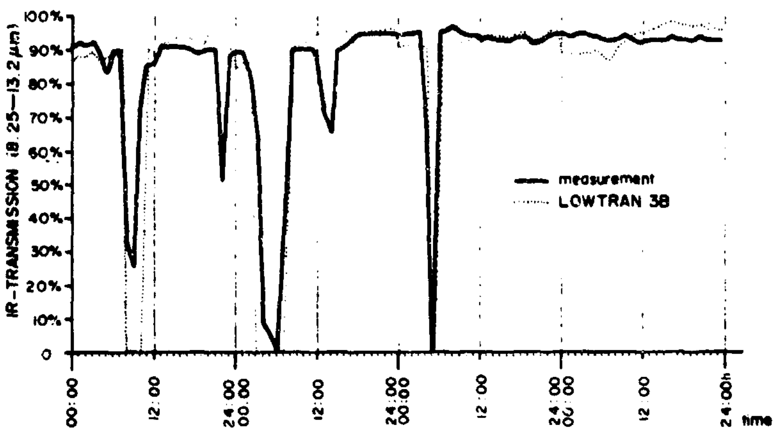


FIGURE II-26. COMPARISON OF MEASURED IR TRANSMISSION (8.25 to 13.2 μm) AND CALCULATION AFTER LOWTRAN 3B FOR A 500-m RANGE DURING OCTOBER 27-30, 1977

Looking first at heat generation, we would expect the vulnerability of a Corps Tactical Headquarters to be high because of its generators; of a 155-mm Howitzer Battery to be moderate because of its hot gun barrels shortly after firing; and of an Infantry Brigade to be low because it has few if any major heat sources or massive equipment having substantial thermal lags.

Thermal inertia λ is defined as $(k\rho c)^{-1/2}$, where k is the thermal conductivity, ρ the density, and c the heat capacity. It is a measure of the time lag before a heated object returns to equilibrium with its surroundings. The importance of thermal inertia is shown by Figures II-27, II-28, and II-29.

At any temperature, the thermal total emission is influenced by the effect of the surface emittance on the self-emission and the surface reflectance on scattered IR. In the 3- to 5-μm region, the reflectance of solar radiation is much more important than in the 8- to 14-μm region. Quantitatively, 4°C at 300°C represents about 3×10^{-5} w/cm^2 ster in the 3- to 5-μm band and 3×10^{-4} w/cm^2 ster in the 8- to 14-μm band.

Those target qualities that modify the scattered radiation and its detectability--reflectance, 'color,' and contrast with background--are equally important, but not unique to this spectral region. Finally, system performance is affected by all the other target parameters found significant in the visual (interpreted in the context of the MWIR and LWIR spectrum), i.e.,

- size and subtended angle relative to sensor resolution
- location with respect to FEBA
- shape
- motion

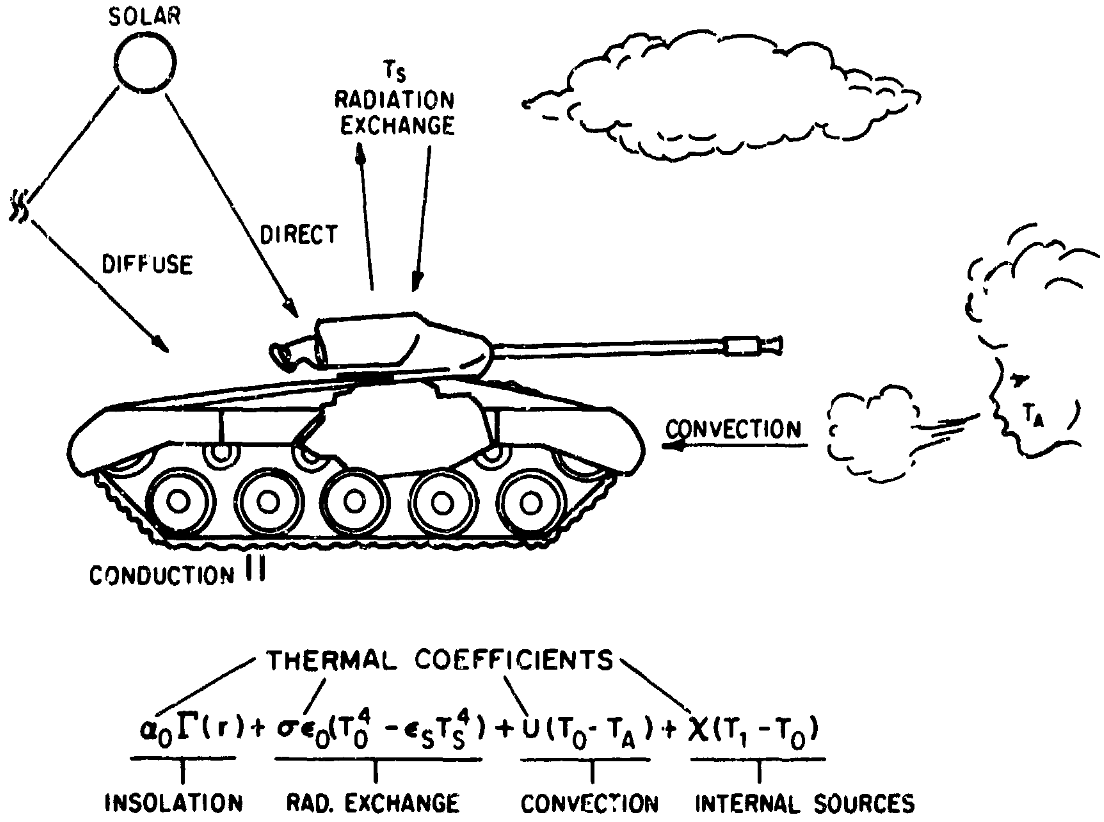


FIGURE II-27. FACTORS TO BE CONSIDERED IN THERMAL MODELING OF A SCENE OBJECT

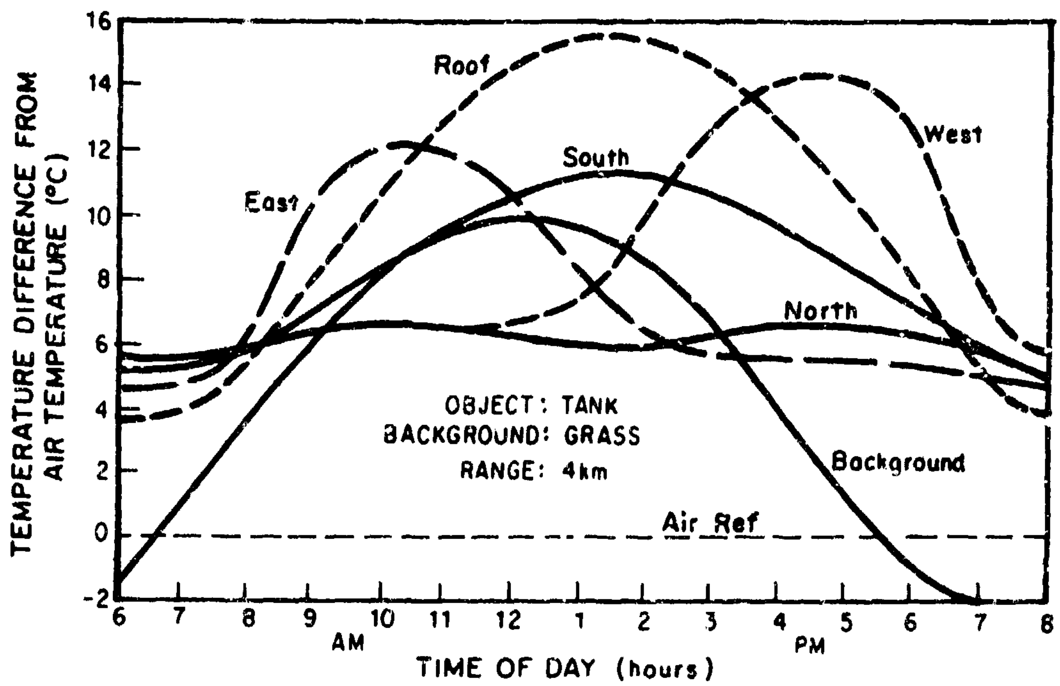


FIGURE II-29. TEMPERATURE DIFFERENCE BETWEEN A TANK AND AIR AS A FUNCTION OF THE TIME OF DAY FOR VARIOUS VIEWING DIRECTIONS

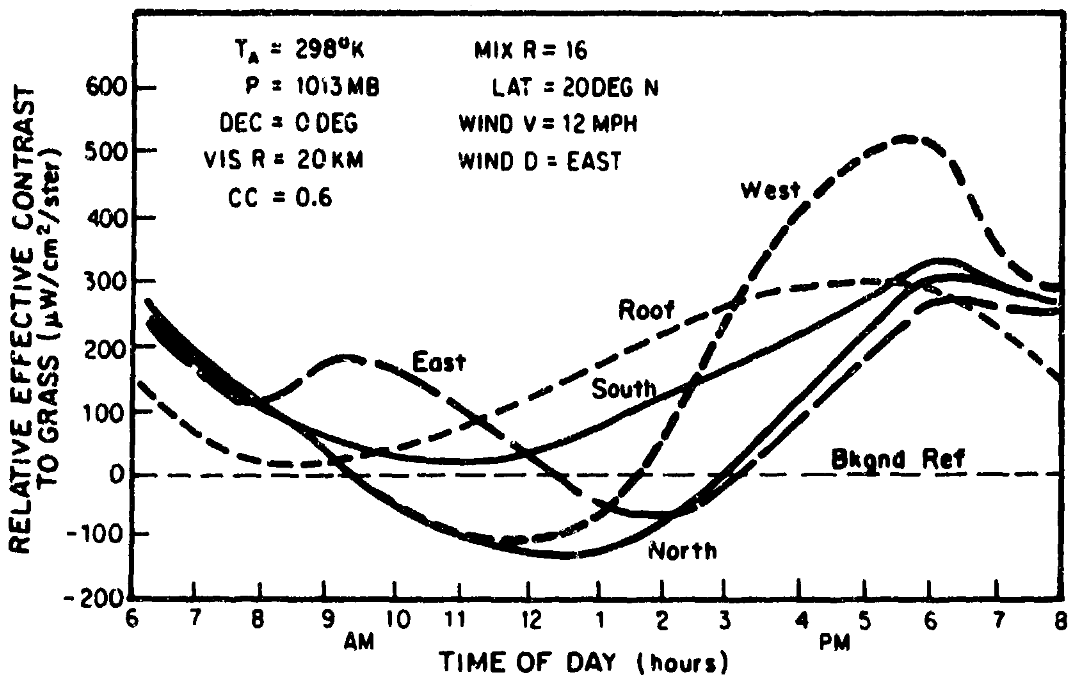


FIGURE II-29. EFFECTIVE RADIANT CONTRAST BETWEEN THE TANK AND THE GRASS BACKGROUND AS A FUNCTION OF TIME OF DAY FOR VARIOUS VIEWING DIRECTIONS IN THE 8- TO 12-μm SPECTRAL BAND

F. PERFORMANCE OF RADAR SURVEILLANCE AND TARGET ACQUISITION SYSTEMS

1. How Much Can Radar Really Do?

Radar was originally developed to detect and track enemy aircraft. In this application, the antenna is pointed up at a quiet medium, the sky, and target discrimination is based on the amplitude of the return: any received signal larger than the very uniform background noise was interpreted as an aircraft. Before long, it was recognized that radar in an aircraft receives recognizable returns from the ground below that can be used to aid navigation. Radars were also adapted to look for ships at sea, both from flying aircraft and from ships. In all these cases, the radar is either looking for a single or a very small number of isolated localized returns in a quiet or featureless background of environmental or circuit noise; or else it is looking at interrelations among the returns due to scattering by the environment itself. Under these conditions, target detection and identification are relatively straightforward and a good estimate of radar performance can be based on calculations.

Detection, location, and identification become much more complicated when a radar must "look down" at small non-cooperating targets such as combat vehicles. The radar receiver accepts all back-scattered signals without "knowing" which are the target returns and which are the undesired or "clutter" returns. The returns from terrain features are large and are found in almost every part of the radar's field of view. For stationary targets of reasonably large radar median cross-section (RCS), such as 100 square meters or greater, the "target" return may appear as a bright spot on the display if the clutter rejection is good and if there are no other bright spot returns to confuse the operator. However, a target with an RCS of 100 square meters is relatively large, and even so, many clutter highlights are even larger.

Here we confront the basic dilemma of radar detection: how is the display to be interpreted? How does one pick out the real targets from all the clutter and other returns?

Once the technology has been exploited, the answer lies in the experience and knowledge of the operator or interpreter of the radar display. If he has seen a great many examples of vehicles in a given terrain on a display and has correlated these images with a "ground truth" provided by photographs or ground observers, he may be able to identify some ground targets correctly. Such skill in radar interpretation depends on integrating knowledge and experience far outside of the study of radar circuitry and signals.

Battlefield radar interpreters are frequently combat tactics and equipment specialists whose experience is used to spot the "cues" contained in radar display target groupings and locations to make the detection or identification decision. They usually work closely with collateral intelligence inputs which provide background data on the terrain, disposition, and movements of enemy equipment. The integration of these data can provide the basis for the combat commander's decision if conditions are such as to make radar the principal source of battlefield information.

It would be useful if the target returns from a single object could help the operator discriminate among classes of targets, but the resolving power of most radars is too low. Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radars (SLAR) are somewhat of an exception. Under good viewing and low clutter conditions, these radars can resolve stationary vehicle targets. They not only can detect multiple highlights but also can show their relative position, distinguish the narrow from the long dimension of a vehicle, and estimate its gross physical size. If the target is roving, the motion itself can be detected, but the resolution of the radar is degraded so other clues are lost. In general, when a group of ground targets is detected, we can tell a considerable amount about their positions relative to one another, like whether they are set out in a row, or in a circle; a considerable amount about their relation to the terrain, like whether they are on a road or in a field; something about the size and shape of the larger stationary targets; and which of them are moving. However, SAR and SLAR must be flown in specially equipped, sometimes dedicated, aircraft at great trouble and expense. Even so, they yield far from perfect detection and even more uncertain identification of even large ground targets such as trucks, field artillery, and rocket-launchers. Conventional scanning radars on the ground can do even less.

Why is radar a threat at all? First, because for larger targets (say having a scattering cross-section greater than 100 square meters) it can provide battlefield detection and localization and some meager target identification clues at night and under adverse weather conditions. It provides some of the same information, somewhat less reliable and in bits and snatches, about smaller targets. It can also provide real-time observation from a platform such as a helicopter or a high ground surface surveillance post for detection of large equipment and personnel movements. When it detects at all, it yields an extremely precise range measurement. Finally, the SAR and SLAR imaging radars with high resolutions can provide strip maps of the battlefield for the interpreters and intelligence personnel to scrutinize and update their estimates of enemy disposition and action.

The radar threat is likely to increase in the future. Range, resolving power, and response time of radars will be improved. New techniques for target discrimination will be perfected and will come into general use. For example, new SOTAS has been designed to discriminate between wheeled and tracked vehicles on the basis of the spectral shape of the Doppler return. However, radar is in a mature state of development, and digital filtering and signal processing are steadily improving radar's ability to separate moving targets from stationary background and make other distinctions that enhance the detectability and identification of important targets relative to the background. With these thoughts in mind, we will proceed to describe and characterize the radar threats for ground combat targets.

2. Radar Surveillance and Target Acquisition Threats

We considered six categories of radar (Ref. 23):

(1) Airborne Imaging Radars (SAR, SLAR) with data link,

(2) Airborne Moving Target Indicators (MTI) with data link,

(3) Air-to-Surface Missile (ASM) guidance radars,

(4) Ground surveillance radars, MTI and others,

(5) Mortar and artillery locating radars,

(6) Millimeter-wave radars.

a. Airborne Imaging Radars

(1) Airborne Synthetic Aperture Radar (SAR) with Data Link. This kind of radar was specifically developed as a battlefield combat surveillance system. Airborne radars are always limited by antenna size, range, and resolution capability so that truly fine detail, less than 100' (30 m), was not generally available from such equipment. Modern SAR equipment is capable of along-flight-track resolution of 10' (3 m) at aircraft altitudes of 40,000' (12 km) and at ranges up to 10 miles (15 km). In addition, modern SAR's have MTI capabilities, but their resolution is somewhat degraded when they operate in the MTI mode. In general, SAR's are used on high-flying reconnaissance aircraft, and until recently, had the disadvantage of requiring up to eight hours to produce a processed output of the terrain surveyed. With modern signal processing advances plus an air-to-ground data link, this processing time has been reduced to a reported half-hour or less, which seems to be sufficiently short to make timely decisions regarding the target information contained in these out-

puts. A significant amount of on-board signal processing equipment is required for SAR units, and also for the ground processing stations.

A large amount of investigation and experimentation has gone into evaluating SAR's as battlefield target identifiers and locators. It is difficult to make a definitive statement regarding this capability, particularly for specific vehicle identification. However, the SAR's value in providing reconnaissance information on the disposition of vehicular and fixed equipment of Army units under conditions of night, rain, fog, or smoke is of significant value. Its greatest value is the ability to obtain a high resolution image of the target areas which provides the radar interpreter with a precise data base.

(2) SLAR. These are Side-Looking Airborne Radars, aircraft mounted, and functioning substantially in the same way as the SAR's. The difference is that instead of having a relatively small SAR antenna system, the SLAR's have quite large physical apertures up to 30 wavelengths long. These systems have been extensively developed for strip mapping and can produce high quality imagery of the surveyed terrain. Once again, their value as ground target detectors is a significant function of the observer's or radar interpreter's skill.

The problem of resolution is easily understood in terms of wavelength. The resolving power of all electromagnetic images, radars, visual and IR alike, is proportional to the ratio of aperture to wavelength. Optical and IR devices now in use depend on electromagnetic radiation with a wavelength from $3 \cdot 10^{-7}$ meters to 10^{-5} meters. Radars operate at wavelengths of roughly 10^{-2} to $3 \cdot 10^{-1}$ meters, about 10,000 times as long. (Millimeter-wave radars for specialized uses operate in the spectrum from $5 \cdot 10^{-4}$ to 10^{-2} meters, and the spectrum from 10^{-5} to $5 \cdot 10^{-4}$ meters is available for exploitation by infrared technology, but many considerations will limit its usefulness in surveillance and target acquisition.)

Considering that the aperture (antenna size) of a radar is likely to be perhaps 100 times that of an optical device, the typical angular resolving power of a radar is 100 times worse than that of an optical device, tens of milliradians rather than fraction of a milliradian. SLARS can achieve resolution of a few milliradians and SAR's, whose angular resolution is inversely proportional to distance do better at long range, but not at short range. Still, the angular resolving power of the best SLAR at ranges of several tens of kilometers is barely as good as the unaided human eye, and what can the eye resolve at 20 kilometers?

Table II-12 shows the resolution of a number of typical modern U.S. SLAR and SAR radars. Achieving this performance with a SAR is contingent on keeping the motion of the antenna straight within a fraction of a wavelength, preferably not more than 1/20 but at most 1/8, or compensating for lateral motion electronically. At 10 GHz, the wavelength is 3 cm, and the desirable standard of straightness is 0.38 cm or less deviation from true. If the desired synthetic aperture is 280 meters, the deviation from straightness is less than one part in 50,000 of the length of the synthetic aperture path, and it is a formidable challenge to fly that smoothly. At 600 mph (264 m/s) a lateral acceleration of 0.01 g for less than a second will produce such deviation. Those who have tried to write or draw on a flying aircraft and who appreciate the reason for keeping seat belts fastened in flight can understand the magnitude of the problem.

TABLE II-12

CAPABILITIES OF AIRBORNE IMAGING RADARS

AGAINST STATIONARY TARGETS

Designation	Frequency (GHz)	Angular Resolution (m/km)	Transverse Resolution (m)	Range Resolution (m)	Effective Range (km)
SLAR-1	10	7.7		15	50
SLAR-2	35	1.7		8	20
SAR-1	10		15*	15	100
SAR-2	10		6*	6	20
SAR-3	10		3*	3	15

*Distance independent.

SAR and SLAR appear to pose the greatest detection threat to ground targets since they have the highest angle and range resolution of all airborne radars. Their principal disadvantage lies in the relatively long processing delay between the reconnaissance flight and the presentation of the displayed data for interpretation. This can range from a half-hour under idealized conditions to more than eight hours under more realistic circumstances.

The comments above refer to stationary targets since, in general, currently used Airborne Moving Target Indicator (AMTI) methods tend to degrade the fixed-target resolution because of the additional signal processing involved. This will continue to be a problem at the higher frequencies, possibly exaggerated by the additional precision required for filtering or background cancellation techniques. Obviously, moving clutter such as windblown foliage is a significant factor in raising the background clutter, and further complicates the moving target problem. Anything that changes the round-trip pathlength from transmitting antenna to scatterer to receiving antenna by more than a fraction of a wavelength during the time or over the space in which processing takes place violates the assumption that this elementary picture of imaging and moving target discrimination is based on.

(3) METTRRA - Metal Target Re-radiation Radar. This is a radar based on the non-linear scattering from man-made metallic objects. When such objects are illuminated by a single frequency signal, they re-radiate harmonics as well as the originally transmitted fundamental. The ability to use lower fundamental frequency in transmission for good foliage penetration, and receive returns at higher frequency, i.e., higher resolution, suggests improved operation against ground clutter and the ability to resolve small ground targets. This equipment has been built and tested, but we do not have enough operational data to make a useful estimate of its effectiveness against ground combat targets.

b. Airborne MTI Radar with Data Link

Some characteristics of these radars are: frequencies of 10 to 50 GHz, high PRF on the order of 2000 to 5000, ranges from 10 to 20 miles (15 to 30 km), and range resolutions in the order of 50' to 100' (15 to 30 meters). They are frequently equipped with anti-jamming, anti-chaff and other ECCM capabilities. They are mounted on high-speed aircraft and frequently perform as multi-function radars, such as search and tracking, available to the pilot/operator depending upon his need. In the MTI mode, they may employ a CSC^2 (cosecant-squared) fan beam whose sweep coverage may be ±60° in azimuth and +10° to -60° in elevation.

In some equipment, beam shapes are selectable by operator switching. A number of display options are available in the cockpit, and, depending on the existence and nature of the communications link, the form of the information received at the ground station can range from operators' radio reports to an automatic transmission of coded target positions and identifications.

The MTI feature of these radars makes them high priority threats against combat vehicles and mobile missile and conventional artillery. AMTI radars have the advantage of extended line-of-sight because of their altitude, but they are complicated by the need for compensation of aircraft motion and velocity.

c. Air-to-Surface Guided Semi-Active Missiles

This designation is usually applied to an aircraft launched missile for which the aircraft provides the radar signal transmission to the target, and the return is received by a guidance receiver in the missile.

Much more accurate guidance to the target can be achieved for the air-launched missile if the launching aircraft transmits not only the target signal, but also a reference signal to the missile. The signals scattered back from the target to the missile are essentially corrections to the missile's initial guidance, while the reference signal permits Doppler recovery. A CW Doppler radar having operating characteristics similar to those discussed under the AMTI category is used. In this case, the receiver is on the missile, and the receiver scattered signal can be processed to provide greater accuracy for the terminal flight phase. In general, such missiles are launched from lower flying aircraft than reconnaissance, and against targets which have already been detected. The threat in these circumstances is the clear and short-range view the attacking aircraft has of the potential target. An effective countermeasure would require that the signal scattered back to the missile receiver be sufficiently confusing so as to change the trajectory and cause a miss. The principal threat revolves around the accuracy and operation of the launching aircraft radar and the ECCM capability of the missile's guidance receiving equipment.

d. Ground Surveillance MTI Radars

These radars are usually transporable units mounted on truck or van-like vehicles and tend to operate quite close to the FEBA at ranges inside 10 miles (15 km). A number of such units can be disposed on high ground overlooking the battlefield area and have fan beams which are swept to provide complementary coverage of the forward area. Also available are so-called manpack surveillance radars which are literally carried by troups and erected as small observation posts. The AN/PPS-5 is representative of this class of radar.

Our battlefield surveillance radars operate at frequencies from 1 to 9 GHz. The Warsaw Pact countries are reported to be pushing to higher frequencies, as high as 35 GHz. They usually have electro-mechanically scanned antennas, although some of the higher frequency modern versions have phased arrays, electronically scanned. Some units have anti-chaff and anti-clutter capability and are equipped with MTI mode options. Although U.S. versions of these kinds of radars tend to separate the search and track functions, it is reported that enemy units may combine both of these functions in a single equipment. This means that they cannot simultaneously track while scanning for other targets, a limitation which is overcome by disposing a larger number of such radars along the front which is to be surveyed. The lower frequencies of operation provide some better penetration of foliage and other clutter, but have lower-range resolution. Their most severe limitation is the large amount of ground clutter picked up in the antenna beam. Clearly, one important function of these radars is to provide target disposition and location information to artillery units, and frequently this is their principal use. It is not known to what degree their outputs are used or are useful to enemy field commanders to determine the overall battlefield situation.

e. Mortar and Artillery Locating Radars

Even the most general quantitative statements about the performance of mortar and artillery locating radars are classified. When set up and operated according to specifications, they are reported to be very reliable at detecting and determining the source of single mortar rounds and missiles. However, they must be placed close enough to get a clear look at the target at a substantial elevation angle during the rising part of its trajectory.

f. Millimeter Wave Radars

Radar designers have searched constantly for methods to produce narrow beams from relatively small physical sized antennas. In addition, target resolution capability varies directly with the wavelength of the transmitted signal. These factors have caused considerable interest in developing equipment which could operate in the millimeter wave region (Ref. 24), defined here as frequencies from 30 GHz up to 600 GHz. The principal limitations have been the availability of transmitter sources capable of producing adequate power levels in these frequency ranges, and the precise fabrication of the very small size componentry and transmission lines associated with this frequency region. This holds true also for antenna aperture surface tolerances, which must be maintained at less than one-tenth of a wavelength rms, about one one-hundredth of an inch at 100 GHz.

Recent advances have produced millimeter wave transmitter sources both in the solid state and in the more conventional tube technologies. Because of propagation losses in the atmosphere in the millimeter wave band, development of power sources have proceeded along the specific frequencies of 35 GHz, 94 GHz, 140 GHz, and 220 GHz, where atmospheric attenuation is at relative minimum. Radar transmitters usually generate their prime frequency powers at relatively low levels and then pass it through a final power amplifier (FPA) prior to transmission to the antenna. Hybrid combinations of millimeter wave tube source exciters followed by a solid state millimeter wave FPA are becoming common. Power output levels up to 20 watts CW can be achieved by this method. For the pulsed FM-CW, pulse coherent, and CW doppler radar the fundamental power source may be a varactor tuned Gunn oscillator, or a bias tuned IMPATT oscillator. Output amplifier stages can be solid state tube or hybrid types.

Compared with conventional microwave radar, millimeter wave units offer very narrow beam widths with small antennas. This leads to many desirable features such as high tracking accuracy, low angle tracking with reduced multi-path and ground clutter, small-target resolution, and high immunity to jamming. Detecting and tracking vehicular targets in ground clutter and hilly terrain has been demonstrated fairly consistently.

At their present state of development, millimeter wave radars are considerably less efficient than their lower frequency counterparts, but continued development is producing more and more feasible designs. Atmospheric attenuation and the difficulty of achieving high transmitter power limit them to short- and medium-range applications. On the other hand, their small size recommends them for many particular applications. At present they are used in seekers for airborne targets and missiles (beyond the scope of this report) and terminal guidance for air-to-ground and ground-to-ground missiles. As the development of millimeter-wave solid state sources progresses, power levels will approach those now available at X-band, and millimeter-wave radars will be very desirable for surveillance, air defense and fire control applications (although long-range performance will always be limited by atmospheric attenuation at the higher frequencies).

The circuitry in a terminal guidance system is relatively simple, for it must be cheap enough so a system can be destroyed in each mission. A typical strategy is to deliver the missile within a kilometer or so of the selected target, activate the millimeter radar and find, lock in on, and home on the largest point reflector within terminal guidance correction distance of the missile trajectory. If there is a single large truck, tank, or other massive metallic object in the search field, the homing radar will probably find it. However, if the millimeter wave back-scattering cross-sections of high-value targets have been reduced, or artificial millimeter-wave scatterers introduced, or both, the effectiveness of such a naive search strategy will probably be severely degraded. The bulk and weight of radar anti-reflecting and attenuating layers (Chapter IV, Section D) is proportional to wavelength, and screens and coatings that are quite thin could be designed to reduce millimeter-wave target strength considerably.

3. Operating Parameters of Particular Radars

The parameters of a number of radars of Warsaw Pack nations, our allies, and the United States, are readily accessible in classified sources such as References 23 and 25. An extensive tabulation of operating parameters culled from the unclassified literature is found in Reference 26, Chapter 1.

4. The Radar Detection Process

In most radars, the probability that a target will be detected is a rather steep function of the received signal-to-noise ratio, so that a reduction of few decibels in the radar target return could, in principle, reduce detection from near 100% to near 0. However, in practice, small variations in signal strengths are masked by large variations in the noise background. The signal from the target on the ground must always compete with signals from nearby ground, buildings, trees, and man-made objects other than the desired target. As shown in Reference 23, the statistical distribution of the received signal-to-noise ratio in many radars which looking at the ground targets can be approximated by a normal distribution with a standard deviation of 10 to 15 dB. Translated into a measure of effectiveness of camouflage, this means that a reduction in signal strength of 15 or 20 dB is required to reduce the probability of detection of a target from 75% to 25%, or that 1 dB of reduction in effective signal-to-noise ratio is worth at most 2% or 3% reduction in detection probability. For example, let us assume a simple radar in which the signal strength is proportional to the fourth power of range, and plot probability of detection in percent as a function of distance. The result is shown in Figure II-30. It comes as a surprise to discover how closely this resembles the curves in Figure II-12. In all three curves, the range must be increased about six times to reduce the detection probability from 90% to 10%, and the range to 50% probability of detection is slightly closer than the midpoint between 10% and 90%. Thus, in spite of the fact that the process of detection and recognition by the human eye and the radar detection process are very unlike, the overall result is much the same.

5. Important Target Parameters

The parameters that affect radar target detectability most are those which affect the signal-to-noise ratio. When a clear path exists between radar and the target, the target scattering cross-section is the only target parameter that influences the received signal. The signal-to-noise ratio is also strongly affected by returns from the immediate neighborhood of the target. As shown above, the resolving power of most radars at reasonable operating ranges is likely to be measured in tens of meters, so the "immediate neighborhood" of the target is rather a large region. This gives the defender of the target considerable latitude in choosing the location among objects on the ground that will produce a high level of clutter background at the radar receiver.

A radar can produce an accurate map of the spatial patterns among units in a cluster, for unlike the eye, it has good range resolution as well as useful angular resolution. As a result, configurations such as the layout of guns in a battery may become revealing detection and identification clues. In higher resolution radars, radar detectability

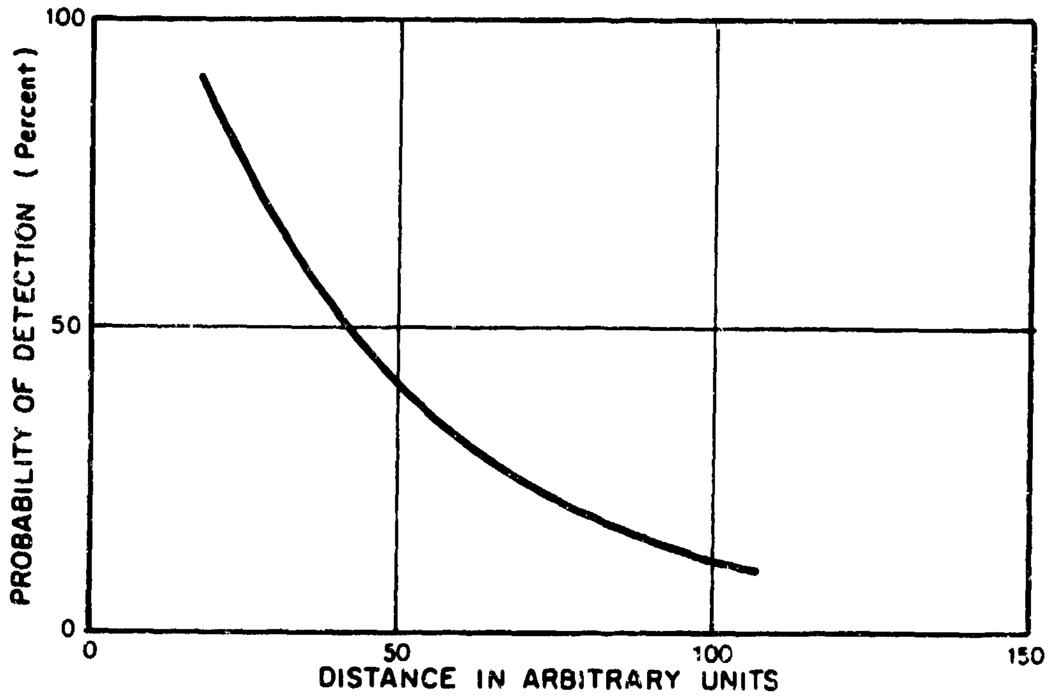


FIGURE II-30. DETECTION PROBABILITY AS A FUNCTION OF DISTANCE FOR A RADAR WHERE SIGNAL IS PROPORTIONAL TO THE FOURTH POWER OF DISTANCE AND SIGNAL TO NOISE RATIO IS NORMALLY DISTRIBUTED WITH A STANDARD DEVIATION OF 12.5 dB will also be influenced by factors that modulate the scattering cross-section. These factors include highlights, curvature, surface roughness, and the aspect angle which controls how these will be perceived. In the very highest resolution synthetic aperture radars and possibly in other radars at a very short range, shape of individual units may be significant. Shape may also be significant if the target is very large, like a building, or is conspicuously related to a natural feature, like a bridge crossing a river. The time resolution of radar is excellent, and radar signal processing is very sensitive to motion. This can be turned to advantage with moving-target-indicator circuitry which has the effect of wiping out or much reducing returns from targets that do not move so that returns from moving targets can be more readily perceived. Unfortunately, MTI circuitry obliterates many of the clues that radar relies on for target identification, and in a complex environment target identification is already one of the weak links in the generation of useful information by radar. The image-forming signal processing in synthetic aperture radars is incompatible with moving target analysis and the return from a target in motion is reduced or, occasionally, spuriously translated to a false location on the display.

G. SEISMIC AND ACOUSTIC DETECTION SYSTEMS

Firing a large gun creates a mechanical disturbance that radiates sound waves in the air and micro-seismic vibrations in the ground. The acoustic effect of the blast of hot gas from the barrel can be reduced somewhat, but there is no way to emit an object the size of an artillery shell at supersonic velocity without creating an acoustic shock-wave, nor is there any way to balance the momentum of the shell except by transmitting an impulse to the ground. These acoustic and seismic waves are used to detect and localize firing guns.

If the time of firing can be established by visual or infrared detection of the blast, the time of arrival of the acoustic or seismic impulse at two or more sensors suffices to localize the source. If the time of the blast is not known, hyperbolic (time-difference) localization is possible with three or more sensors. The atmospheric propagation of sound waves is erratic because variations in density due to temperature and humidity gradiants refract the waves, wind displaces them, and turbulence disturbs the coherence of the wave-fronts. Seismic propagation is erratic because the ground is not homogeneous and its elastic properties vary from place to place. Consequently, acoustic and seismic gun localization are unreliable and inaccurate. The shortcomings can be partly overcome by using a larger number of detectors spread over a large space with signal-processing that uses the redundant signals to smooth out some of the errors introduced by the vagaries of propagation; but they are aggravated by the longer standoff ranges at which modern military operations are carried out, which are themselves the result of longer weapon ranges and longer effective ranges of other types of sensor systems.

For everyday use to localize artillery, acoustic localization is the best there is. Localization within 100 meters at distances of several kilometers is typical. Under battle conditions, system saturation due to receiving signals from many sources is a real handicap, and it is difficult to sort out the impulses from a single source at multiple sensors without a preliminary idea of the source location, which makes "first round" localization especially difficult. It has been reported* that in World War II and the Korean and Vietnam conflicts, four-fifths of the artillery localizations that were made were made in the acoustic sound ranging. But in spite of acoustic sound ranging being the best there is, it is not highly effective and it is unlikely to get substantially better because the limitation is in the acoustic propagation itself, not in the instrumentation or the signal processing.

Acoustic and seismic detection are also used to detect and localize items of equipment other than guns. Many vehicles and pieces of equipment make a lot of noise and shake the ground. They are easily detected at

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*Verbal communication from MERADCOM.

ranges up to a few hundred meters by the human ear or a locally emplaced (telemetered) sensor. (Long range propagation--kilometers--is sporadic and is not to be relied on, however tantalizing.) The motor-generator sets required by modern missile systems like Patriot are easily detectable by the unaided ears of covert patrols and guerillas.*

It must also be remarked that some of these pieces of equipment are outrageously noisy. The noise level around some pieces of equipment is so high that personnel working in the vicinity must wear ear protectors to avoid damage to their hearing. Such high noise levels are absurd. Experience with submarines, where acoustic signatures are very effective clues for detection, localization and target identification, has shown that machinery can be designed to radiate dramatically less noise without impairing its efficiency or effectiveness. In fact, once the knowledge of how to do it has been mastered, the machinery may be more efficient and wear much better because of reduced vibration. Almost any vehicle allowed on a public highway today must be designed so that its machinery and exhaust noise is less than its tire and aerodynamic noise at cruising speed. The machinery in a patrol quiet submarine is so quiet that crew members must wear padded overshoes to keep their footfalls down to the same noise level.

As long as vehicles and machinery are as noisy as the noisier pieces of field army equipment, there are many reasons, including acoustic and seismic detectability, for making them quieter. However, it would probably be a distortion to claim camouflage as the primary reason for doing it.

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*Verbal communication from MERADCOM.

H. SURVEILLANCE AND TARGET ACQUISITION SENSOR DEVELOPMENT TREND SUMMARY

Enemy technology has advanced in recent years and is posing increased threats to existing levels of Army camouflage. Advances have been made in essentially all sensor areas including:

- the human eye,
- electromagnetic imagers with visual readout,
- photographic systems,
- lasers,
- radar, and
- acoustic and seismic detectors.

1. The Human Eye

a. Unaided

There is essentially no change in the characteristics of the human eye.

b. Binoculars, Telescopes, etc.

Poland and the USSR have and are still developing higher quality binoculars and telescopic optics. Specifications on the performance of binoculars, telescopes, periscopes and other human eye aids approach those of the United States. In quantitative terms, however, performance improvements will be small, for the performance of today's instruments is not far from limits imposed by physics. Periscopes are implemented technology in the USSR.

c. Search Lights and Night Lights

The Soviets are reported to have been developing Xenon arc discharge lamp technology. This will allow them to increase the range of their search light systems. See also 3a below.

d. Optical Range Finders

The USSR is developing improved optical range finders for use with their large-caliber-gun fire control systems. Again, the quantitative performance improvement is not expected to be great.

e. Overall Trend

The properties of the eye will not change, and improvements in optical instruments will be minor.

2. Electromagnetic Imagers with Visual Readout

a. Combat Television

Soviets, Poles, East Germans, Hungarians, and Czechoslovakians now use TV systems for ground surveillance. Such information is telemetered back to central headquarters at considerable distance. TV's are also used in reconnaissance aircraft.

b. Low-Light TV

The USSR has improved the reliability, ruggedness, and spectral response of low-light TV. As the technology matures and applications spread, considerable performance improvement is anticipated.

c. Image Intensifiers

The USSR has also made substantial progress in the development of multi-stage image intensifier tube detectors. Beyond 1980, this implies that one should expect a profusion of passive sights and vision aids replacing active search lights used for tracking and gun alignment. Small goggles for drivers requiring second generation intensifier tubes are also reported to be available to the Soviets.

d. The Near IR

Most of the USSR's IR equipment is in the near IR range. Advancement of Xenon lamp technology is improving their active near IR night vision aids significantly. They are also using metascopes, but generally their range is relatively limited.

e. Thermal IR

The developmental status of USSR military thermal imaging technology in the thermal IR spectrum is not known. It is believed they have a classified thermal imaging program underway and that they have the ability to implement thermal imaging systems at the airborne reconnaissance level and also at the satellite reconnaissance level. There is considerable interest, and it is expected that the USSR's thermal imaging project will represent a direct threat to our camouflage efforts by the end of 1983. They are also fielding uncooled and moderately cooled thermal homing devices for terminal guidance.

f. Overall Assessment

The quantity and availability of low-light, remote and near IR imaging systems with visual readout will increase, and their performance will improve incrementally. USSR's thermal IR imaging instruments are not yet a serious threat, but will be a direct threat soon, probably by

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3. Photographic Systems

a. Cameras, Optical Components and Film in General

In terms of resolution and photographic capabilities, the quality of most Soviet cameras and film can be described as ranging from adequate to good. Both frame and strip cameras are being used for low-altitude reconnaissance. High-altitude reconnaissance is being performed by frame cameras. The USSR has also developed special cameras for night reconnaissance. It is also suspected that newer, higher quality cameras are being developed or have been developed by the Soviets. In conjunction with the East Germans, it is quite likely that better optical components have been designed and developed. In addition, the quality of Soviet film has improved considerably both in false color compatibility and sensitivity. They have increased ability to detect camouflage with their Spectrozonal film.

b. Camouflage Detection Film

The USSR has made advances in false color IR film approximately equivalent to Kodak's aerochrome IR film. With it they can detect targets that are concealed in natural foliage and vegetation and unconcealed vehicles that may be pattern painted only.. It is expected that the existing reconnaissance system in the IR range is not effective to a large degree against equipment painted with improved IR reflective paint or covered with lightweight net systems.

c. Thermal IR

See 2d above.

d. Multi-Spectral Narrow-Band IR

Multi-spectral narrow-band infrared--both photographic and direct reading--are more sensitive to differences in spectral reflectivity between target and background than are broad-band color and pseudo color. The USSR has multi-spectral narrow-band equipment in the field, and continued improvements are anticipated.

e. Overall Assessment

Substantial incremental improvements in cameras, optical systems, platforms, and processing will lead to steady moderate improvements in the capability of USSR photographic systems. The spectral range is being extended gradually toward longer wavelengths. For thermal IR, see 2d and 2f above.

4. Lasers

a. Laser Illuminators

It is suspected that laser illuminators may be used as the visible or near IR source of radiation for active night vision systems. This may replace the tungsten filament IR search lights now being used which also may be replaced by the Xenon filament search lights.

b. Laser Target Designators and Beam-Riders

It is believed the Soviets already have target designators to allow bombs to home using laser-reflected energy. Soviets' YAG technology is judged equivalent to that of the United States. Advances in closely related beam-rider technology are potentially comparable.

c. Laser Range Finders and Lidars

Reports of a USSR tripod-mounted laser range finder have been confirmed. Indications are that it is in widespread use among grouped Soviet forces in Germany. There may also be laser range finders mounted on Soviet tanks. Advances in very similar lidar technology should be expected to be comparable.

d. Overall Assessment

In general, USSR laser technology is evolving rapidly, with corresponding performance gain.

5. Radar

The USSR has ground-to-ground radars that are straightforward, reliable and should be considered very effective. These ground radars have considerable range given the fact of high clutter background, and large numbers of them are in use. The Soviets are known to have counter-fire radars, and at this point it is hard to assess their full capabilities; but they should be considered a future threat to camouflage programs. The air-to-ground radar threats posed by the Soviets should be considered serious. They have been assessed as having MTI capability. They also have side-looking airborne radars with real time TV data links. Some of the airborne radars are also being utilized by helicopters. The frequency capability of USSR radars is expanding into the millimeter range because of an active program in improving and developing their microwave tubes, and they are also applying low-power millimeter wave radar to missile terminal guidance. It is expected that they will have improved airborne radars for reconnaissance missions by 1986. It is also expected that airborne and battlefield surveillance radars will have higher power and greater frequency range including the option of multi-mode operation and techniques to enhance clutter rejection. Generally, noise figures for both transmitters and receivers will be improved.

6. Acoustic and Seismic Detectors

The USSR's acoustic and seismic technology is outstanding, but the opportunities to apply it to battlefield surveillance and target acquisition are limited. According to some sources, continued improvement in their current sound ranging systems is forecast. The improvements will occur both in set-up time and computation time, and by 1985 the Soviets may have compact sensors with narrow band spectrum capability, signal processing and Doppler capability. Even if this improvement takes place, the absolute performance level of the equipment will probably not be a serious threat.

The unaided ear is still a threat, but no improvement in performance can be anticipated. Improvements in unattended ground sensors are imaginable, but we have no information about current trends.

Apparently, no significant seismic sensor activities are deployed by the Soviet/Warsaw nations for Army surveillance application; thus, there does not appear to be any new threat in the near term.

I. TARGET PARAMETERS THAT MOST AFFECT SENSOR SYSTEM PERFORMANCE

Obviously, many different target parameters affect the performance of the various kinds of surveillance and target requisition sensor systems. They can be grouped in some general categories, as shown in Table II-13. Each row represents a class of sensor systems, each column a class of target parameters. The key to the entries in the table is:

X Important
x Less important
I Identification only
(1) Gun flashes
0 Detracts from or degrades performance

TABLE II-13

TARGET PARAMETERS THAT MOST AFFECT SENSOR SYSTEM PERFORMANCE

SENSORS	TARGET PARAMETERS: Size, subtended solid angle, scattering cross-section, etc.	Contrast, signal-to-noise ratio	Color, spectral reflectance, interaction with polarization	Intensity, total emissivity, signal-to-noise ratio	Spectral emission, color	Shape, outlines, etc., of individual units	Spatial patterns among related units	Highlights, features, curvature, surface roughness, aspect angle	Motion, Doppler shift	Travel time	Temporal modulation—duration, frequency, pulse shape, repetition rate
EYE, unaided or aided with binoculars, telescopes, etc.	X	X	x			I	I		x		(1)
as specialized sensor in theodolite, range finder or guidance system	x	X	X			X		X	x		0
as sensor of photographs or in image conversion systems	X	X	X			X	X	x	0		x
CAMERA, black and white or infrared	X	X				X	X		0		0
color or pseudo-color	X	X	X		X	X	X		0		0
IR DETECTORS & IMAGERS--FLIR's and line scanners at LWIR, MWIR & SWIR	X	X	x	X	x	x	X	X	x		
REMOTE AND LOW-INTENSITY IMAGERS at visible, VSWIR and some SWIR	X	X			x	X	X		X		x
RADAR, scanning, no MTI	X	X					X	X		X	x
scanning, MTI	X	X					x	x	X	X	0
synthetic aperture	X	X				X	X	x	0	X	0
millimeter wave	X	X				x	x	x		X	
LASER, range finder and lidars	x	X	X					X		X	
target designators and beam-riders	x	X	X					X			
ACOUSTIC				X	X					X	X
SEISMIC				X	X					X	X

*KEY: X - important x - less important; I - identification only; (1) - gun flashes; 0 - detracts from or degrades performance.

III. ABOUT THE TARGET

A. INTRODUCTION

For the purposes of this study, the targets at risk are the items in the so-called CC and CS lists, more completely, "Categories of Materiel Items and Systems Designated Camouflage Critical (CC)" and "Categories of Materiel Items and Systems Designated Camouflage Sensitive (CS), issued by Headquarters AMC, AMCRD-SE, 11 December 1975. These lists are reproduced in Tables III-1 and III-2. The items on the Camouflage Critical and Camouflage Sensitive lists are arranged in order of decreasing priority within each list. Overall, the items on the Camouflage Critical list have a higher priority than items on the Camouflage Sensitive list and clearly reflect the Army's requirement to be prepared for nuclear conflict. Although the lists do not purport to be exhaustive, they contain all of the items of major importance to the Army and one or more items closely similar to any other Army materiel item or system to be expected on the battlefield. Thus, with minor and obvious generalization, they can be applied to be effectively all-inclusive.

For study purposes, the CC and CS lists have certain limitations in their raw form:

- The lists are too long and extensive for individual treatment of each item. While ideally it would be good to devise a camouflage solution tailored to each equipment item, practical considerations preclude this course of action.
- The lists are essentially a prioritized reflection of the need to preserve critical assets. They do not account for differing characteristics, vulnerabilities, missions, battlefield locations, etc., which bear on the solution to the camouflage problem.

TABLE III-1

CATEGORIES OF MATERIEL ITEMS AND SYSTEMS DESIGNATED CAMOUFLAGE CRITICAL

DESIGNATION	ITEM/SYSTEM
CC1	Nuclear Delivery Means
CC2	Air Defense Systems
CC3	Army/Corps/Division Tactical Headquarters
CC4	Data Centers or Centrals Associated with Higher Headquarters
CC5	Combat Vehicles and Armored Carriers
CC6	Aircraft, Assault, Attack and Scout

EXAMPLES OF CAMOUFLAGE CRITICAL (CC) ITEMS AND SYSTEMS

CC1 NUCLEAR DELIVERY MEANS

A. Missiles
Pershing, Lance.

B. Guns
Towed 155mm M114A1, 155mm XM198

Self Propelled 155 mm M109A1, 8 inch M-110 & M110E2

C. Special Ammunition Supply Points
Nuclear Warheads

CC2 AIR DEFENSE SYSTEMS

A. Guided Missiles
Chapparal, Hawk, Nike-Hercules, Redeye, PATRIOT, ROLAND, SAM-HIP, Stinger, ATAADS

B. Guns
Gun Air Defense Artillery 20mm, SP-M-163, Towed M-167 (Vulcan).

CC3 ARMY/CORPS/DIV TACTICAL HEADQUARTERS

Antennas - Modified Ground Plane and Dish Types

Heaters - Space - 45,000 BTU and 400,000 BTU

Field Range, Gasoline Fired, 50 men multiples

Generator Sets, Gasoline or Diesel Engine 30 and 45 KW

Tents - Gen Purpose - Med, Kitchen, and Frame Type Maintenance

Carrier Command Post M-577

TABLE III-1 (Continued)

DESIGNATION	ITEM/SYSTEM
CC4	DATA CENTERS OR CENTRALS ASSOCIATED WITH HIGHER HEADQUARTERS
	Tactical Fire Direction System (TACFIRE), Tactical Operations System (TOS), Air Defense Command and Control System AN/TSQ-73 (Missile Minder).
	USASA Control and Analysis Centers (CAC)
	Communications Technical Control Centers AN/TSQ 83 and 84, Combat Service Support System (CS 3).
	Tactical Communications Switching Centers.
	Topographical Support System (Data Base Module) (including Antennas, Masts, and Dishes).
CC5	COMBAT VEHICLES AND ARMORED CARRIERS
	A. Tank Combat Full Tracked Combat Engineer Vehicle, M-728 105mm Gun M60 Series, 152mm Gun M60A2, XMI.
	B. Carrier Personnel Full Tracked Armored M-113 Series, Mech Inf Combat Veh (MICV).
	C. Carrier Command and Reconnaissance M-114 Series, Armored Recon Scout Veh (ARSV).
	D. Other Carriers For 81mm Mortar - M125AL, for 107mm Mortar M-106, M206A1. For Flame Thrower - M-132, M132A1 for Chaparral GM, M730. For TOW, M236.
	E. Recovery Vehicle Full Tracked (Armored) M806, M88, and M578.
	F. Carrier Assault or Anti-Tank Armored Recon Airborne Asslt Veh (ARAAV) M551, Vehicular Mtd TOW. Vehicle Rapid Fire Weapons Systems (Bushmaster), Hyper Pressure/Hyper Velocity 105mm Gun, Vehicular Mtd 106mm Recoilless Rifle.
	G. USASA SIGINT Collection and Electronic Warfare Facilities.
	H. Division and Corps Area Communications Shelters.

TABLE III-1 (Continued)

DESIGNATION	ITEM/SYSTEM
CC6	AIRCRAFT, ASSAULT, ATTACK AND SCOUT
	A. Helicopter - Attack AH-1 Series, Advanced Attack Helicopter (AAH).
	B. Helicopter - Observation OH-58 Series, OH-6, Aerial Scout
	C. Helicopter - Utility UH-1 Series (HUEY), UTTAS.
	D. Aircraft Observation OV Series
	E. Forward Area Refueling Equipment (FARE)
	F. Forward Area Refueling and Rearming Point (FARRP).

NOTE: Each of the above designations include the essential support equipment which is necessary to provide a full operational capability or a total systems capability.

TABLE III-2

CATEGORIES OF MATERIEL ITEMS AND SYSTEMS DESIGNATED CAMOUFLAGE SENSITIVE

DESIGNATION	ITEM/SYSTEM
CS 1	Field Artillery and CB/CM Radar
CS 2	Radar - Ground Surveillance
CS 3	Brigade and Battalion HQ
CS 4	Anti-Tank Devices, Ground Mtd.
CS 5	Infantry Equipage and Fighting Positions
CS 6	Ammunition Supply Points
CS 7	Tactical Pol
CS 8	Aircraft - Support
CS 9	Tactical Bridges
CS 10	Trucks - Tactical and Logistical
CS 11	Combat Engineer Equipment
CS 12	Division Support Command
CS 13	Army Wide Items (High Signature)

EXAMPLES OF CAMOUFLAGE SENSITIVE (CS) ITEMS AND SYSTEMS

CS 1 FIELD ARTILLERY (CONVENTIONAL ROUNDS) AND CB/CM RADARS

A. Howitzers and Guns

Towed	SP
105mm M101, M102, XM204	M107

B. Radars Counter Battery/Counter Mortar
AN/MPQ-4, AN/TPQ-36, AN/TPQ-37

CS 2 RADAR - GROUND SURVEILLANCE

Radar Sets AN/TPS-25, AN/TPS-33, AN/TPS-58, AN/PPS-5, AN/PPS-15 and AN/TPS-58A.

TABLE III-2 (Continued)

DESIGNATION	ITEM/SYSTEM
CS 3	BRIGADE AND BATTALION HQ* Antennas - Ground Plane or Dish Heaters - Space - 150,000 BTU, 250,000 BTU and 400,000 BTU. Heaters - Immersion - Liquid - Fuel Fired. Intrenching Outfit - Infantry Stove - Gasoline Burner, Heavy Duty, 5000 BTU per Head. Field Range, Gasoline Fired, 50 Men Multiples Generator Sets, Gasoline Engines 1.5, 3, and 5 KW Radio Sets, AN/VRC-46, 47, 49, 64, and GRC-106 (Van). Trucks and Vehicles - Utility, 1/4T, Cargo, 3/4, 1-1/4, 2-1/2, 5T Ambulance - 1/4T, Wrecker 5T, Van 2-1/2T Fuel Service 2-1/2T, Water Tanker 400 gal, 2-1/2T, and Trailers - 1/4, 3/4 and 1-1/2T.
CS 4	ANTI-TANK DEVICES, GROUND MTD. Dragon, M202, TOW, LAW.
CS 5	INFANTRY EQUIPAGE AND FIGHTING POSITIONS A. Clothing and Equipment Coat, Shirt, Trousers (Man-Utility) in Tropical, Cold Dry, Cold Wet, Chem Protective, Camouflage Patterned, Overwhite, Raincoat and Poncho Versions, Underclothing and Handkerchiefs. Boots, Combat Black, and Insulated Cold-Wet-Black. Armor, Body Frag Prot, Nylon and Titanium/Nylon, Helmet Steel and Helmet Lightweight. Equipment, Load Carrying, Rucksack, Pack & Ammunition Vest and Frame LINCLOE. Gloves, Wet or Cold. Covers - Intrenching Tool, Canteen, Ammo Pouch, First Aid Kit. B. Tents and Shelters Shelter Half, 2 Man Tent, 5 Man Tent, 10 Man Tent (Arctic), and Sleeping Gear Cold Weather. C. Small Arms. D. Crew Served Weapon Lightweight Company Mortar System, 60mm XM-224, 60mm M-19, 81mm M29A1, 4.2 in M-30.

*Note: Items common to CS3 and CC3/CC5 will use designation of CC3.

TABLE III-2 (Continued)

DESIGNATION	ITEM/SYSTEM
CS 6	AMMUNITION SUPPLY POINT Small Arms Ammunition, Mortar, Howitzer, Artillery Projectiles, Rockets, Missiles.
CS 7	TACTICAL POL A. Bulk Storage (Includes Tank Farms, Manifolds, Pumps, etc.) Tank, Fabric, Collapsible, 1250 BBL, 10,000 and 50,000 Gal, Bolted Steel Tank 10,000 BBL. B. Pumps 6" and 8" Diesel Driven; 50, 100, 350 GPM, 6 in. 2 Stage Pipeline Pump; 6" and 8" Flood and Transfer, 8" High Pressure Turbine Driven. C. Pipelines 6" and 8" Lightweight Coupled; 6" High Pressure Hoseline; 6", 8" and 12" Fiberglass Reinforced Line. D. Fuel Dispensing Systems CL III Supply Point, 12 Point Helicopter Fueling System, Airfield Refueling System. E. Laboratories (Fuel Analysis) Lab, Airmobile, Aviation Fuel (Semi-Trailer).
CS 8	AIRCRAFT - SUPPORT A. Helicopter Cargo Transport CH47 (Chinook) Series, CH54 Series B. Heavy Lift Helicopter (HLH)
CS 9	TACTICAL BRIDGES A. Mobile Assault Bridge (30 ft). (Floating) Armored Veh Launched Bridge (60 feet). Bailey Bridge B. Ribbon Bridge (Floating). Med Girder Bridge (MGB) 100 ft. Class 60. Armored Veh Launched Bridge (90 feet).
CS 10	TRUCKS - TACTICAL AND LOGISTICAL 1/4T, 1-1/4T, 2-1/2T, 5T, 10T, HET, and GOER (All Body Types - Emphasis on Utility, Cargo, Dump, Wrecker, Ambulance, Firetruck, Fuel Service, Water, and Vans - Expansible).

TABLE III-2 (Continued)

DESIGNATION	ITEM/SYSTEM
CS 11	COMBAT ENGINEER EQUIPMENT A. Dozers Tractor, Full Tracked, Low Speed, Medium, Light Airmobile, and Sectionalized Classes. Universal Engineer Tractor (UET), FAMECE, Heavy, Medium and Light Tractors. B. Cranes 5T Rough Terrain, 20T Rough Terrain, 7-1/2T Rough Terrain, 20T Hydraulic. C. Machine, Ditching, Wheel Mtd, Rough Terrain, Parsons, Unit Rig D. Loader Bucket 1 cu/yd, 2-1/2 cu yd, 4-1/2 cu yd. E. Graders Medium, Heavy, and Sectionalized Medium. F. Commercial Construction Equipment (CCE) EXEMPT - except for items forecast for issue to combat units in forward areas. G. Water Purification Equipment
CS 12	DIVISION SUPPORT COMMAND A. Shops, Shelters, Tents Shops, Contact Maintenance, Electrical Repair, Electronic Repair, Gen Purpose Repair, Hydraulic Repair and Other. Shelters - Kitchen 8x8x20 ft. Tents - Small, Med, Large, Extra Large B. Containers - Shipping and Storage MILVAN, Ammo 8x8x20, Optimized, Family of Ammo Containers, Dry Cargo 8x8x20, Refrigerated Cargo 8x8x20. TRI-CON, 8x8x6-2/3, 4x8x6-2/3, and 8x8x40 feet. C. Materiel Handling Equipment Rough Terrain Fork Lift or Fork Trucks 2,500, 6,000, 10,000 and 15,000 lb cap, Rough Terrain Crane 50,000 lb cap, Cargo Handler (Man-Amplification) 60T capacity.

TABLE III-2 (Continued)

DESIGNATION	ITEM/SYSTEM
CS 13	ARMY WIDE ITEMS (HIGH SIGNATURE)
	Engine Generators, Gasoline Engine (0.5 to 10 KW).
	Engine Generators, Diesel Engine (15 to 60 KW)
	Antennas - Radio or Radar (MAST, Aerial, or Dish).
	Kitchen, Field (and Immersion Liquid Heaters).
	Shower Units, Field (with Heaters).
	Engine Generators, Gas Turbine (10 to 60 KW).
	Air Scatterable Land Mines, Special Ammunition.

- Dual-purpose weapons systems (nuclear/conventional), e.g., 8-inch Howitzers, are found on both lists, and satisfaction of the CC requirement also meets the CS requirement.
- The lists, by definition, are materiel oriented and do not address the types and missions of Army units which use the materiel. In fact, mission plays an important role in determining camouflage needs and the practicality of fulfilling those needs without undue detraction from mission accomplishment. To this extent, an appropriate ground rule would seem to be: "the purpose of camouflage is to enhance mission accomplishment." As a corollary, camouflage measures, even if so extensive as to virtually preclude detection, which at the same time unduly hamper operational capability, are counterproductive.

In view of these limitations, the CC and CS lists have been subjected to review and analysis in order to translate the material therein into more useful form. The results are discussed in the following paragraphs.

B. CATEGORIZATION CRITERIA

A set of target categorization criteria has been devised to allow grouping of items on the CC and CS lists into target classes having common characteristics. The criteria are of two types: general and sensor specific. (See Table III-3.)

1. General

The five general criteria are size, location, mobility, detection value, and signature. Size includes physical size and also those attributes of the target which determine whether the signal it creates in a detection sensor will be large or small. Thus, with respect to visual observation, it includes consideration of subtended solid angle and contrast; with respect to radar observation, it includes consideration of scattering cross-section; with respect to thermal IR observation, it includes consideration of amount and effective temperature of thermal emission, etc.

TABLE III-3

TARGET CATEGORIZATION CRITERIA

I. GENERAL

A. SIZE - physical dimensions or distribution on the battlefield.

Diffuse - distributed throughout an area measured in hundreds of square meters to square kilometers in low enough density to minimize vulnerability to shelling or bombing, e.g. deployed Infantry Brigade.

Large - measured in hundreds of meters square, e.g. Corps Tactical Headquarters.

Medium - measured in tens of meters square, e.g. 155-mm Howitzer Battery.

Point - measured in meters square, e.g. Counterbattery Radar.

B. LOCATION - proximity to FEBA determining vulnerability to ground as well as airborne sensor platforms or airborne sensor platforms only.

Front - vulnerable to ground and airborne sensor platforms, e.g. Mechanized Infantry Company.

Rear - vulnerable to airborne sensor platforms only, e.g. Division Tactical Headquarters.

C. MOBILITY - frequency of movement during normal battlefield operations.

High - measured in minutes to hours, e.g. Tank Company.

Medium - measured in hours to days, e.g. 8-inch Howitzer Battery.

Low - measured in days to weeks, e.g. Army Tactical Headquarters.

D. DETECTION VALUE - degree to which detection would allow target acquisition and engagement as opposed to battlefield surveillance.

Targeting - within range of enemy artillery and short-range missile systems, e.g. 155-mm Howitzer Battery.

Surveillance - indicators of operational plans, but requiring aircraft or long-range missiles for target engagement, e.g. Corps Tactical Headquarters.

TABLE III-3 (Continued)

E. SIGNATURE - degree to which shape and/or location and/or physical phenomenon associated with use, e.g. gun flash, gives cue to identify.

High - reliable cue without further verification, e.g. HAWK Anti-Aircraft Battery.

Medium - verification may be required, e.g. resemblance of Tanks and Self-Propelled Artillery.

Low - sufficient commonality of equipment that association with specific type unit or use is difficult, e.g. Quartermaster Truck Company.

II. SPECIFIC

A. Visual Vulnerability - probability of visual (aided and unaided) detection based on qualities of size (range), usual location on the battlefield, contrast, shape, color, and mobility. (To an extent, the criterion of "signature" covers some of these same qualities.)

High - operates near FEBA where visual surveillance is most concentrated and/or moves frequently and/or has color or shape which stands out from background.

Medium - normally not subject to direct ground observation but vulnerable to airborne stand-off visual sensors and/or has medium degree of mobility and/or has color or shape that blends with background when not moving.

Low - subject only to long-range airborne sensors and/or low degree of mobility and/or color or shape that is easily blended with background.

B. VSWIR Vulnerability - degree to which size, location, shape, and VSWIR contrast will contribute to detection by imaging systems using scattered light in the VSWIR spectrum.

High - operates near FEBA within short and medium line-of-sight range, where recognizable images will be formed, with sufficient contrast from background to result in detection.

Medium - not generally within line-of-sight range of detectors, either because of distance or because of operation under concealment; poor VSWIR contrast, non-distinctive signature.

Low - normally out of sight or out of range of VSWIR imaging sensors.

TABLE III-3 (Continued)

C. SWIR VULNERABILITY - degree to which target characteristics contribute to detection by SWIR imaging system. Most of these systems use uncooled IR detectors that sense very hot sources, so the primary criterion is the existence on the target of a very hot spot.

High - has very hot spots and is within line-of-sight of sensors.

Medium - has warm but not hot spots that sometimes stand out in uncooled detector, or has hot spots not always within line-of-sight of the sensors.

Low - no warm or hot spots, or generally not within line-of-sight of the sensors.

D. MWIR Vulnerability - degree to which MWIR contrast, size, shape, and location contribute to MWIR sensing systems sense scattered light and target self-emission using moderately cooled infrared sensors in the MWIR spectrum.

High - operates within short and medium line-of-sight range with enough IR signature and contrast due to a combination of related and self-emitted radiation to result in detection.

Medium - not generally within line-of-sight of detectors either because of distance or because of concealment; poor MWIR contrast; non-distinctive signature.

Low - normally out of sight, out of range, or lacking a detectable MWIR signature.

E. LWIR Vulnerability - thermal signature resulting from thermal lag, surface emittance, and size.

High - large conspicuous sources like Corps Tactical Headquarters (engine generators).

Medium - smaller or intermittent thermal signature like 155-mm Howitzer Battery (hot gun barrels after firing) or tactical bridges (large area, thermal lag).

Low - few major heat sources or massive equipment items with thermal lag, e.g., Infantry Battalion.

TABLE III-3 (Continued)

F. Laser Vulnerability - degree to which surface characteristics, such as composition (coating) and roughness, aspect angle, and contrast with background provide laser reflectivity of useful quality.

High - significant amount of energy is reflected toward detector.

Medium - reduction of reflectivity at particular wavelengths.

Low - minimum reflectivity.

G. Radar Vulnerability - magnitude of target scattering cross-section and signature relative to background based on combination of size, configuration, and metallic composition.

High - ideal reflectivity characteristics, e.g. Tactical Bridge.

Medium - reflectivity sufficient to warrant further investigation, e.g. 155-mm Howitzer Battery.

Low - reflectivity low enough to blend with normal battlefield background, e.g. Infantry Brigade.

H. Acoustic and Seismic Vulnerability - vulnerability to detection by acoustic and seismic detectors band on magnitude, characteristics, shape, and duty cycle of vibrations transmitted to the air and ground.

High - large impulses delivered to air and ground near FEBA, e.g., mortars firing.

Medium - smaller vibrations, or vibrations emitted at longer range.

Low - lacking vibrations with readily identified characteristics, or out of range of sensor systems.

Location is an operational parameter, but also contributes to the magnitude of the signal detected by a sensor. In most cases, the signal strength at the receiver falls off with increasing distance from the target, so some sensors will be effective only if they are close to the target. Others are effective only if there is an uninterrupted path between the target and the sensor, and some are effective at long distances.

Mobility is significant in some instances as a criterion for target detection and identification. Also, some sensors can more easily detect targets in motion than targets standing still, or vice versa. A sensor which observes only intermittently and has a considerable time lag between observation and delivery of processed information may yield useful information about an immobile target but not about a target that moves frequently.

Detection value attempts to distinguish between those targets which are likely candidates for engagement by direct and indirect fire weapons and those targets more likely candidates for surveillance purposes or engagement by long-range weapon systems.

Signature comprises characteristics of shape, color, temporal and spatial pattern, highlights, characteristic motion, characteristic emission, and other qualities which make particular targets stand out from others.

2. Sensor-Specific

The five sensor-specific criteria relate to those attributes of a target which determine its relative vulnerability to the known and forecast detection sensors which the enemy is expected to use. These vulnerabilities, thermal, radar, visual, laser, and VSWIR, are the subject of more detailed technical discussion in the report and will not be elaborated on here.

C. CATEGORIZATION

Next, each item on the CC and CS lists has been subjected to the categorization criteria described above. Based on this analysis, the items have been grouped into eleven target classes. Recognizing that categorization cannot be an exact science, care has been taken to strike a balance between assigning targets so discriminately that an unmanageable number of classes are created, and assigning targets in so gross a manner that unlike targets are lumped into the same class. The resulting eleven target classes and the CC and CS items they represent are shown in Table III-4. It will be noted that the categorization is heavily mission-oriented and makes use of such mission-associated characteristics as location on the battlefield, type of material employed, mobility, etc. Further, to the extent possible, the categories have been sequenced in order of proximity to the FEBA with Target Classes I and II representing those units having direct contact with the enemy. A matrix summary of how the target classes respond to the categorization criteria, is shown in Table III-5. The vulnerability of the target classes to the various sensor types are shown in Table III-6.

D. CAMOUFLAGE OPERATIONAL FLEXIBILITY

Recognizing the ground rule pertaining to mission accomplishment, the target classes have been assigned a "camouflage operational flexibility index," an indicator of the amount of resources that reasonably could be devoted to extra-materiel camouflage measures without undue detraction from mission accomplishment. Table III-7 summarizes whether the target classes have low, medium, or high operational flexibility indexes. In general, where the index is high, camouflage measures that require time, manpower, and logistics and that place constraints on operations might be acceptable, provided they are effective. On the other hand, where the index is low, the only acceptable camouflage measures are those that can be built into the equipment before it reaches the battle-

TABLE III-4

TARGET CLASSES FOR CAMOUFLAGE PURPOSES

TARGET CLASS I		Motorized, airmobile or airborne forward area combat units, controlling headquarters and auxiliary support.
CS2	-	Radar, Ground Surveillance
CS3	-	Brigade and Battalion Headquarters
CS4	-	Anti-Tank Devices, Ground Mounted
CS5	-	Infantry Equipage and Fighting Positions
CS10	-	Trucks-Tactical and Logistical
CS13	-	Army Wide Items (several)
TARGET CLASS II		Armored and/or mechanized forward area combat units, controlling headquarters and auxiliary support.
CS5	-	Combat Vehicles and Armored Carriers (less G and H)
CS2	-	Radar, Ground Surveillance
CS3	-	Brigade and Battalion Headquarters
CS4	-	Anti-Tank Devices, Ground Mounted
CS11	-	Combat Engineer Equipment
CS13	-	Army Wide Items (several)
TARGET CLASS III		Self-propelled and/or towed cannon and rocket artillery, and anti-aircraft combat support units and associated fire control and target acquisition support.
CC1B	-	Guns (Nuclear Capable)
CC2	-	Air Defense Systems (less Nike Hercules)
CS1	-	Field Artillery (Conventional Rounds) and CB/CM Radars
CS3	-	Battalion Headquarters only
CS10	-	Trucks, Tactical and Logistical
CS13	-	Army Wide Items (several)
TARGET CLASS IV		Tactical bridges
CS9	-	Tactical Bridges
TARGET CLASS V		Forward area aircraft in flight
CC6	-	Aircraft, Assault, Attack and Scout

TABLE III-4 (continued)

TARGET CLASS VI		Rear area aircraft in flight
CS8	-	Aircraft, Support
TARGET CLASS VII		Aircraft operating bases
CC6	-	Aircraft, Assault, Attack and Scout
CS8	-	Aircraft, Support
CS10	-	Trucks, Tactical and Logistical
CS13	-	Army Wide Items (several)
TARGET CLASS VIII		Surface-to-surface missile units
CC1A	-	Missiles
TARGET CLASS IX		Large rear area command, control, communications and support installations heavily dependent on electrical power
CC3	-	Army/Corps/Division Tactical Headquarters
CC4	-	Data Centers or Centrals Associated with Higher Headquarters
CC5G	-	USADA SIGINT Collection and Electronic Warfare Facilities
CC5H	-	Division and Corps Area Communications Shelter
CS5	-	Infantry Equipage and Fighting Positions (to some degree)
CS10	-	Trucks, Tactical and Logistical
CS13	-	Army Wide Items (several)
TARGET CLASS X		Large rear area ammunition, POL, supply and combat service support installations with low to moderate electrical power requirements
CC1C	-	Special Ammunition Supply Points
CS5	-	Infantry Equipage and Fighting Positions (to some degree)
CS6	-	Ammunition Supply Point
CS7	-	Tactical POL
CS10	-	Trucks, Logistical
CS12	-	Division Support Command
CS13	-	Army Wide Items (several)

TABLE III-4 (continued)

SPECIAL CLASS		Missile, cannon, rocket and mortar units vulnerable to counterfire radar
CC1A	-	Missiles (Lance only)
CC1B	-	Guns (Nuclear)
CC5D	-	Other Carriers (Mortars only)
CS1A	-	Howitzers, Guns and MLRS (future item)
CS5D	-	Crew Served Weapons (Mortars only)

TABLE III-5. CHARACTERISTICS OF VARIOUS TARGET CLASSES RELATING TO DETERMINATION OF VULNERABILITY TO DETECTION BY VARIOUS SENSOR SYSTEMS

CRITERION	I	II	III	IV	VII	VIII	IX	X	SP
	TARGET CLASS								
SIZE									
Diffuse	X	X							
Large							X	X	
Medium			X		X	X			
Point				X					X
LOCATION									
Front	X	X	X	X					X
Rear				X	X	X	X	X	
MOBILITY									
High	X	X							
Medium			X	X	X	X			X
Low							X	X	
DET VALUE									
Targeting	X	X	X	X					X
Surveillance				X	X	X	X	X	
SIGNATURE									
High				X	X	X			X
Medium		X	X				X	X	
Low	X								

TABLE III-6. SUSCEPTIBILITY OF NINE TARGET CLASSES TO VARIOUS SENSOR SYSTEM TYPES

	TARGET CLASS								
SENSOR TYPE	I	II	III	IV	VII	VIII	IX	X	SP
VISUAL--0.4-0.72 μm optical, eye, photographic	H	H	M	H	M	L	M	L	-
VSWIR--0.72-1 μm photographic, photoemissive imagery	H	H	H	M-H	L	L	L	L	-
SWIR--1-1.29 μm uncooled IR det., chiefly missiles--very hot targets only	L	M	L	L	L	L	L	L	-
MWIR--2.9-5.5 μm moderate cooling	M	H	M	L	L	M	M	L	-
LWIR--7.5-14 μm cryogenic cooling	M	H	M	L	M	M	H	M	-
LASER	L	H	L	H	M	M	M	M	-
RADAR	L	H	H	H	H	M	M	H	H
ACOUSTIC SEISMIC	M	M	H	L	L	L	L	L	-

TABLE III-7. CAMOUFLAGE OPERATIONAL FLEXIBILITY INDEX

TARGET CLASSES / INDEX	OPPORTUNITY FOR APPLICATION OF CAMOUFLAGE MEASURES NOT EQUIPMENT - INHERENT BASED ON COMBINATION OF MISSION, USUAL BATTLEFIELD LOCATION AND FREQUENCY OF MOVEMENT		
	LOW	MEDIUM	HIGH
I	X		
II	X		
III		X	
IV		*X	
VII		X	
VIII		X	
IX			X
X			X
SPECIAL	X		

* BASED ON USE OF DECOY INSTALLATIONS

field tactical situation or of such basic nature, e.g. nets, that they can be applied without detracting from accomplishment of the mission.

E. DESCRIPTION OF THE TARGET CLASSES

Each of the eleven target classes is briefly described below, taking into account the analysis just discussed. Following the description of each class is a short list of "troubles," considerations which call for particular attention in the context of camouflage. These "troubles" in effect provide the basis for determination of design goals for a camouflage system for the field army.

Target classes V and VI -- aircraft in flight -- are included for completeness only. Responsibility for camouflaging them does not rest with MERADCOM, and they will not be considered further. The Special Class is special because all of the items in that class belong to other classes also, and are identified with the Special Class also only during a particular short-duration phase of operation.

The vulnerability evaluations can be presented in the form of an analog chart as an alternative to the tabular form of Table III-6. This has been done in Figures III-1 to III-9 for nine of the eleven target classes (classes V and VI are excluded). In each case where the vulnerability of a particular target class to a particular type of sensor is high, additional information about the targets and sensors has been drawn on to deduce a very brief statement of the amount of camouflage required to reduce the vulnerability to "medium" or "low." Because of the heterogenicity of the target classes and the variety of systems using each type of sensor, it is not possible to make firm quantitative estimates of requirements, but the estimates in the nine figures give a general perspective and provide a starting point for more detailed analysis.

TARGET CLASS I - Motorized, airmobile or airborne forward area combat units, controlling headquarters and auxiliary support

This we refer to as to base case since it is so representative, in many respects, of common items found in any Army unit (people in camouflage uniforms, small arms, foxholes, mess gear, jeeps, trucks, crew-served weapons, tents, etc.). It has a low operational flexibility index denoting that camouflage measures, by and large, should be "built in" and not detract from mission accomplishment. This target class contains largely a heterogeneous array of equipment with few signature items in the visual, radar, thermal, or laser areas that make it stand out for special attention. By nature, its target elements are spread over a large area in low density and they move often. It is the most subject to visual observation in all its forms, day and night, and such observations will be target-acquisition oriented. These characteristics argue for a basic level of camouflage that allows blending in with the terrain and against any special measures that would impact in the areas of time, manpower, and logistics.

TROUBLES: Visual vulnerability
Targeting vulnerability
Low operational flexibility index

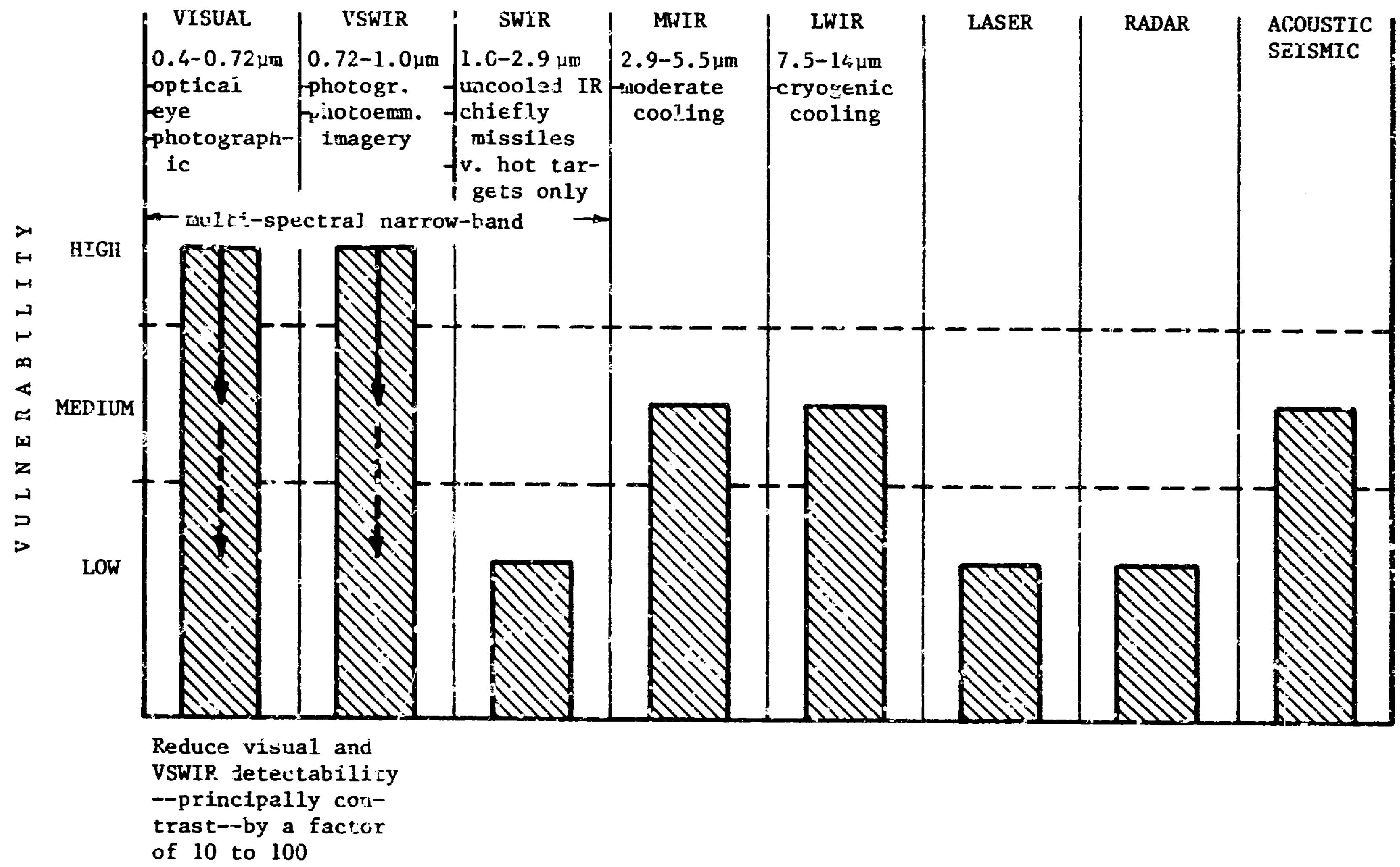
[See Figure III-1]

TARGET CLASS II - Armored and/or mechanized forward area combat units, controlling headquarters and auxiliary support

This class differs from Class I primarily in its preponderance of massive metallic items with signature characteristics and greater vulnerability to radar, thermal, and laser sensors. The location, distribution on the battlefield, mobility, detection value (targeting) and operational flexibility index are essentially the same. Because of the importance the enemy attributes to tanks, APC's, and other armored or mechanized vehicles, this class will probably be subject to more intense search than Class I. Since, with this class, mobility is a hallmark, the same restrictions to "built-in" camouflage measures apply.

FIGURE III-1. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS I

Motorized Airmobile or Airborne Forward Area Combat Units, Controlling Headquarters and Auxiliary Support -- Typical Target: heterogeneous



TROUBLES: Visual vulnerability
Targeting vulnerability
Radar vulnerability
Thermal vulnerability
Laser vulnerability
Millimeter-wave radar vulnerability
Low operational flexibility index

[See Figure III-2]

TARGET CLASS III - Self-propelled and/or towed cannon and rocket artillery, and anti-aircraft combat support units and associated fire control and target acquisition support

This class shares with Class II a preponderance of large metallic items and the vulnerabilities that ensue. Unlike Class II, the items of metallic mass are grouped into smaller areas by mission (about 100M X 300M maximum) and offer a signature because of deployment pattern. The physical phenomenon associated with their use (flash and bang) further add to their signature characteristics. This class is usually located far enough behind the FEBA to preclude direct ground visual observation, but is subject to emeny artillery and short-range missile fire when located. It moves less often than Classes I and II and usually has more organic transport capability; hence, it has a higher operational flexibility index, and there is greater opportunity for application of camouflage measures.

TROUBLES: Signature
Targeting vulnerability
Visual vulnerability (from the air)
Radar vulnerability
Thermal vulnerability
Laser vulnerability
Millimeter-wave radar vulnerability
See special case below

[See Figure III-3]

FIGURE III-2. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS II

Armored and/or Mechanized Forward Area Combat Units, Controlling Headquarters and Auxiliary Support -- Typical Target: Tank

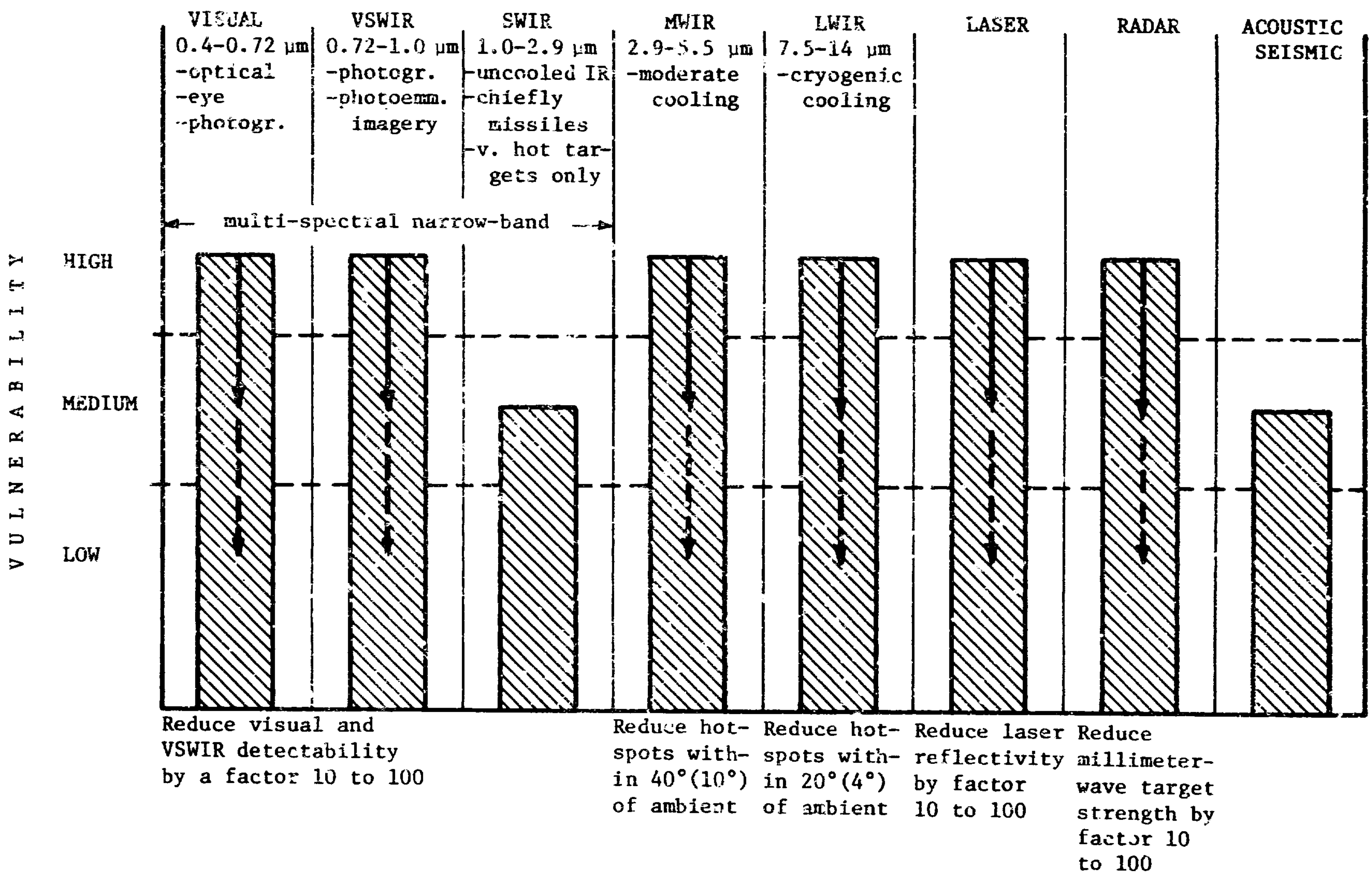
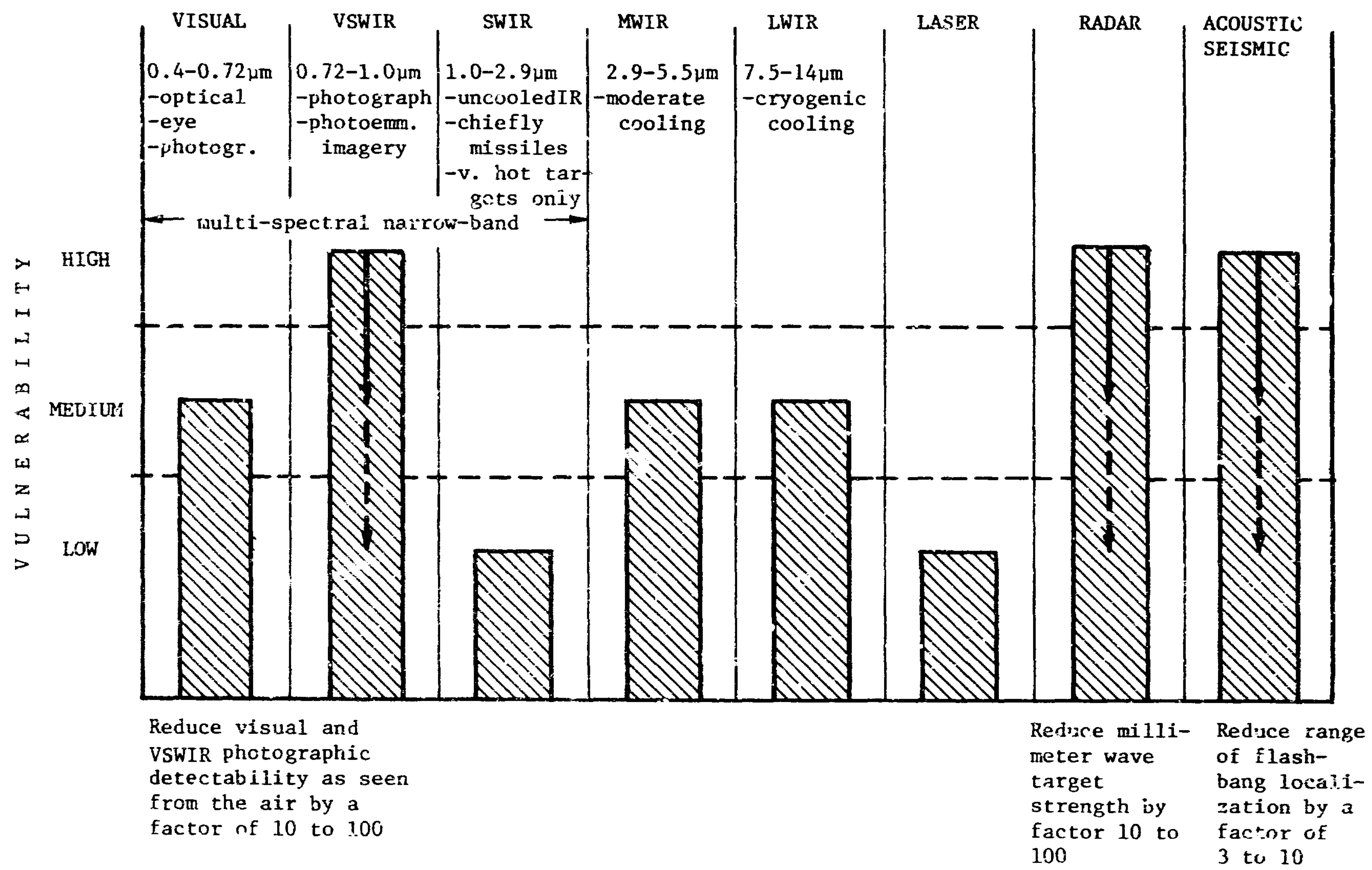


FIGURE III-3. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS III

Self-Propelled and/or Towed Cannon and rocket artillery, and anti-aircraft combat support units and associated fire-control and target acquisition support -- Typical target: artillery or missile-launcher



TARGET CLASS IV - Tactical Bridges

This is a unique target class because of its geometric pattern and water background. By nature, it reduces the enemy's search problem, but it is seldom subject to direct ground observation. It is an ideal radar and thermal target. Its nature also minimizes camouflage measures that can be used, but its higher operational flexibility index allows application of any found feasible. It may or may not be within range of enemy artillery or short-range missiles: nevertheless, it will be high priority for take-out.

TROUBLES: Signature
Priority target
Visual vulnerability (from the air)
Radar vulnerability
Thermal vulnerability

[See Figure III-4]

TARGET CLASS V - Forward area aircraft in flight

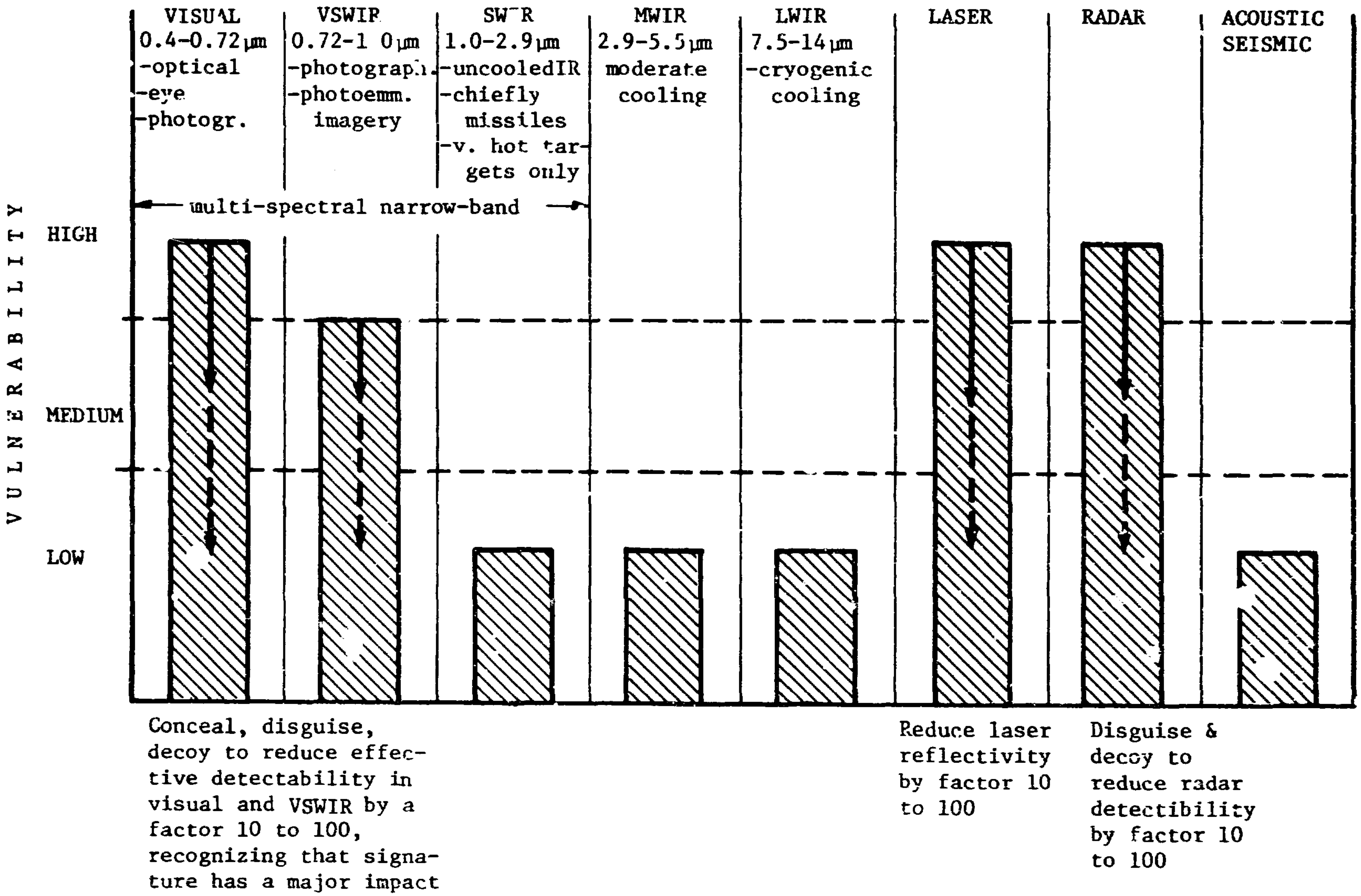
This is a point target subject to ground observation and targeting as well as aerial observation and targeting. It is a moving target, but has high radar vulnerability, due to its sky background, and thermal vulnerability due to its engine(s). The nature of the target virtually dictates that any camouflage measures be "built-it." It has the utmost in signature, and it could be illuminated by laser for target engagement.

TROUBLES: Signature
Visual vulnerability
Targeting vulnerability
Radar vulnerability
Thermal vulnerability
Laser vulnerability
Low operational flexibility index

Because camouflage for this target class is not the responsibility of MERADCOM, the class will not be considered further.

FIGURE III-4. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS IV

Tactical Bridges -- Typical target: tactical bridge



TARGET CLASS VI - Rear area aircraft in flight

This class target differs from Class V only in its area of operation. This makes it virtually immune from ground observation and fire and takes it out of the range of many ground-based radar, thermal, and laser platforms.

TROUBLES: Signature
Visual vulnerability (from the air)
Vulnerability to airborne sensor platforms
Low operational flexibility index

Because camouflage for this target class is not the responsibility of MERADCOM, the class will not be considered further.

TARGET CLASS VII - Aircraft operating bases

This class target has high signature characteristics since some aircraft will usually be present within a relatively small area. Located in the rear, it is not subject to ground-based sensor platform detection or attack by artillery or short-range missiles. Even for airborne sensor platforms, it is less vulnerable than aircraft in flight because of natural background and an operational flexibility index that allows some application of camouflage measures. Aircraft operations and use of auxiliary equipment will present a fairly strong thermal signature of a recurring nature.

TROUBLES: Signature
Thermal vulnerability
Radar vulnerability

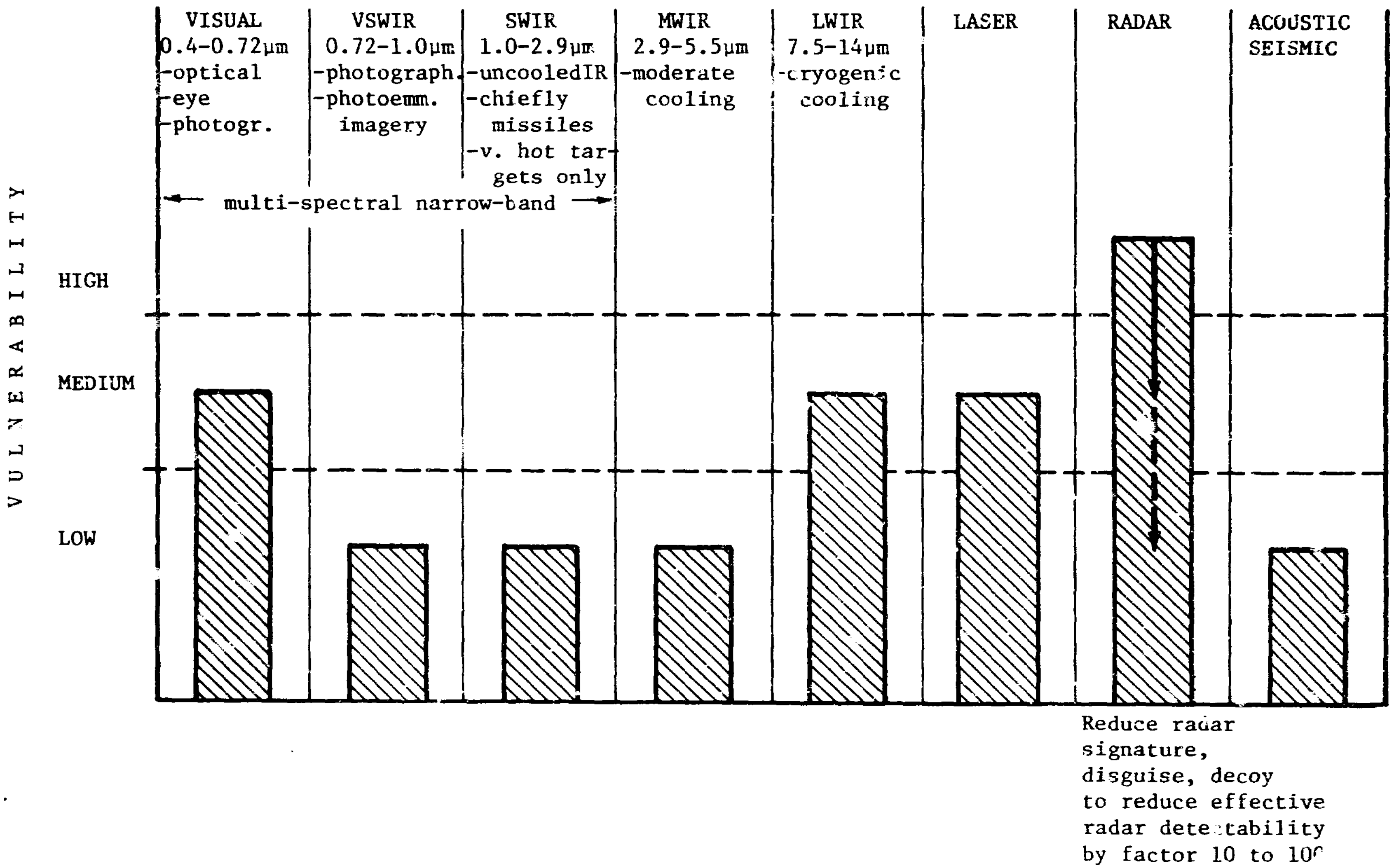
[See Figure III-5]

TARGET CLASS VIII - Surface-to-surface missile units

This class target operates in the rear, out of range of ground-based sensor platforms and enemy artillery and short-range missiles. It deploys in small increments which reduce the thermal, radar, and laser vulnerabilities. It is high in signature characteristics, both shape and firing phenomenon, but hedges against the latter by "shoot and scoot" tactics. It has more leeway in seeking natural cover and con-

FIGURE III-5. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS VII

Aircraft operating bases -- Typical Target: aircraft operating base



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cealment and usually remains in place sufficiently long for application of some camouflage measures. The mass of metal and generators used for operations present a moderate radar and thermal target.

TROUBLES: Signature
Thermal vulnerability
Radar vulnerability

[See Figure III-6]

TARGET CLASS IX - Large rear area command, control, communications and support installations heavily dependent on electrical power

This class target covers a relatively large area with significant density. It is outside range of ground-based sensor platforms and enemy artillery or short-range missiles. It has some items, particularly large vans, which present visual signature unless properly concealed. Its major vulnerability is thermal because of the large number of generators used to power the various elements of the installation. It normally remains in position for some days, hence it has a high operational flexibility index with opportunity to apply camouflage measures.

TROUBLES: Visual vulnerability (from the air)
Thermal vulnerability
Radar vulnerability
Some signature items

[See Figure III-7]

TARGET CLASS X - Large rear area ammunition, POL, supply, and combat service support installations with low-to-moderate electrical power requirements

This class target differs from Class IX in only two respects: in most cases, fewer generators will be used, and, the target will usually remain in place for a longer period of time. It should also be noted that, in some cases, indigenous structures and installation, e.g. peacetime military bases, will be used to accommodate this type target. In any event, the time and opportunity for application of camouflage measures should be greater.

FIGURE III-6. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS VIII

Surface to Surface Missile Units -- Typical Target: Surface-to-surface missile unit

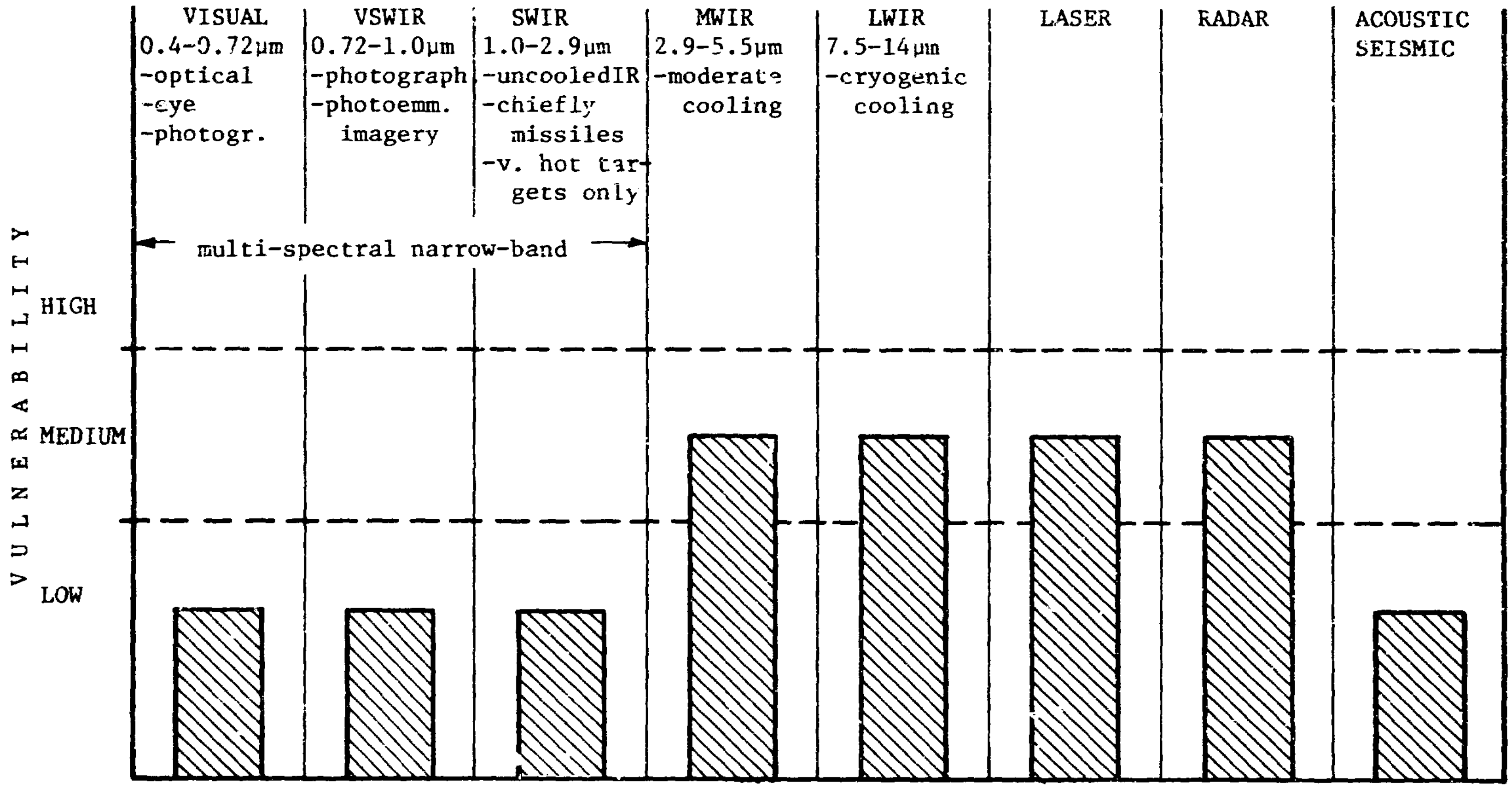

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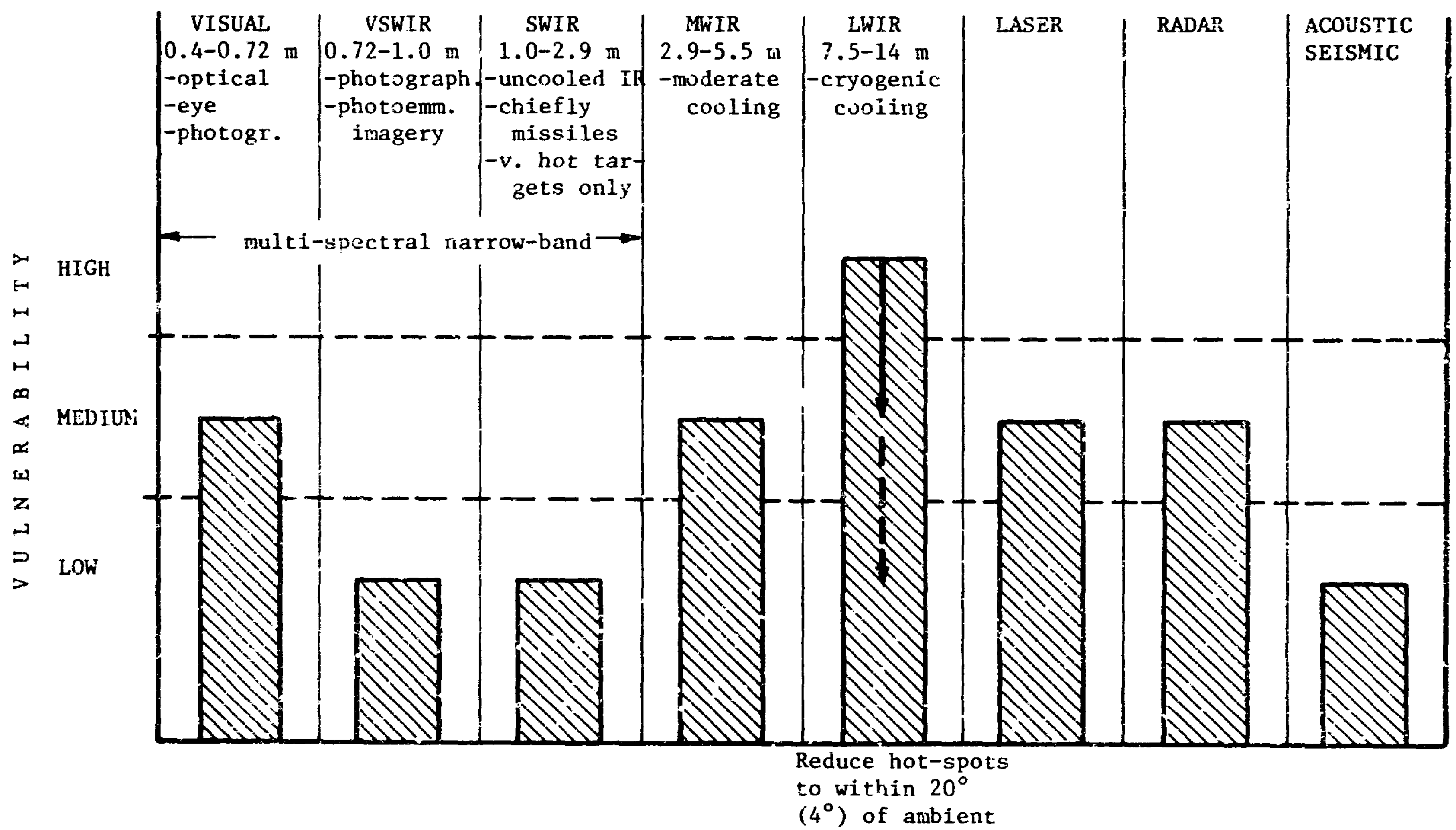
FIGURE III-7. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS IX

Large rear-area command, control, communications and support installations heavily dependent on electrical power -- typical target: Division or Corps tactical headquarters



TROUBLES: Thermal vulnerability
Radar vulnerability (particularly ammunition dumps with large metallic mass)

[See Figure III-8]

SPECIAL CLASS - Missile, cannon, rocket, and mortar units vulnerable to counterfire radar

This class denotes those indirect fire weapon systems with ordnance following essentially a ballistic trajectory from the weapon to the target. Note that all the equipment items in this class already belong to one of the other ten classes, and belong to the Special Class as well during the brief phases of their operation when a shell or missile is aloft. Counterfire radars have the capability of intercepting a portion of the ascending leg of the trajectory and, by computation, reconstructing the trajectory back to the weapon location. This capability allows location and targeting of the firing location despite any other camouflage measures that may have been applied to the firing location per se (nets, decoys, natural cover, etc.). The operational measures which can be used to defend against this capability (movement) are limited since the counterfire radars can direct fire on the weapon location within a few minutes. Shells, rockets, and missiles are finely honed in terms of weight, size, and ballistic characteristics; therefore, doing something to them to make them invisible is not an easy task.

TROUBLE: Radar intercept vulnerability

[See Figure III-9]

FIGURE III-8. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS X

Large rear-area ammunition, POL, supply and combat service support installations with low to moderate electrical power requirements -- Typical target: ammunition supply point

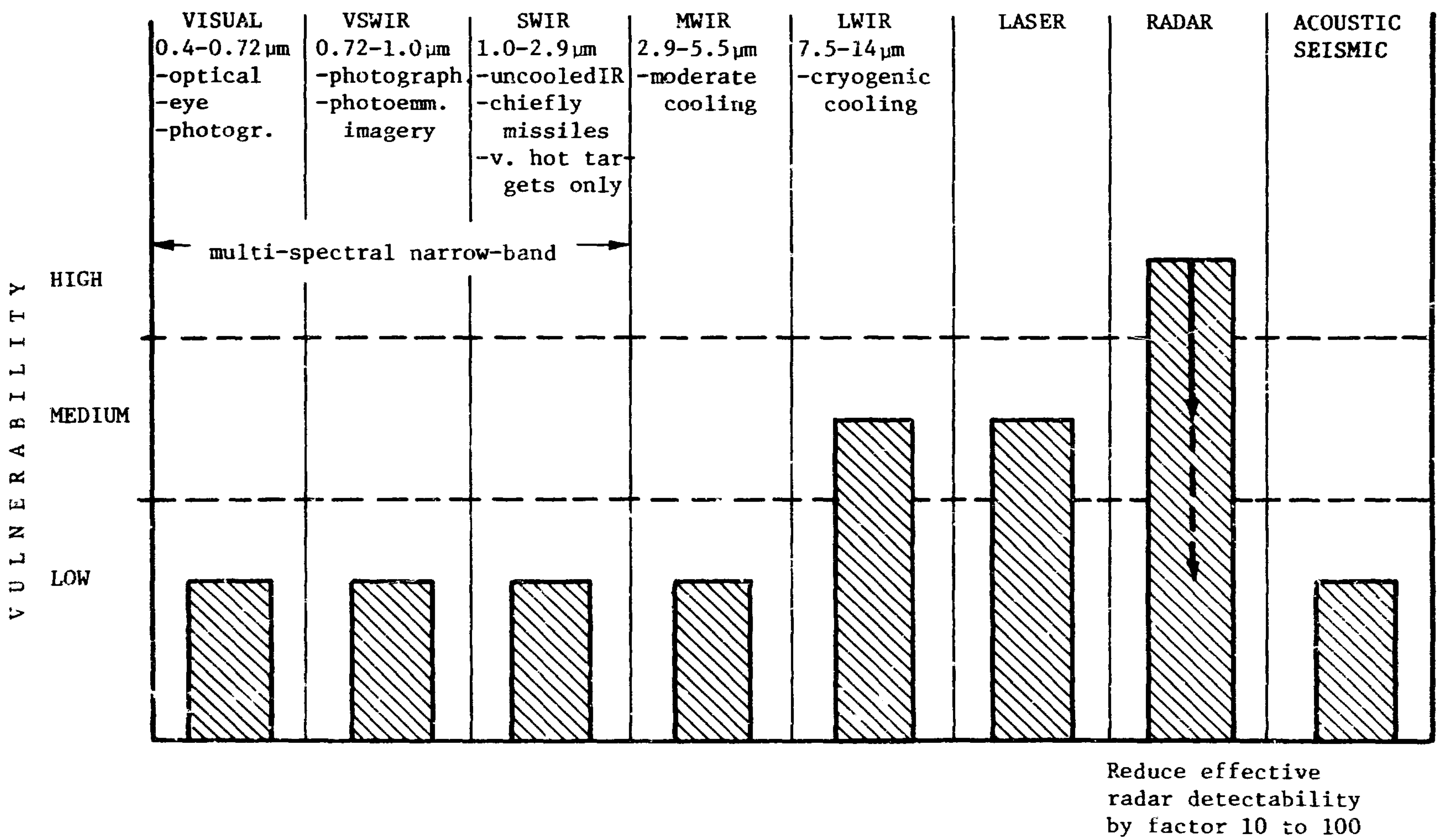
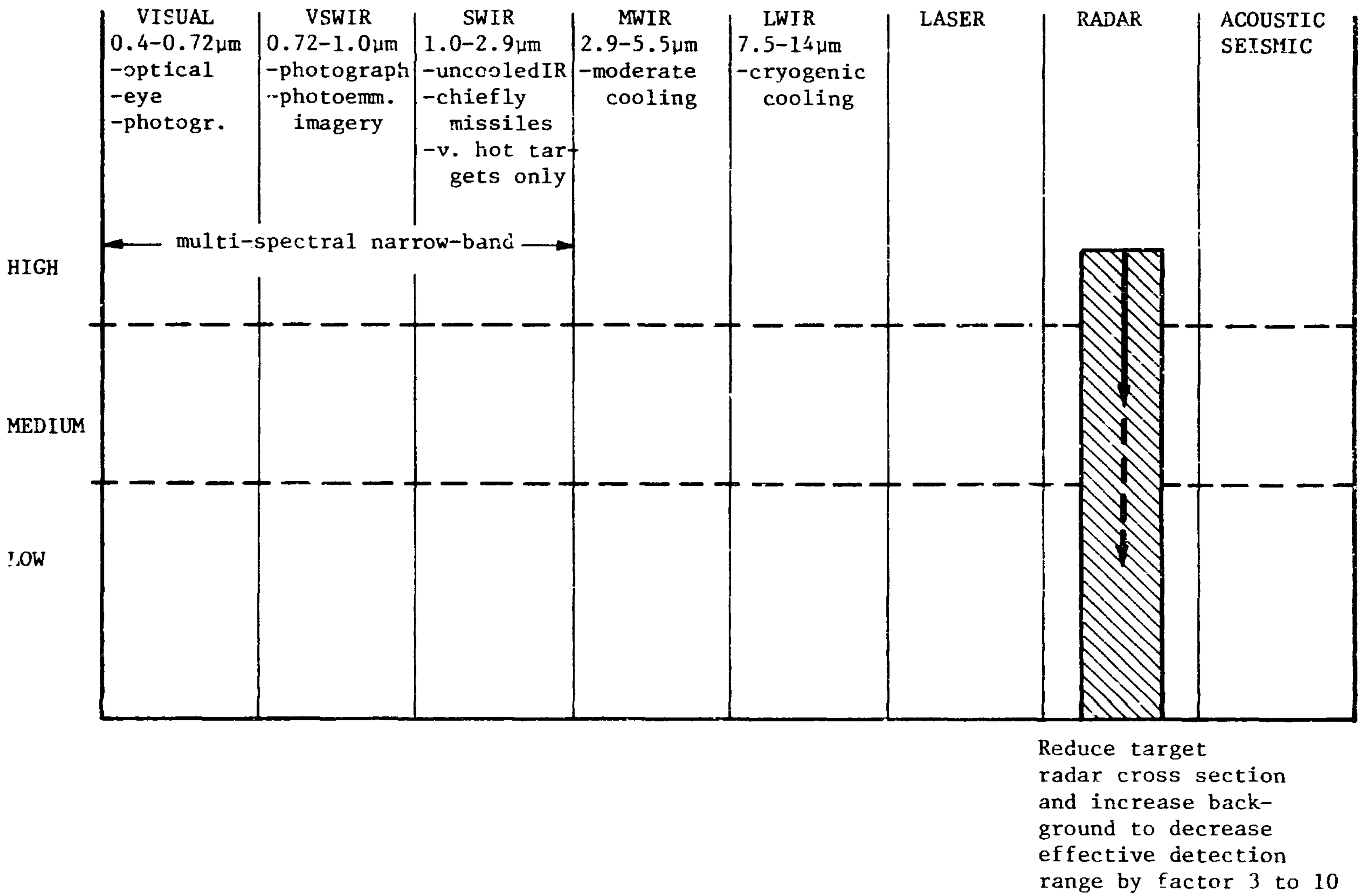


FIGURE III-9. CAMOUFLAGE REQUIREMENTS FOR TARGET CLASS "SPECIAL"

Missile, cannon, rocket and mortar units vulnerable to counterfire radar -- Typical target: mortar shell in flight



IV. TECHNOLOGY ASSESSMENT

A. INTRODUCTION

This chapter is a summary of the characteristics of passive camouflage technology. Its purposes are to:

- list the principal means available for meeting the surveillance and target acquisition threat with passive camouflage,
- show how effectively these measures might be expected to work against the threats of the future, and
- suggest areas where worthwhile improvements might be achieved with further research and development.

The subject is dealt with in the following order:

- camouflage against sensors in the visual, IR and laser regions, excluding systems responding to target thermal self-emission,
- camouflage against systems responding to IR self-emission or to a mixture of IR radiation scattered by and self-emitted by the target,
- camouflage against radar, and
- camouflage against acoustic and seismic sensors.

Figure IV-1 shows the classic methods of camouflage and some of the specific ways they can be implemented. Not all of these are available in every area of camouflage technology. All should be reviewed from time to time, but where we have omitted mention of any one it is because we believe it to be relatively inapplicable, ineffective, or unpromising. Particular camouflage measures can be grouped alternatively in the following natural groupings:

FIGURE IV-1

CLASSIFICATION OF CAMOUFLAGE METHODS

HIDE

SIGNAL REDUCTION AND BACKGROUND AUGMENTATION

1. Opaque or scattering shields and nets
2. Opaque or scattering clouds--smoke, aerosol, chaff, etc.
3. Increase background return
4. Shadow
5. Blackout

BLEND

CONTRAST REDUCTION

1. Tone target down (or up)
2. Emission control
3. Reduce scatter cross-section by geometric shaping
4. Control of color and texture patterns
5. Tone background up (or down)
6. Shadow elimination and obscuration
7. Creation of a false background
8. Use of mirrors
9. Insulation
10. Decoupling from transfer medium
11. Energy conversion

DISGUISE

SUBSTITUTION OF IDENTITY CUES

1. Elimination and obscuration of identity cues
2. Incorporation of background cues
3. Incorporation of second item cues
4. Modification of spoor and activity cues

DECOY

CREATION OF FALSE IDENTITY

1. Creation of false signals
2. Creation of false part, item, system or activity that duplicates major detectable identity cues of an archetype
3. Creation of cues not related to an archetype

Source: Adapted from Reference 1.

- camouflage applied or built into the target
  - paints, surface treatments, and coatings
  - substitution of materials with less undesirable scattering reflecting, and radiation characteristics
  - spoiling, disguise, or signature alteration by superficial changes
  - alteration of underlying shape or structure to reduce signature
- camouflage applied near the target
  - blankets, screens, and nets
  - natural cover, defilade, tactical siting, etc.
- camouflage removed from the target
  - aerosols, smoke, and chaff
  - artificial scatterers to augment background
  - decoys and deliberate deception.

Our categorization of targets is found in Chapter III. The principal discriminator of the appropriateness or applicability of various types of camouflage is the operational flexibility index, defined in Section III.D. The operational flexibility index is a composite indicator of how much the emplacement, mobility, and operation of the target can be restricted to make camouflage possible before those restrictions themselves become prohibitive. Other target parameters that indicate or correlate with applicability of various camouflage measures are explained in Chapter II.

B. CAMOUFLAGE AGAINST SENSORS IN THE VISUAL, INFRARED AND LASER REGIONS

Camouflage in these spectral ranges, except for instances involving thermal self-emission discussed in Section C below, is very thoroughly treated in Reference 1.

In the visual domain, data are usually gathered in the form of images. Shape, size, contrast, location, color, and sometimes motion are clues that must be protected against. Since enemy sensors in the visual domain can be expected to have enough resolution to easily "see" military objects at ranges of kilometers, the job of camouflaging such targets in all aspects is indeed difficult. Under most circumstances, one cannot hope to make the target impossible to see: one can only make it more difficult to see, delay its detection and identification, and increase the enemy's likelihood of overlooking or misidentifying it.

The two things that distinguish the visual spectrum from other parts of the electromagnetic system are that the human eye is sensitive to it and it includes the region of peak intensity of the solar radiation. However, the same techniques that produce visible images in the visual spectrum can produce images in the VSWIR, SWIR, MWIR, and LWIR detectable with image convertors or IR photographic film.

Laser range finders, target designators, beam riders, and radars (lidars) differ from the visual and IR systems in four major respects:

- the bandwidth of the illuminating radiation is very narrow,
- the source of the illuminating radiation has a very narrow solid angle,
- most laser systems do not form images, and

- the target parameter that most influences performance is not contrast but amount of energy returned (i.e., a "black" target would be less vulnerable to a laser device than a low-contrast target).

1. Camouflage Applied to the Target

The first job of camouflage applied directly to the target is blending. Disguising is also a function of camouflage applied to the target, but before trying to make the target look like something else, it is well to make it as inconspicuous as possible. Visibility and identification are completely independent of any target characteristics other than completely superficial appearance--the combination of brightness, color, texture, and shape, and the motion and pattern clues that combinations of those four superficial qualities reveal. The appropriate technology is paints, coatings, surface treatments, and superficial shape modifications to achieve desired blending and some measure of disguise. As explained in Reference 1, all of these techniques are in current use.

The key to a successful blend in any spectral region is the degree to which the surface matches the measured radiated energy (reflected, scattered, or self-emitted) of the ambient background. (The sole exception is camouflage against laser range finders and target designators, pointed at a target that has already been detected by other means. Under these circumstances the best strategy is not blend but return the smallest possible energy, a form of hiding the target.)

The optical properties of a paint or coating are tailored by suitable choice of materials, particle sizes, and thicknesses of the outer layer and its surface texture. As the properties of the background vary not only with location but also with wavelength, only very general rules can be formulated for successful camouflage barriers.

One begins with the materials used in the formulation. Every material has its characteristic spectral signatu , absorption as function of frequency characterized grossly by the presence of absorption bands of different lo ations and strengths. The combination of material absorption and layer thickness determines the optical density. If a substance has a strong absorption ban , then this band itself produces a high surface reflectance so that both the phenomena of a sorption and reflectio are involved in tailoring the signature prese ed to a viewer. The reflection itself can be specular if the surface is smooth, or diffuse if it is not. A body reflectance is also related to the absorption scattering ratio.

$$R = 1 + \frac{K}{S} - \sqrt{\left(\frac{K}{S}\right)^2 + 2\,\frac{K}{S}}$$

where K and S are the absorpt on and back-scattering cross-sections. The absorption-to-scat ering ratio is a complicated f nction of the refraction and absorption indices of the individual components. The angular dependence of radiation reflected by a target is mentioned elsewhere, but variation of the angular distribution is another method of varying the effectiveness of the camouflage.

The particle size of the components of the barrier layer (this may include voids in a foam) is another adjustable parameter that can used to tailor absorption and reflection properties. General scattering properties of particles are strongly dependent o particle size r particle size distribution, and both the overall absorption and scattering cross-sections and the angular distribution of the scattering are vitally affected.

Reference to Kirchhoff's Law (that the absorptance equals the emittance) for materials that are optically thick shows that once the reflectance is known from the combination of the above factors, emittance is also known. This is because at any wavelength all of the radiant energy incident on a block of material must be accounted for by three mechanisms: absorption, reflection, and transmission. Equating the incident energy to the sum of absorbed, reflected and transmitted energy leads to the equation:

$$\varepsilon = \frac{(1-R)\ (1-T)}{1-RT}$$

Now if any material has zero transmittance because of thickness or inherent absorption, the equation can be seen immediately to reduce $\varepsilon = 1-R$. Thus, the properties of a barrier layer are immediately apparent once its reflectance is known.

Unfortunately, no pre-applied camouflage can blend perfectly, because it cannot match all the possible backgrounds. While there is no technical reason why a target cannot be matched within 2% contrast to any particular background, there is rarely an incentive to do so; for as soon as the target progresses to another location the blend will be destroyed. The best that can be achieved is a combination of color, brightness, and texture typical of the range found in backgrounds in a general area. This is the purpose of pattern-painting as presently practiced, and occasionally augmented with cloths, screens and shape spoilers to modify highlights and disrupt outlines. While the effectiveness of pattern-painting might be improved with some variation of colors, textures, and pattern, it is unrealistic to expect greatly improved effectiveness, for the variety of backgrounds is inescapable, and many combinations of color, texture and pattern have been assiduously studied for sixty years.

In the visual range, pattern-painting achieves a combination of brightness, colors, and gross texture typical of a pre-selected class of backgrounds. The "colors" of the paints have been matched to the background over progressively broader spectra. Until now the mismatch is serious only in the LWIR. (There is no known reason why the spectral match cannot be extended to the LWIR also, but further development is required.) Pattern-painting reduces the ability of an observer to detect and identify a target, but will hardly ever reduce the contrast to the levels discussed in Chapter II which would make the target truly undetectable.

Against laser instruments, camouflage applied to the target should reduce its retro-scattering to as near zero as possible. Many approaches to reduction of retro-scattered laser illumination are possible, and the more promising ones are discussed in Chapter II and summarized in Chapter V: but to the best of our knowledge, none of them has yet been applied to general Army battlefield equipment surveillance.

2. Camouflage Applied Around and Near the Target

For any target that stands still for an extended period of time, a net treated to conceal the target and blend with the background is an effective camouflage measure. The effectiveness of the net is limited only by the time and effort required to correct imperfections and inadequacies in the blend and the camouflager's knowledge of the threat, sensor systems. Unfortunately, a material chosen to blend in one spectral region may contrast in another. The factors that must be controlled for successful blending are described in Section 1 above. Unless the contrast can be maintained or decreased in every threat spectral band, the net may be ineffective; for it is always bigger than the target it conceals. Unfortunately, nets are nearly useless for camouflaging targets in motion.

By concealing the target, a net will interfere with the working of many laser instruments. It should be remembered, however, that laser target designators, beam riders, range finders and similar instruments are used in a two-stage operation: first, the target is detected and identified by some means other than a laser, and second, the laser instrument is used for the additional purpose of localizing the target or leading or guiding a weapon towards it. If the first stage is defeated, the second stage cannot be used.

Where it is available, hiding under and behind natural cover and terrain is an effective camouflage against all sensors in these spectral ranges (and against radar as well). Blending the cover with the environment is not an issue, because the cover is part of the environment.

3. Camouflage Applied Away from the Target

A cloud of smoke, aerosol, or radar-scattering and -absorbing chaff between the target and the sensor both reduces the strength of the target signal and adds scattered energy to the receiver channel, thus contributing both to hiding and contrast reduction. It is physically possible to produce clouds of any opacity in these spectral ranges. They have two important disadvantages that limit their use. First, the cloud itself is highly detectable, and its presence is an indicator of activity we would usually prefer to carry out unnoticed. Second, the cloud needs constant replenishment. Their use is limited to short periods when the enemy probably already knows roughly where and when some activity is going on, but there is value in denying him more detailed information about the operation. Such uses fall more into the category of tactical concealment (often associated with complementary tactical deception) rather than camouflage.

Any other alteration of the environment on a scale grand enough to interfere with an imaging system operating at wavelengths of around 10^{-5} meters or less is hard to credit. In these spectral regions, typical spatial resolution is measured in tenths of a milliradian, and typical contrast discrimination is measured in percent. Any treatment applied to or in front of the natural background will be detected, resolved, and recognized for what it is. Unless it completely blocks transmission over a solid angle, like a cloud of smoke, then the sensor will see through the chinks almost undegraded. Again, laser countermeasures are an exception: possibly a high density of retro-reflectors ("cat's-eyes") could interfere with the operation of a laser instrument whose receiver and transmitter are co-located.

Modification of spoor and activity cues is a technique of camouflage that can be used to good effect in this spectral region. It is hard to make a quantitative estimate of the protection it affords, especially since it is normally part of a coordinated effort combined with other camouflage measures.

Technically, decoys are possible in this spectral region. However, because of the high discriminating and revolving power of optical instruments in the visible and IR spectra, the decoy must be as large as its prototype and have considerable detail to be convincing. This will make decoys expensive and also operationally and logistically burdensome. Decoys operating in these spectral regions probably do not belong in a general-purpose camouflage system, but rather in camouflage tailored to a particular high-value target or as an occasional feature in a coordinated large-scale pattern of combined camouflage and tactical deception.

C. CAMOUFLAGE IN THE IR THERMAL EMISSION SPECTRAL REGION

1. The Significance of Thermal Self-Emission

At visible and VSWIR wavelengths, the electromagnetic emission from almost all targets is scattered ambient illumination. The amount of energy scattered toward the receiver is controlled by the reflectance and texture of the surface. At longer wavelengths, however, thermal self-emission from the target contributes increasingly to the target emission. The thermal self-emission of a hot target may contribute significantly to the total emission at wavelengths from 1 to 2.9 μm (SWIR). In the band from 7.5 to 14 μm (LWIR), the thermal self-emission energy vastly exceeds the scattered energy at night, even when the target is at ambient temperature, and is larger than the scattered energy by day. In between (MWIR), a warm target in the dark radiates more thermal self-emission than scattered light, but an ambient temperature target in daylight returns as much scattered energy as self-emission.

A sensor system in these spectral regions responds only to total radiation, regardless of the source, although the spectrum of sunlight has a very different slope in the MWIR and LWIR than the self-emission from normal targets. The typical thermal IR imager operates only in a comparatively narrow band, where the atmosphere is transparent. In principle, the total target emission can be adjusted by controlling either the scattered energy or the thermal radiation separately. However, if we match the emission of a particular target to the background by controlling thermal emission only, and the ambient radiation level changes, the background radiance changes but the target radiance* does not. If we match the target to the background by controlling the target's scattered illumination only, and the background temperature changes, then again, the background brightness changes but the target brightness does not.

For effective control of contrast, we must therefore control the sum of the target's scattered and self-emission to match the sum of the background's scattered and self-emission. For such a match to hold when the ambient irradiation (illumination from the sun or from the surroundings) changes, the target must match the background in temperature and emittance/reflectance. A sufficient solution is first to match the scattered radiation by matching the surface reflectances. By Kirchhoff's Law, the emittances are now the same and the self-emittances can, in theory, then be matched by making the surface temperatures the same. Actually, a tolerable match over a moderate range of ambient conditions can be achieved with more reflection and less radiation, or more radiation and less reflection, but any attempt to totally ignore either component is certain to fail.

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*"Radiance" is the term used for infrared "brightness." It is power per unit solid angle per unit area.

A fundamental consequence of this fact is that heat flow must be controlled. It is not sufficient to control only the surface reflectance and emittance. If the target absorbs heat when illuminated by the sun during the day and cools off in the shade or at night, the rate of heating and cooling must be controlled so that the diurnal fluctuation in total target emission tracks the diurnal fluctuation in total environmental emission.

The situation is even more critical if the target has a source of heat within; for example, an engine. If the unavoidable heat flow is not channeled correctly, parts of the target--the radiator, the engine block, the exhaust--will become warmer than ambient temperature and "glow" in the long-, medium-, and even the short-wavelength IR as "hot spots." Insulating the source will hold the heat in for a bit, but eventually it will have to go somewhere.

If the target contains a heat source, camouflage requires that the excess heat be leaked, pushed or pumped out in a harmless manner. Otherwise, it will "ooze" out in unpremeditated ways, making thermal hot spots and destroying locally and conspicuously the match between target radiation and environmental radiation.

The most obvious way of efficiently disposing of the heat is by heating the air, because reject heat cannot be observed by an IR sensor if it does not heat some substance (local objects such as trees, or the ground, or dust) capable of radiating in the IR bands of interest. If the rejected heat is blown out into the atmosphere away from any objects, it will chiefly warm up only the local atmosphere, and air cannot emit IR radiation, except in the absorption bands of atmospheric water vapor and CO_2. However, Kirchoff's Law again ensures that the atmosphere will absorb at those wavelengths where it can emit, and these bands are effectively self-masked at moderate radiating temperature by the atmospheric absorption bands, especially from large distances. (See Figure II-23.) Also, an efficient thermal imager carefully filters out radiation from all those wavelengths where the atmosphere emits. That energy would merely load the detector and contribute statistical noise. It has thus a spectral sensitivity curve matched to the atmospheric windows. For exceedingly high temperature air streams, self-masking will not work because the broadening of the hot gas bands enables the radiation to penetrate the earth's atmosphere at wavelengths that are not fully absorbed. This situation prevails in the exhaust plumes of aircraft and missiles, but rarely in the exhaust of ground equipment. Exhaust air temperatures up to 300°C are probably safe.

When using thermal insulation and air cooling to suppress the signature of a hot engine, one must be aware that the insulator skin may exhibit an unusually short thermal time constant and thus produce a detectable signature in changing ambient temperatures.

2. Thermal Suppression

The basic objective of thermal suppression is to develop a thermal control subsystem that will maintain all viewable exterior surfaces within ±4°C of the background. A gas exhaust stream can be hotter than the ±4°C limit, provided it does not heat any other viewable surface or radiate in the atmospheric windows.

The simple temperature criterion serves to uncouple the thermal suppression subsystem design from the related design of any optical suppression subsystem. Further optical suppression techniques require then tailoring the IR spectral emittance of exterior surfaces to control the radiative energy emitted or reflected in selected wavelength bands. The surface optical properties of solar absorptance and IR hemispherical emittance are, of course, key elements in the thermal energy balance at an exposed surface and cannot be uncoupled from the design of the thermal suppression subsystem. A thermal suppression system could involve the use of such hardware items as:

* thermal blankets and radiation shields,
* forced and natural air flow systems,
* optical properties of surface coatings,
* cavity geometries,
* thermal fins, and
* heat pipes or other means of deliberate internal heat transport.

Table IV-1 compares a number of candidate thermal suppression techniques.

a. Ambient Air Considerations

The ambient air is the only easily accessible, non-radiating or at least self-masked heat sink for most practical heat sources, as well as for absorbed solar energy. The basic thermal problem is to transfer the generated and absorbed heat to the ambient air in a reliable and cost-effective manner, while maintaining all viewable exterior surface within 4°C of the temperature of the ambient background. With much greater effort, heat can be dissipated underground or in water in configurations that will not generate a detectable hot spot on the surface, but these alternatives are hardly suitable for general-purpose camouflage.

b. Thermal Blankets

The use of thermal blankets to reduce the flow of heat in certain directions will not solve the problem by itself. The heat still has to be disposed of. A poor quality blanket will result in heat leaks and cause concentrated hot spots. A high quality thermal blanket can show a rise in surface temperature of the exposed layer due to solar heating. A thermal blanket that is otherwise well made can also show local hot spots from necessary penetrations, e.g., cables, or from the effects of

TABLE IV-1

COMPARISON OF CANDIDATE THERMAL SUPPRESSION TECHNIQUES

THERMAL SUPPRESSION TECHNIQUES	COMPARISON FACTORS
Air Entrainment	• Can be used to cool hot gas stream with ambient air. • Fan power may be required--potential noise source. • Must guard against entrainment of particles at inlet to avoid continuum radiation from hot aerosols not masked by the atmosphere.
Air Flow--Natural Convection	• Used to transfer heat from vertical surface to surrounding air. • Heat transfer rates on the order of 8 W/m^2 with 4°C temperature difference. • Passive design--no power required--no noise generation. • Thermal fins can be used to enhance heat transfer.
Air Flow--Forced Convection	• Used to transfer heat from surface to surrounding air. • Heat transfer rates on the order of 50 W/m^2 with 300 FPM and 4°C temperature difference. Proportional to air velocity to 0.8 power. • Fan power required--potential noise source. • Thermal fins and heat exchanger matrix can be used to enhance heat transfer.

TABLE IV-1

COMPARISON OF CANDIDATE THERMAL SUPPRESSION TECHNIQUES

(continued)

THERMAL SUPPRESSION TECHNIQUES	COMPARISON FACTORS
Porous Layer	• Acts as a heat exchanger when cooled by air flow through thickness. • Can absorb incident solar energy over an extended depth. • Can partially transmit incident solar energy. • Pore size, thickness, choice of material and optical coatings (paints and dyes) will all affect optical characteristics and heat transfer rates. • Can absorb IR emissions from underlying warmer regions. • Can absorb and transmit a large fraction of incident laser illumination.
Liquid Entrainment	• Cooling of hot (exhaust) gases can be achieved by mixing with small droplets of evaporating water. • Cooling liquid is being expended--resupply is required. • Power may be required to pump water into gas streams. • Transpiration cooling of heated surfaces is possible.
Heat Pipes	• Simple and rugged passive device for transferring heat over an extended distance with low temperature differences. • Condensing section must be above evaporating section in gravity field with no low points in system. • Can be used to transfer heat from a small, high powered source to an extended, air cooled finned heat exchanger. • Can be flexible for ease of installation.

TABLE IV-1

COMPARISON OF CANDIDATE THERMAL SUPPRESSION TECHNIQUES

(continued)

THERMAL SUPPRESSION TECHNIQUES	COMPARISON FACTORS
Liquid Loop	• Can be used to transfer heat over an extended distance. • No severe limitations on size or elevation of heat source or heat sink, e.g., can be used to cool extended lengths of electrical cables. • Pump power required--potential noise source. • Can be made closed loop and self-contained to eliminate need for filling and draining. • Vulnerable to damage (loss of coolant).
Optical Coatings--Thermal Suppression Only	• A reduced solar absorptance will reduce the heat that is absorbed by solar illuminated surfaces, minimizing the heat to be transferred. • A high IR hemispherical emittance at wavelengths outside the windows will maximize the power emitted at a given surface temperature, thereby minimizing the heat that has to be transferred by other means while maintaining the surface within ±4°C of ambient air temperature (for low emittance in the windows). • Coatings (surfaces) that permit a significant fraction of the incident solar energy to be transmitted to a substrate layer will reduce the quantity of heat to be transferred away from an illuminated surface. • Specular coatings will cause mirror type reflections of environment and any incident radiation. • Lowest solar absorbance/IR emittance coatings (α/t) are specular second surface mirrors (optical solar reflectors). • Coatings for visual camouflage effects will not typically have a low (<.3) solar absorptance.

TABLE IV-1

COMPARISON OF CANDIDATE THERMAL SUPPRESSION TECHNIQUES

(continued)

THERMAL SUPPRESSION TECHNIQUES	COMPARISON FACTORS
Geometric Cavity--Micro Scale	• Surface cavities will increase effective solar absorptance and IR emittance of exposed surface. • Can trap small particles, e.g., dirt. • Will enhance the diffuse (Matte) finish visual effect. • Can act as an extended surface for heat exchange with air flow.
Geometric Cavity--Macro Scale	• Can be used to send emitted or reflected radiative energy in preferred directions. • Can locally concentrate incident solar energy causing local hot spots. • Can increase retro-reflected energy, e.g., radar. • A smooth, convex exterior configuration is easier to insulate with uniformly good quality thermal blankets.
Thermal Blankets	• An effective technique to restrict radiative, and conductive heat flow in selected directions. • Foams, powders, and metallized plastic sheets are common materials of construction. • A rugged and passive item of hardware that can be easily fabricated in large areas. • Exterior layer can be coated to achieve desired effect, e.g., visual camouflage. • Most easily applied to smooth, flat surfaces. • Good design and fabrication techniques needed to achieve a high quality blanket of uniform quality, i.e., no local hot spots.

installation, e.g., local compression around a mounting point. Thermal blankets can be used to reduce both conductive and radiative heat transfer. The use of a thermal insulation system that stands off from the equipment being protected permits the use of a cooling system between the blanket and the equipment, thereby reducing the temperature difference across the blanket.

The use of forced convective air flow is an obvious way to cool a heat source or any other part of the thermal suppression system to near ambient air temperature. Cooling air flow rates on the order of 100 to 300 feet per minute are typically used in commercial equipment where consideration of total power consumption and self-generated noise levels are important. Since the temperature of the ambient air increases as it picks up heat from the equipment being cooled, it is important that the exterior viewable surfaces be the first surfaces to be cooled by the ambient air. Air flows across the exterior surface are thus not as good as an air flow inward through the exposed surface.

The pressure drop associated with drawing air through a porous exterior surface will impact both the fan power required to provide the air flow for cooling and the structure required to support the exterior layer. Also, a relatively airtight seal will be needed between the exterior layer and the ground. Such a seal could be provided by a sand- or dirt-filled or air-inflated fabric tube around the base of the system. The power required to drive the fan will depend on the volume of air flow and the total pressure drop as well as the fan and motor efficiency.

The total air flow requirements for surface cooling could be partially provided by the intake air to an engine. The total air flow required could be reduced by selectively air cooling only those exterior surfaces which are heated by the sun. This could be accomplished for stationary equipment by selectively orienting the exterior cooled section toward the sun at installation time. As an example, an air flow velocity of 300 feet per minute through five sides of a 1-m cube would require a total volumetric flow rate of 16,200 ft^3/minute. If only three sides have to be cooled, the total flow rate requirement drops to 9,700 ft^3/minute.

c. Coatings

Optical coatings such as paints, dyes, and thin-film interference layers on the exterior surface will affect the amount of solar energy absorbed, reflected, or transmitted by the exterior layer and the amount of energy emitted in the IR for a given surface temperature. The goal of maintaining the exposed surfaces within ±4°C of the ambient background temperatures will require control of the amount of solar energy absorbed by the exterior surface layer, while ensuring that the proper visual (and radar) camouflage is maintained. Solar energy that is not absorbed at the exterior surface layer is either reflected, absorbed in the bulk of the layer, or transmitted through the layer.

d. Porous Layer

A ventilated porous surface layer is one approach to satisfy the requirements of a thermal suppression system. A porous felt or fabric layer partially absorbs and partially transmits the incident solar energy. The layer is cooled by slowly drawing air inward from the surface. The thickness of the layer, density of the material, pore size, and the choice of paint would all affect the amount and depth of the solar heating and the air pressure drop (power required to cool the surface).

e. Cavity Effects

The "cavity effects" in a thermal suppression system occur at both the macro- and micro-scale of dimension. At the macro, or full system, level, it is much easier to design a temperature control system when the exterior surface geometry is smooth and convex; i.e., planar, cylindrical, conical, etc. A complex exterior shape with concave geometries can cause local concentrations of reflected and absorbed sunlight (with a resulting temperature rise) as well as compound the difficulty of applying a uniformly good thermal blanket. Concave exterior cavities can also increase the intensity of retroreflected radiation.

On the microscopic scale of pores in the exterior layer, the "cavity effect" will cause an increase in the effective solar absorptance or IR emittance of the surface because of multiple internal reflections. The micro-scale cavities will also increase the absorptance of the exterior surface to illumination from laser sources.

f. Heat Pipes and Fluid Loops

A heat pipe is a passive device capable of transferring a significant amount of heat over an extended distance with a low temperature difference. In a gravity field, however, it works only when the evaporating section is lower than the condensing section and when there are no intermediate low points. A heat pipe could be used to transfer heat from a small package with a high power dissipation to an extended air-cooling fin mounted above the source, and to solve other specific thermal problems.

3. Elimination of Hot Exhaust Gases

The basic thermal problem in hot gas elimination is to get rid of the hot gas without heating viewable surfaces. Thermal blankets on the exterior of the exhaust system hardware will minimize heat leaks and maximize the exhaust heat that is transferred to the gas stream. Additional air cooling of the exterior layer of the thermal blanket will further reduce the IR signature from the exposed surfaces surrounding the exhaust system.

The exit aperture of the exhaust system, however, is potentially a very strong source of thermal IR. Its temperature is very high and it forms a cavity, thus increasing its effective emittance. The exit aperture must therefore be shielded from view as a first step in reducing the IR signature from this source. Any change in final direction of the hot exhaust gases away from a vertical direction would also have to be examined for adverse effects, particularly in a prevailing wind. It can readily lead to raising the temperature of nearby surfaces by several degrees.

The elimination of heat cannot be accomplished entirely without some radiant thermal emission. A radiation detector looking directly in along the axis of the stream of exiting hot air will see a radiation hot spot. However, the designer can choose the direction. Vulnerability can be limited to a small cone of viewing angles near vertical or away from the FEBA by directing the hot gas appropriately. This will materially reduce the thermal IR signature.

4. Other Countermeasures

All of the countermeasures mentioned in Section B above can also be considered in the thermal IR range. Those affecting the target reflectance are effective only if thermal emission and suppression are also taken care of. Nets, screens, barriers to electromagnetic propagation, protective cover, and defilade are effective alone, providing only that target heat does not produce a hot spot in the camouflage. A thermal IR decoy would, of course, contain a radiation source. Such a countermeasure is not passive.

D. COUNTERMEASURES IN THE RADAR SPECTRUM

1. General Categories of Radar Countermeasures

In a radar surveillance or target acquisition device, electromagnetic energy from the radar transmitter illuminates the target, the target scatters some of the incident energy, some of the scattered energy returns to the radar receiver, and the receiver detects and displays the returned energy. At the same time, circuit noise and scattered energy from scatterers other than the target also produce returns at the receiver. These returns are called clutter. Detection and target identification are achieved only if the target return is large enough to be seen among the clutter and if, after detection, it can be distinguished from non-target returns. The two most obvious ways to degrade radar performance are to decrease the magnitude of the target return and to increase the number or magnitude of the clutter returns.

Radar does not produce an image of the target like an optical image on the retina or a photographic plate. The radar signal is a train of electrical pulses. The picture generated in a PPI (plan position indicator) or a side-looking (scanning) airborne radar (SLAR) is synthesized from the electrical signals by a process very much like the synthesis of a TV picture from a video signal. The synthesis of a picture in a synthetic aperture or moving-target-indicator (MTI) radar is even more complex. In no case is there a direct analog picture that can be perceived by the human brain. The process of synthesizing the picture is fragile and susceptible to many forms of disruption. Altering the signal from the target to interfere with this signal processing or confusing the discrimination between target signals and noise and clutter is a third valid countermeasure. All passive countermeasures can be identified with decreasing the target return, increasing the clutter, interfering with the signal-processor's ability to discriminate between target and non-target returns, or some combination of the three.

Table IV-2 lists the available types of radar passive countermeasures and shows which of these three mechanisms they invoke. The several types will be considered in succession.

2. Absorbing or Isolating Surfaces

Radar absorbing material (RAM) is a term used for a variety of materials that absorb energy from radar waves. Practical radar absorbing materials must either be complex or thick. There is no such thing as "black paint" in the radar spectrum, because any simple homogeneous layer is partly transparent unless it is thick compared to the wavelength of the incident radiation. The wavelength of radar waves is typically from one to 30 centimeters. A common form of RAM is a distribution of carbon or ferrite particles in a supporting rubber or plastic layer, with the particle density varying with depth below the surface. Other common forms are impregnated plastics, fibers, and cloth in which metal and graphite materials have been interspersed. All of the materials can be made up in rigid, semi-rigid, or completely flexible formats.

RAM is frequently classified as "magnetic" or "dielectric gradient" depending on its construction. Magnetic RAM is based on ferrite constructions, while dielectric gradient RAM is composed of a number of lossy layers of a carbon foam. These are sometimes referred to as "volume" dielectric gradient absorbers. Another form is a laminate of thin sheets of lossy material separated by low dielectric layers. This is referred to as a "Jaumann" absorber, and depends for its effectiveness on destructive interference from multiple reflections among the layers.

Another form of RAM is realized by creating geometric patterns of resistive material on a substrate which can be sandwiched into a honeycomb structure. The resistive patterns are usually matrices of dipoles or loops or squares and can be represented by equivalent circuit analogs. The key parameter of these devices is the admittance of the printed

TABLE IV-2

GENERAL CATEGORIES OF RADAR CAMOUFLAGE TECHNIQUES

AND HOW THEY DEGRADE RADAR PERFORMANCE

RADAR CAMOUFLAGE (PASSIVE RADAR COUNTERMEASURE) TECHNIQUES	ALTER OR REDUCE TARGET RETURN		INCREASE NOISE CLUTTER AND FALSE TARGETS		DEGRADE SIGNAL PROCESSING OR DECEIVE DISCRIMINATOR
	INCREASE TRANS-MISSION LOSS	DECREASE OR ALTER TARGET SCATTER	INCREASE EFFECTS OF EXISTING SCATTERERS	ADDING NEW SCATTERERS	
Absorbing or isolating surfaces.					
. resistive coatings		✓			?
Impedance-matching or isolating layers.		✓			?
Substitution of materials with less undesirable radar scattering properties.		✓			✓
Alteration of surface shape.					
. to scatter in less undesirable direction		✓			✓
. to facilitate absorption		✓			✓
Screens-scattering, absorbing or both.					
. fixed in place	✓			✓	✓
. suspended or slowly falling in the atmosphere	?			✓	✓
Natural--tactical siting					
. In foliage	✓		✓		✓
. By defilade	✓		✓		
. In high clutter terrain			✓		✓
Artificial scatterers.					
. large aggregate cross section to force elevation of radar detection threshold				✓	✓
. Numerous significant false targets to saturate initial target recognition mechanisms				✓	✓
Patterns of scatterers and reflectors					
. Distributed in space and time to mislead final discriminator by mimicking real targets				✓	✓

array, which depends on the geometry of the figures and the conductance of the resistive material used. The sheet on which the array is printed is then laminated to a dielectric spacer which is in turn attached to a metal sheet. The thickness of the spacer is one-fourth of a wavelength of the frequency of the incident field which is to be attenuated. The principle involved is that of the Salisbury screen: if a thin sheet with the impedance of free space, i.e., 377 ohms per square, is placed one-fourth of a wavelength in front of a conducting plane, incident RF fields will not be reflected from the surface. Obviously, choosing a particular spacing restricts the operation of such a device to a single frequency, which is undesirable for RAM applications. The remedy is to laminate several screens with several layers of differing thicknesses so that a number of frequencies can be attenuated. The frequency-thickness dependence limits the application of circuit analog RAM made with dielectric spacers to the higher frequency ranges from 2 to 18 GHz.

Hybrid RAM combines the techniques of circuit analog and magnetic RAM in a single design to take advantage of the capabilities of each of those techniques. In so doing, it retains the superior low frequency performance and small thicknesses of the magnetic type of materials, and the controlled design procedures developed for the circuit analog material. Hybrid RAM is an attempt to respond to the need for a broadband and yet thin radar absorbing material. In general, hybrid RAM offers very promising performance characteristics, but it possesses some inherent difficulties in terms of its weight, which generally runs from two to four pounds per square foot compared to less than one pound for the dielectric gradient types, and it is made up as a multi-layer laminate with ferrite layers that are complex to fabricate and control. Generally speaking, the dielectric materials tend to be light in weight, less than one pound per square foot, relatively thick for broadband operation and fairly effective in the higher frequency regions. Magnetic types of RAM are generally heavy, two to four pounds per square foot, relatively thin and function more effectively at the lower frequencies. Circuit analog RAM offers greater design freedom for which the tradeoff is a greater complexity in design and fabrication, and potentially lower reliability. Hybrid RAM, which attempts to combine the best qualities of the circuit analog and magnetic RAM, tends to possess many of the qualities of magnetic RAM in terms of weight and material control: although it offers the greatest promise in overall bandwidth, it remains a quite complex and costly material to produce.

Under field conditions, the effectiveness of any of these materials in reducing signal returns from ground targets of the combat vehicle or artillery class is not at all evident. Most of the data on RAM attenuation are obtained from reasonably large flat panels in laboratory set-ups with very few data on the effects of angles or incidence, or polarization. Values of the order of 10 to 15 dB of echo reduction are reported in many cases over the bands of frequencies discussed, but the effects of covering an actual target with all of the edges, corners, curves, and other geometric effects present could render such values academic. Actual tests performed using tanks covered with RAM have not been encouraging, for the reductions in target strength achieved rarely exceed 4 dB.

While some of the forms of materials discussed were ostensibly rugged, the nature of most of the RAM designs is rarely geared to survive operational wear, handling and maintenance on aircraft, much less ground vehicles such as tanks. The effects of distortion or other degradation caused by the environment, such as continuous wetting, abrasion, or loading with sand or salt, and other conditions encountered in ground operations remain open questions. One can speculate that the use of RAM is most feasible when applied to aircraft, missiles or stationary ground structures.

Some materials let electromagnetic energy pass into or through them in one direction, but will experience very high attenuation in the opposite direction. These non-reciprocal properties are the result of Faraday rotation, and are achieved by the application of a magnetic field to a ferrite material through which the electromagnetic wave is passing. A significant amount of work has been done in developing isolator devices to be used in transmission lines as phase shifters, isolators, or circulators.

To use such materials to camouflage ground targets would require that they be supplied in sheets or panels just as the magnetic type of RAM discussed previously. Furthermore, weight and limitations on frequency range would again become significant. At present not enough information and data have been found on applications of such radar isolator materials (RIM) for use as radar attenuators to provide the basis for a serious evaluation.

Another form of isolator depends on a polarizing grid spaced one-quarter wavelength from a metallic surface. Realization of such an isolator requires precise control of the conditions of the incident electromagnetic wave, the polarizing grid, and the received or reflected electromagnetic wave. The required degree of control and the sensitivity of polarized radars to random polarized scattering from the target would appear to make polarizing isolators impractical for any but very exceptional targets.

Although the reflectivity of large flat sheets of RAM and RIM is less than that of a metal plate by 15 dB or more, the materials are not so effective in reducing target strength. Reductions reported in actual measurements range from almost zero to 4 dB or so. The principal reasons are the finite-wavelength diffraction effects at curves and edges, departure of the angle of incidence from normal to the surface, and the difficulty of keeping the surface perfectly clean.

At higher frequencies (millimeter waves) the difficulties of reducing radar target strength with reflection-reducing coatings should become easier, for two reasons. In the first place, the thickness of material required to make an effective impedance match is proportional to wavelength. The layers should be one-third as thick from 30 to 100 GHz and one-tenth as thick at 300 GHz as they are at 10 to 30 GHz. Alternatively, the electrical thickness, that is, the thickness in wavelengths, can be greater at the higher frequencies without exceeding practical limits. In the second place, the diffraction effects of edges and corners are reduced relative to the surface effects of large smooth faces, and so the behavior of reflection-reducing material on the necessarily irregular surface of a target will more closely approximate the behavior of an infinite plane sheet at the higher frequencies.

3. Materials with Less Undesirable Radar Scattering Properties

Metals are almost perfect reflectors of electromagnetic radiation at radar frequencies. Many glasses, plastics, and composite materials are nearly transparent, and many can be loaded with lossy fillers to have a desired degree of radar absorption. This, together with structural reshaping, has proved effective in drastic reduction of the radar cross-section of missiles and aircraft when the importance of radar camouflage warranted the total structural redesign of the threatened target.

4. Alteration of Shape

The multi-edge and re-entrant corner geometry of many targets enhances the radar return at particular angles of incidence and orientation, but the reductions possible by refurbishing or redesigning most targets are far too small to make it worthwhile undertaking the major effort involved. While new designs should take into account the fact that planar orthogonal intersections and edges tend to produce enhanced radar returns, a program to physically alter the shape of existing vehicles does not seem feasible. Larger targets whose shapes may be dictated more by convenience than by operational requirements might benefit from a re-shaping program to avoid offering re-entrant geometry at typical observation angles and orientations. Any such reshaping will rarely cause the median radar scattering cross-section of the target to drop by more than 4 dB. However, for those cases where reshaping can be applied conveniently to existing structures and built into the design of new structures, further investigation of relative cost/benefit is warranted.

5. Screens

A fixed net or screen made of materials transparent to radar can be transformed into a radar absorber by adding to it controlled amounts and distributions of lossy and radar scattering material. This is the principle of "radar garnish" applied to visual camouflage nets. Radar absorption can be built into the net initially, rather than treated as an add-on. The present net specification calls for low transmission of radar through the net to obscure the radar signature of the target under the net. Unfortunately, the elementary ways to reduce transmission in a thin layer result in high reflectance or scattering. If the net, which is physically ten to one hundred times larger than the target it hides, has high reflectance or scattering, it is itself a large, conspicuous, and often characteristic target. Better built-in radar absorbers are required.

The same or similar scattering and lossy materials can be suspended in the atmosphere to impede the propagation of radar waves. (See Section 7 below.) Clouds of pieces of metal foil, called chaff or window, have been used since World War II to defeat radar aimed at aircraft, and have the same effect on radar propagation that a cloud of smoke has on propagation of visible light. Because constant replenishment is costly, the method is of limited use. Also, the cloud of chaff itself is an enormous, although featureless, radar target whose presence reveals some kind of purposeful activity. For brief protection against counterfire radar, chaff could be made quite effective.

6. Tactical Siting

A very simple and effective way to avoid radar detection is for the target to be under cover either of vegetation such as trees or in defilade, i.e., the shadow of large natural obstructions such as hills, embankments, or tree lines. Such cover almost guarantees protection from detection since the radar cannot see the target. The next best remedy is to stay in areas of high clutter such as ground vegetation or very rocky irregular surface terrain which present a high clutter level to the observing radar. Obviously, it is difficult to move in such terrain, so that such solutions are not always feasible for combat vehicles; however, for less mobile targets such as missile or SAM batteries, or headquarters structures and other supply points, such natural siting cover is ideal in terms of radar protection. This approach is as much a matter of battlefield discipline as it is a countermeasure which can be "applied" to ground targets. Implementation of this technique would require a field operating manual to train personnel to recognize the value of terrain, foliage, or tree cover to avoid or delay enemy detection and identification.

The effectiveness of tactical siting depends entirely on what is available. A few tens of meters of leafy foliage is an almost complete absorber of any radar frequency contemplated today, as is a few meters (in most cases, a few decimeters) of rock or earth. If the observer is looking down at a steep angle from above, the protection afforded is less, for simple geometric reasons; but this is partly compensated for by the fact that ordinary ground clutter increases with the steepness of the observation angle.

Even if no actual cover is available, some protection can be achieved by locating near places where natural features such as rugged outcroppings, ploughed fields, and clusters of buildings produce large background clutter. An urban dump or junkyard produces a tremendous radar return.

7. Artificial Scatterers

Many materials scatter or reflect incident radar energy in a relatively random fashion, possibly with some lossy absorption. These materials include aerosols, metal strips or fibers, solid or flexible materials whose surfaces are electromagnetically rough, and tinsel made either of conducting material such as aluminum, or metal coated non-conducting strips or pieces.

Of all the possible forms of scattering materials, tinsel* has the longest and most successful record. Small, very thin strips of metal foil are cut to lengths corresponding to near-resonant dipoles at the frequencies which it is desired to attenuate. Each strip, considered to be a dipole, has a median scattering cross-section of $0.16\lambda^2$.

In the 3- to 30-GHz frequency range, it is easy to form material of such dimensions that one kilogram has an aggregate potential scattering cross-section of 2,000 square meters. With practical dispersal mechanisms, in spite of all the vagaries of frequency, wind and weather, an effective back-scatter level over a broad band in excess of 200 square meters per kilogram of material can be achieved reliably and repeatedly.

A kilogram spread over a region whose projected area is many hundreds of square meters will create scatter energy nearly isotropically, and will create a false target with a radar cross-section of 200 square meters or more. The same amount in air, suspended in a volume whose projected area perpendicular to the direction of propagation of the radar wave is 200 square meters or less, will scatter most of the incident energy, effectively attenuating the direct transmitted wave.

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*Material of the type described in this paragraph is commonly called chaff, but the term chaff is properly assigned only when the material is suspended in (or designed to be suspended in) the atmosphere. We use the word tinsel to emphasize that we are not limiting ourselves to airborne suspension.

That which gets through the cloud of airborne tinsel and strikes the target is reflected back through the tinsel and is once again scattered so that there is a very efficient attenuation of the radar signal. If it is desired to avoid scattering back even the small fraction of initially incident power, the tinsel can be made up in the form of lossy strips or wires whose parameters of thickness to length and resistivity can be controlled to produce almost no back scatter and high absorption of the incident wave. Once again, any power that passes through the tinsel cloud to the target is reflected back into the cloud and is further attenuated. Both the specular and the absorbing type of tinsel are extremely effective in shielding the target from observation.

The use of such materials to protect ground targets remains largely a question of deployment. In air strike tactics the usual method has been to have a "tinsel aircraft" fly in before the attacking aircraft and sow corridors of the material to prevent radar observation of the following attackers. In the case of ground targets, friendly aircraft would have to fly over the area to be protected and sow a cloud of tinsel at a sufficiently high altitude and of a proper density and material to float slowly down to shield ground activity from enemy reconnaissance aircraft. This may not be practical for very large areas of many square miles; however, for local assembly of vehicles or personnel where a delay of several hours in terms of enemy observation would be significant, the air-dropped tinsel may offer some advantage. Deployment by artillery shells of such tinsel material is also quite feasible and has been used for camouflage purposes.

The sources we have consulted do not state whether dipoles strewn on the ground, or hillsides, on trees or on grass would be equally effective scatterers. Knowing the mechanisms of electromagnetic coupling to a short straight conductor, one would imagine that a dipole lying on a non-conducting surface or dangling a half-wavelength or more from material objects would couple to the electromagnetic field about as well as when suspended in the air. If any serious thought is given to using tinsel to create decoys and artificially augment clutter, the issue must be investigated.

8. Radar Decoys

Originally, decoy meant a small vehicle of low value outfitted with reflectors to make its radar return resemble that of a larger, higher value target. The word has been extended to mean any assembly of reflectors deliberately formed to mimic the radar characteristics of a high-value target, or to make the radar return of one class of target look like that of another. Decoys can be made up of reflectors shaped in re-entrant geometries such as dihedrals and trihedrals, or Luneburg lenses or reflecting antenna arrays. A large number of such reflectors scattered in an area containing other real targets create enough background return to make real target detection or identification extremely difficult. In the simplest application, such decoys can be used to simulate fixed targets such as bridges or buildings or stationary ensembles of combat vehicles and other army ground equipment.

Since most radars are not imaging radars, that is, they do not provide a physical picture of the targets and terrain observed, differentiation of decoys from real targets is almost impossible without very informed radar interpretation. Indeed, all detection and identification depends very heavily on the skill and a prior knowledge of the interpreting observer. Usually the cues used are the brightness of the target return, the configuration or grouping of targets, and the location of the targets. The interpretation is usually performed by individuals who are specialists not only in radar displays, but also in ground force tactics and operations.

E. ACOUSTIC AND SEISMIC CAMOUFLAGE

The most important sources of sound and vibration are large guns, heavy vehicles and mobile equipment, and large engines. The sound that is radiated and the impulse that is transmitted to the ground when a large gun is fired can be reduced somewhat by blast deflectors, silencers and recoil momentum absorbers, but inevitably anything that launches a mass of tens of kilograms at supersonic velocity will make a loud noise and a big shock. Whether these are detected at a distance depends more on the vagaries of the transmission rather than on a reduction of five or ten decibels at the source.

With respect to vehicles, mobile equipment, engines and noisemakers other than guns, the situation is different. Suspensions, drive trains, exhausts, pumps, impellers, turbines, and all kinds of mechanical systems and subsystems can be designed and built to reduce noise and vibration. This has been demonstrated in military equipment with submarines and certain reconnaissance aircraft, and in the civilian sector with highway vehicles and airport noise abatement programs.

In recent years, vulnerability of army equipment to acoustic detection has not been a critical issue, and there is no reason to believe it will become more critical soon. However, acoustic detection, especially by telemetered remote sensors and covert patrols, is important enough to add motivation for a program of noise and vibration reduction. The noise and vibration of vehicles and machinery can be reduced considerably without impairing its effectiveness, and the people working around it will benefit in many ways besides less vulnerability to acoustic detection.

V. CAMOUFLAGE SYSTEM SPECIFICATIONS

A. INTRODUCTION

Battlefield camouflage against surveillance and target acquisition sensor systems was selectively reviewed from three different points of view in Chapters II, III, and IV. Chapter II is primarily concerned with sensor systems and what they can do, now and in the future. Chapter III is concerned with targets, their vulnerability to detection, identification and target acquisition, and their ability to withstand, resist or avoid the consequences. Chapter IV is concerned with passive surveillance and target acquisition countermeasures and the contribution they might make to softening the consequences of perception of targets. The purpose of Chapter V is to describe a synthesis of these three points of view in a time-phased program of passive countermeasure development.

The development, deployment and use of passive surveillance and target acquisition countermeasures is limited by the availability of resources. The decision about what to do and what to leave undone must be based on a joint evaluation from the three points of view, briefly:

- How effectively can various sensor systems detect and identify targets?
- How important are various targets and how grave are the consequences of their detection and acquisition?
- How effectively can various countermeasures prevent, delay, or ameliorate the consequences of detection or identification within acceptable costs, operational constraints, and logistic and manpower burdens?

From a development engineer's point of view, it is tempting to develop anything that promises to defeat a sensor system. However, enthusiasm for a particular development must be moderated (1) if the sensor it defeats is unlikely to be used, is known to be ineffective, or can more easily be defeated by other means; (2) if the target is unimportant, the circumstances under which it might be detected are rare and specialized, or the consequences of detection and identification are insignificant; or (3) if the probability that the countermeasure will be successful is small, or the cost of developing it is excessive, or the logistic, manpower and operational constraints that its use places on the target are excessive in proportion to the benefits.

Judgments would be easier to make if the requirements for passive surveillance and target acquisition and countermeasures were firm, of the form "reduction of the radar scattering cross-section of target A to a mean over all aspect angles of 1 square meter and a peak of 5 square meters at S, X and K bands is required, no further reduction in target strength has value, and no less reduction in target strength is worth pursuing." Unfortunately, firm and precise requirements like these will never be found in passive countermeasures. In a sufficiently detailed scenario one might be able to show that a given family of radars would detect a 10-square-meter target with near certainty and a 2.5-square-meter target with almost negligible probability, but it would have to be controlled as strictly as a laboratory measurement. When we consider the variety of targets, battlefield tactical situations, and sensor systems, all surveillance and target acquisition countermeasure requirements become soft. In Reference 23, theoretical arguments were developed to support the observation that under normal field conditions many radar targets will be detected while many similar targets will remain undetected, and that an enormous amount of radar signal suppression is required to reduce the detectability of a highly visible population of targets under varied conditions of exposure to a negligible amount. The example of the very gradual reduction of visual detectability of a tank with increasing range shown in Figure II-12 shows that much the same is true for visual camouflage. At this level of generalization, IR imaging systems can be expected to behave much like visual detection systems, and laser systems much like radars. Overall, many countermeasures will reduce average detectability somewhat, but none will eliminate detection and target identification completely.

Radar scattering cross-section must be reduced 20 dB or so, that is, by a factor of 100, to have a major impact on the radar detectability of a large population of targets. Visual contrast must be reduced from the order of unity to below 0.02, again by a factor of around 100, to assure successful camouflage of a large population of targets by blending, and the same will be true of IR imaging systems. Surface temperature differences must be reduced from hundreds of degrees Celsius to less than 4 degrees to be sure of defeating thermal sensors all the time--again a factor of around 100. The situation is somewhat more vague with laser instruments, but one could postulate that the target strength must be reduced below the level of atmospheric and foreground back-scattering to be a completely effective countermeasure. Again, a reduction of at least a couple of orders of magnitude appears to be called for. When we talk about interrupting the transmission between the target and the receiver with barriers, screens, or attenuating clouds, an equivalent reduction in signal-to-noise ratio must be achieved. Similar arguments hold when one reduces the probability of detection or recognition by artificially augmenting the noise, as with decoys and artificial clutter.

Generally speaking, if the average performance of a surveillance or target acquisition system is good under the wide variation of conditions found in the field, passive camouflage must reduce its effective signal-to-noise ratio (or its equivalent) by two orders of magnitude to make it unsuccessful under the most favorable conditions. On the other hand, reductions of the effective signal-to-noise ratio by a factor 10 or less may still confer significant benefits.

B. OBSERVATIONS, ISSUES AND LONG-RANGE GOALS

1. Paints and Coatings against Imaging Devices in the Visual and Infra-Red (VSWIR, SWIR, MWIR and LWIR) Spectrum

Visual detection means are characterized by high resolution, low threshold of detection, and patterns that are instantly recognizable to the human eye. Under ideal conditions, hand-held optical instruments can achieve a resolution of a fraction of a meter at 10 kilometers. At short range or when the atmospheric transparency is high and scattering is low, intensity contrasts of a few percent can be detected, and color differences multiply the opportunities to discriminate targets from a background and from each other. The output is a pattern which is instantly recognizable by the human eye on the basis of a lifetime of experience. Where a clear line of sight is available, nothing will prevent a viewer from seeing a target of substantial size, but he may be prevented from recognizing what he sees. The best way is to reduce the contrast below a few percent, that is, to match the brightness, color, and texture of the target extremely well with its background. The viewer still sees the target, but he interprets what he sees as part of the background. "Spoiling," that is, altering the superficial outlines of the target or painting on it a pattern that looks like the outline and shadows of something else, degrades detection but not usually enough to make most targets invisible.

Concealment is the most effective camouflage against visual detection. If the target can be put in defilade, under trees, or behind and under artificial barriers like screens and nets (well matched to the background), it will not be seen. Of course, natural cover can be used only if it is present. Artificial cover itself becomes a secondary target, of necessity as large as or larger than the primary target it conceals, and must itself be very well matched to the background. This is difficult but often not impossible.

But one cannot match every background with one paint. The range of luminosity in a typical background covers an order of magnitude and comprises many distinguishable colors. To reliably escape visual detection, the target must be matched to the environment with a luminous contrast of 2% or less. Only a chamaeleon paint that changes to match all background intensities and colors would be a perfect camouflage. Pattern painting and outline and shape spoilers delay visual detection and may prevent recognition altogether. You can change the appearance of the target, but you cannot give it all possible brightnesses, colors, textures, and no recognizable shape with a single treatment.

In the visual domain, we pattern paint with several colors. The colors match typical environmental colors, the spatial scale of the pattern matches typical textures of many environments, and the pattern breaks match outlines and disguise the target shape. The overall result of pattern painting is a much better blend with the environment, but is usually not a perfect camouflage. It is cheap and rugged, and moves effortlessly with the target. Unfortunately, when the target moves from one environment to another, the blend may not be equally successful in the new environment.

We cannot anticipate much improvement in the performance of sensors operating in the visual spectrum. The eye will not change, and hand-held and portable optical instruments already perform close to the theoretical limits imposed by physical laws. Photography is a mature art. Processing time may be cut, incremental improvements in resolution may be made, and film speed may improve substantially. However, improvements in picture quality much beyond the best that is available today are unlikely. High resolution aerial cameras and satellites may become more numerous, but they will remain expensive and thus difficult to deploy in large numbers, and we can predict how well they will perform ultimately.

Thus, the threat in the visible range, though serious, is not likely to get much worse, and the remedies which have been developed will probably continue to be about as effective as they are now.

Today's paints and coatings do not match the IR environment in the LWIR and MWIR ranges, and some obsolescent paints do not even match in the SWIR. No physical law prevents a match over a broad spectrum. However, we have not yet seriously tried to achieve multi-spectrum blending to the environment. Most paint vehicles in use today are brightly emitting in the LWIR, so there is no real possibility of extending the spectral range just by adding pigments. The whole paint will have to be redesigned.

> A plausible goal is to develop multi-spectral paints and patterns that match the color and texture and spoil shape in

the VSWIR, SWIR, MWIR, and LWIR ranges as well as today's pattern-painting does in the visible, without making the matches in the visible spectrum worse.

2. Paints and Coatings against Laser Sensors

Lasers differ from imaging visual and IR devices in five respects:

(1) Except for lidars, laser devices are not used for search, but for some secondary purpose like range measurement or target designation. This means that the role of camouflage is to degrade a return signal rather than to evade detection.

(2) The source is localized; so that reflection and scattering is important only at certain aspect angles; in lidars and range finders, the transmitter and receiver are co-located, so only retro-reflection matters.

(3) The illumination is coherent, in a very narrow spectral band, and typically pulsed at ten to twenty pulses per second.

(4) The devices typically do not make images; in the range finder, only the round-trip pulse travel time matters, and in the target designator, only the spot of the pulsed scattered light that serves as a target for the homing weapon; and in the beam-rider the laser light that reaches the target is of no significance at all to the guidance system operation.

(5) In the case of laser designators, beam riders, and perhaps, range finders the illumination of the target by the laser means that a weapon has been launched or is about to be.

As a consequence of (1), we should make the target "black" rather than matching it to the environment. All the incident radiation should be absorbed or scattered away from the receiver without regard for contrast.

As a consequence of (2), we need not be concerned with all scattering angles when we deal with range finders, but only with scattering that sends light back in the general direction of the source. We can exploit properties of diffuse and specular reflection. Surfaces pointed toward the receiver should diffuse reflectors, so they return only a small part of the incident energy toward the source; surfaces tilted at a substantial angle may be specular reflectors, reflecting nearly all incident energy away from the source. For defense against designator weapons, however, low reflectance at a large cone of angles is important.

As a consequence of (3), we can conceivably meet the apparently conflicting requirement for the target to be "black" under laser illumination and yet blend with the environment under ambient illumination. A coating or paint could be matched to the environment over most of the spectrum with only a narrow absorption band at the laser frequency. However, this remedy may not be effective for long, because a different or even variable wavelength may come into use.

> A reasonable goal is to alter the surface texture of targets to reduce retro-scattering at anticipated laser wavelengths. A similar goal, probably more costly to achieve, is to alter the shape of targets to reduce retro-scattering in anticipated laser frequency bands. A third goal is a paint or coating having a high absorption coefficient at one or more of the "best" laser frequencies.

This latter tactic will probably not reduce the effectiveness of laser instruments, for we cannot cover all possible laser frequencies, but it may succeed in interdicting the frequencies where the cheapest, most rugged, lowest power lasers would work and forcing the adversary to use something intrinsically less desirable and to scrap a large inventory of equipment.

As a consequence of (5), certain camouflage measures that are transient or that disclose the presence of a target, such as smoke, may nevertheless be effective.

3. Coatings and Surface Treatments at Radar Frequencies

Radar coatings are thick, heavy and difficult to use, and often fragile and expensive. Only when the target is very valuable and vulnerable and the threat very limited will they prove their usefulness. An example is a missile in flight exposed to counter-fire radar. The exposure is brief. The aspect angle is constrained. The sensor is one of a very few different radars of largely known characteristics that are extremely effective.

A thin broad-band radar absorbing coat does not necessarily contradict laws of nature, but to make one requires combinations of materials of very special characteristics in complex configurations. Many difficulties stand in the way, and it is probably unrealistic to depend on developing one. Radar coatings as we know them today probably do not belong as a module in a general camouflage kit. Coatings effective against millimeter-wave radar may be used as special-purpose camouflage for particular targets. If the threat from millimeter-wave radar grows somewhat faster than estimated in Chapter II, they might be assimilated into the general-purpose system.

4. Nets

Almost perfect visual camouflage can be achieved with nets if enough time, trouble, and materials are expended. However, the effort and investment are considerable, and usually not practical. The kind of net that can be erected in the field slows down detection and identification but does not prevent it.

The spectral range of effectiveness of net materials has been extended to VSWIR to combat IR photography.

> A plausible goal is to extend the spectral range of effectiveness of net materials further to the SWIR, MWIR, and LWIR.

It should take very little more weight to match the spectrum over five octaves than it does to match it over one or two. In the radar spectrum, present specifications set a limit on the radar transmission through the net material. This specification is most easily met by making the net a good radar reflector, rather than absorber; but a good reflector the size of a net module is usually a rather conspicuous radar target in itself.

Another goal is to build in radar absorption.

Wherever visual and imaging infrared observation are possible, radar can be expected also. When the various combinations of visual, IR and radar backgrounds are considered, a single two-sided net may turn out to be insufficient to match them all.

> Another worthwhile goal is to find out how many different combinations are needed to be as effective over the whole visual-to-MWIR and radar spectra as the present nets are in the visual and VSWIR.

Unfortunately, the usefulness of nets will always be limited. They impose a high manpower and logistic burden. Efforts to make them easier to use and lighter may well be repaid. Nets restrict the operation of the targets they conceal and are almost totally unsuitable for moving vehicles. Nothing can be done about this. Compatibility between nets and thermal IR countermeasures may be a problem. The only safe way to get rid of a large amount of heat is to send it straight up in a column of hot air. This means that nets should be designed to have ducts or chimney holes so the rising column does not heat the net and make it into an IR emitter. (See Section 5 below.)

At least two streams of camouflage net system development are probably needed.

> The goal of the first stream of camouflage net system development (termed n1 later in this chapter) is lightness and simplicity of operation, with whatever degree of camouflage is consistent with those constraints.

Net n1 is extremely easy to pick up or even disposable.

> The goal of the other stream of camouflage net system development (termed n2) is maximum camouflage against all threats.

The net n1 would be used by high vulnerability/low operational flexibility targets such as Target Classes I and II. The net n2 would be used by high or medium vulnerability/high operational flexibility targets such as Target Classes III and IV, and elements in Classes VIII, IX, and X.

5. Countermeasures against Sensors Operating in the Thermal Infrared Spectrum

Improved LWIR, MWIR, and SWIR sensor systems that detect target thermal self-emission along with scattered energy are being developed and put into service in growing numbers. A typical motor generator or vehicular engine may dissipate 100,000 watts, and the solar energy flux is around 1,000 watts per square meter. If such amounts of power flow uncontrolled from a target, it will have a bright thermal signature and be detectable from many miles.

> An important goal is therefore to develop a family of dissipators, heat suppressors, and heat shields for all motor generators and other large stationary heat sources.

The desired level of performance is to reduce the thermal IR signature below the level that would be caused if the target were to differ by 4 degrees from the ambient temperature. A similar family of dissipators, heat suppressors, and shields for motor vehicles and other mobile heat sources is necessary, but a compromise will be necessary in order not to impair their mobility.

A brief digression:
When noise abatement was first suggested, recall that the aircraft manufacturers said the noise from jet engines could not be reduced without killing the aircraft industry. Yet noise reductions of 10 to 15 dB have

been accomplished and are now routine. Similarly, when exhaust pollution from automobiles first became a target of public wrath, the automobile manufacturers insisted that the pollutants could not be removed without completely undermining engine performance, and this has also turned out to be untrue. When the importance of heat suppression and dissipation has been made clear to designers, perhaps a 10-fold or 30-fold reduction in the thermal radiation from the radiators, engine block, and exhaust will be achieved. Every field army engine should have thermal radiation suppression built in the way it has a muffler built in to cut down acoustic radiation. This will not make it invisible to thermal sensors, anymore than a muffler makes it inaudible; but it will cut down the vulnerability to thermal IR detection and target acquisition, and it will reduce the magnitude of the camouflage problem when additional, more heroic measures are needed to suppress the residual thermal signature.

> A plausible goal is to develop engine designs that inherently reduce thermal radiation signatures by 10-15 dB without substantially degrading performance.

A promising approach to keep the outside surface at close to the ambient temperature is to dissipate the heat in upward-directed columns of air and exhaust. Thermal camouflage will still be less than perfect, for there remains one direction from which a hot spot is visible. Perhaps another approach can achieve more.

> A less urgent goal is to develop a comparable family of heat dissipators for sources other than internal combustion engines in vehicles and generators. Heaters, refrigerators, and air conditioners are prime examples.

This goal is less urgent because vehicles and engine generators are inescapably integrated in and widespreadable to the operation of many high-value, high-exposure targets, while many other heat sources such as air conditioners, for example, are not.

Ambient differential surface heating because of insolation and poor control of heat distribution in the absence of heat sources inside the target is also a problem, but it may be easier to solve because the average heat flow from the target is zero. The obvious remedy is to distribute the target heat more uniformly in space and time by matching its thermal lag to that of the environment. A cruder approach is to surround it with a screen that matches the thermal lag characteristics of the environment. The crudest approach would be artificially to heat and cool the target surface with heaters and refrigerators. Unfortunately, refrigerators inherently produce more reject heat than they remove from their cold end.

> A plausible goal is to redesign or coat each target at risk to have a combination of thermal conductivity, thermal capacity, and emissivity so that its combined scattered and self-emitted radiation matches that of the environment.

> A more limited goal would be a thermal screen or coating material whose thermal surface heating characteristics match those of some common environmental material like rocks or earth.

6. Scatterers and Absorbers Suspended in the Atmosphere

In the visual and infrared, we recognize smokes and aerosols. These have two major shortcomings: they require constant replenishment, and their presence is a conspicuous indicator of some kind of activity, which partly defeats the purpose of camouflage. As a result, they are relatively useful only for a tactical concealment, which is not a surveillance but at most a target acquisition passive countermeasure.

Airborne scatterers and absorbers that work at radar frequencies are called chaff. Chaff suffers from the same two shortcomings. Where these shortcomings do not apply, chaff has been used to great advantage. For example, it can briefly camouflage missiles and rounds that are vulnerable to counter-fire radar, a mission that lasts only seconds and involves an operation whose nature is revealed almost instantly whether the presence of a cloud of chaff announces it or not. It is, however, hard to see where airborne scatterers and absorbers fit into a general-purpose passive camouflage system.

7. Build Up the Energy Level of the Background (Clutter Enhancement, etc.)

The indiscriminate raising of the background noise level in any sensor system will degrade its performance. In the visible and VSWIR, SWIR, MWIR and LWIR, shining the sun in the enemy's eyes or the equivalent is no longer a dependable camouflage tactic, although shining a one-kilowatt searchlight directly toward an on-coming tank at short range, even in daylight, seriously disrupts its firing accuracy, target acquisition, and even steering. The resolution and discrimination of the eye and optical instruments (including cameras) is so high that you would have to paint the whole landscape with additional visual scatterers in order to overload the receiver or blank out the image of a target with any certainty. The same is probably true to a smaller extent at the VSWIR, SWIR, and MWIR when imaging devices are considered.

The resolving power and discrimination of radar is much lower, and it is therefore more vulnerable to such passive jamming. If enough high-value targets are massed to make area clutter saturation worthwhile, it can be done with corner reflectors, dipoles, or other coherent or resonant elements. Calculations suggest that one ton of material distributed over a square kilometer might produce returns as large and as numerous as 1000 or more large vehicles, but to the best of our knowledge this has not been verified experimentally.

Many laser devices might be seriously handicapped if the landscape were festooned with garlands of cats-eye retro-reflectors. The concept captures the imagination, but we are not aware of any serious analysis of the idea. The number of reflectors required would be enormous, but they are small and cheap. The analog in the thermal IR is to set out tens of thousands of flares or other thermal IR sources. However, their power consumption would be enormous — no less than a few hundred watts per decoy. The logistic problems are obvious, LWIR lasers might also be used. None of these would be as effective as radar clutter, because the resolving power of MWIR and LWIR devices is much higher than that of radar, so the clutter units would have to be very numerous and spaced extremely close together. Sources that give off thermal radiation are, of course, not really passive countermeasures.

All clutter enhancement schemes suffer from one of the disadvantages of smokes, aerosols, and chaff, to wit, that laying out the field of clutter enhancement in itself provides a target and an indication of some kind of activity.

> A significant goal is to develop radar clutter enhancement material and deployment systems for area saturation camouflage.

A reasonable performance target is material that can produce the equivalent of 1000 point sources of 100 square meters scattering cross-section or more in 1000 discrete pixels with no more than a ton of material.

> A secondary related goal is to investigate the susceptibility of laser instruments to passive jamming with retro-reflectors.

> A third goal is to investigate the availability and usefulness of thermal IR clutter sources of comparatively long operating life.

8. Decoys

Logically, decoys should be effective in inverse proportion to the resolution and discrimination of the sensor system. In radar, a cluster of a few point reflectors can sometimes be an effective decoy; whereas in the visible range, a decoy must mimic a considerable amount of visual detail to be effective. But the visual range provides some compensation in that the fabricator of a decoy can monitor the effectiveness of his efforts with his eyes. Generations of theatrical and motion picture set designers and painters of trompe l'oeil have demonstrated what can be done with simple materials. Visible decoys are already with us, but are used mainly with a few high-value targets and perhaps more in the context of tactical deception than routine camouflage. A decoy needs less detail in the SWIR and MWIR range, but the detail may be harder to supply because the decoy designers and deployers have few IR viewers to monitor their construction. Thermal decoys have been developed to defeat thermal IR homing weapons, but these are really active and short-life devices. Of all the surveillance and target acquisition systems, the one with the poorest discrimination and resolution is scanning radar, and imaging radars are not much better. To the extent that they are an important target acquisition and surveillance threat, decoys could be used against them. In general, decoys must be matched to specific targets. It follows that decoys probably ought to be associated with the targets they mimic rather than with a general-purpose camouflage system.

9. Information and Sensory Feedback

Visible camouflage gets a lot of attention, but we now realize that camouflage against radar, IR, and laser devices is equally important. However, it is hard for the user to sense his vulnerability to radar, IR and laser systems. He can walk 20 yards away and see for himself whether a tank or gun is concealed from view and blended with environment, but he has no immediate feel for whether it is concealed from radar, laser range finders, or thermal IR detectors, because the human eye doesn't register these energy sources, and their peculiarities are not distinctively familiar to him. We need to be able to "see" these and other detection and identification cues for several reasons.

- Where adaptive countermeasures are used (nets, tactical siting, etc.), we need a way to assess the need for and measure the effectiveness of camouflage that appeals to direct observation rather than to rules and handbooks.
- It might be desirable to have a basis for estimating vulnerability to surveillance and target acquisition, even if there is not much that can be done about it.
- We need to counteract the present overemphasis on visual camouflage. Efforts and resources that ought to be devoted to radar,

infrared and laser camouflage are poured into visual camouflage because we can see the results.

A reasonable goal is to assess the benefits of developing specific instruments for determining the need for and the effectiveness of camouflage measures in other than the visible spectrum, to determine whether existing IR viewers in the field can be adapted for this purpose, and to develop additional instrumentation as required.

We believe that development of sensory feedback instrumentation for field use, with a resulting improvement in the effectiveness and ease of use of tactical siting and all kinds of artificial camouflage, will be the single most cost-effective development that can be undertaken to improve general-purpose multi-spectral camouflage. No quantitative cost-benefit analysis has been carried out, and it is hard to see how a rigorous cost-benefit analysis could be designed. However, qualitative indications are clear, and a sequence of developments could be designed to test this thesis a step at a time relatively inexpensively.

Where it is available, defilade and protective cover give some degree of protection against all surveillance and target acquisition sensors. They should not be ignored. They require no development and impose no logic burden. Of course, they do put a limitation on the operation of the target.

Full exploitation of tactical siting for purposes of camouflage is inhibited by the inability of the average person to figure out how much protection a given position is likely to provide against a sensor that operates on an energy field he is not familiar with.

We know that a leafy growth interferes with vision. It also has a major effect on laser instruments, heat seekers, IR imaging devices, and radars. A good deal is known about what kind of an effect and how important it is under various circumstances, but the knowledge has not been widely disseminated.

A reasonable goal is to determine the camouflaging effects of various kinds of terrain and cover and spell out this information in terms that units in the field can understand and use.

10. Compatibility

Historically it has turned out that countermeasures against particular sensor system threats have sometimes increased vulnerability to detection by other sensor systems. For example, many visual camouflage paints and nets were found to be more conspicuous in the MWIR and LWIR than the original targets were. (Forty years ago this was true in VSWIR and SWIR, and IR anti-camouflage photography was developed to exploit the fact.) The most obvious kind of heat dissipators, if constructed without an eye for visual or radar detectability, would turn out to be extremely conspicuous targets.

An essential goal is to measure the effects of every passive surveillance and target acquisition countermeasure on all sensor systems it may be exposed to, and resist the adoption of any measure that increases vulnerability to any sensor system.

C. CAMOUFLAGE DEVELOPMENT FOR THE NEAR, INTERMEDIATE AND REMOTE FUTURE

Passive surveillance and target acquisition countermeasures can easily be separated into three classes that correspond roughly to the three time periods under consideration. First, there are measures appropriate indiscriminately for a large class of targets. Paints, nets, and artificial radar clutter fall into this category. They can be used as soon as they are developed, and some options could be developed and deployed before 1986.

Second, add-on items can be applied with some interfacing to existing equipment. Examples are modular heat dissipation equipment for motor exhausts, spoilers to alter the radar, visible or IR signature of a target, and superficial coating and texture changes to change the laser detectability or radar reflection characteristics of a target. Even after these are developed, some time is necessary to actually change the equipment in the inventory and in the field. Considerable time will pass before they can be used widely, but many applications could be made in the period 1986-1991.

Third, there are true basic design changes involving structural changes, change of materials, change of shape, and change of method of operation. It might, for example, be possible to make a tactical bridge entirely out of materials transparent to radar. Optimal control of the thermal signature of a motor generator or similar heat-generating device almost certainly will require redesign. The laser and radar scattering cross-sections of many targets could be materially reduced by changes in shape and materials. As we understand camouflage over the whole STANO spectrum better, more and more elements of camouflage will be built in with basic design changes. However, few of these items will be fielded before 1991. A consequence of widespread passive camouflage based on mechanical, thermal, and electrical redesign will be a change in emphasis in general-purpose camouflage systems. Many targets whose need for camouflage is urgent will have camouflage built in, and will no longer depend on a general-purpose system.

When the qualities of the ten target classes are considered, the applicability of major categories of countermeasures to each target type in each of the three time periods before 1986, 1986-1991, and after 1991, can be displayed as in Tables V-1, V-2, and V-3. The several goals stated in general terms in Section 3 above can now be interpreted in terms of particular time periods and specific target classes.

1. Nets and Screens

One component of a general-purpose camouflage system required by targets in most target-classes is camouflage nets.

TABLE V-1

COUNTERMEASURES FOR PERIOD BEFORE 1986

TARGET CLASSES	NETS -visual, IR,R -extend IR and R spectrum	PAINTS AND THIN COATINGS -visible, IR -extend IR spectrum -reduce V & IR signatures	THICK COATINGS AND BLANKETS -radar and mm anti-reflecting -thermal insulating -etc.	SHAPE & TEXTURE -control diffuse, specular reflection -spoilers -reduce V,IR,R, L signatures	MECH/THERM/ ELECTR REDESIGN -new materials and shapes -reduce thermal radar, laser signatures	CLUTTER -general background augmentation (mostly radar)	DECOYS -deliberately deceitful false targets	HEAT SHIELDS & DISSIPATORS -for engine generators -for vehicles, etc.
I motorized, airmobile/airborne forward area combat unit, hq., auxiliary support	n_1	yes	no	? vs. lasers	NA	R, rarely	no	no
II armored/mechanized forward area combat unit, hq. auxiliary support	n_1	yes	mm, perhaps	yes	NA	R, rarely	no	no
III self-propelled/towed cannon, rocket artillery, AA, FC & TA support	n_2	yes	mm, perhaps	L	NA	no	T&R	no
IV tactical bridges	n_2	yes	no	no	NA	no	yes	no
VII aircraft operating bases	n_2	yes	no	no	NA	no	no	no
VIII surf-to-surf missile units	n_2	yes	mm, perhaps	no	NA	no	R	perhaps
IX large rear-area CCC and support installation dependent on electrical power	n_2	yes	no	no	NA	no	no	yes
X large rear-area ammo, POL, supply and combat service support--low electrical pwr needs	n_2	yes	no	no	NA	no	no	no
SP missiles, cannon, rocket and mortar unit vulnerable to counter-fire radar	NA	no	no	no	no	yes	no	no

NA=Not Applicable; R=Radar; L=Laser; mm=Millimeter-Wave Radar; T=Thermal; V=Visible; n and n_2: two versions of nets (see text)

TABLE V-2

COUNTERMEASURES FOR PERIOD 1986-1991

TARGET CLASSES	NETS -visual, IR, R -extend IR & R spectrum	PAINTS AND THIN COATINGS -visible & IR -extend IR spectrum -reduce V, IR & mm signatures	THICK COATINGS AND BLANKETS -radar and mm anti-reflecting -thermal insulating, etc.	SHAPE & TEXTURE -control diffuse, specular reflection -spoilers -reduce V, IR, R, L signatures	MECH/THERM/ ELECTR REDESIGN -new materials and shapes -reduce thermal, radar, laser signatures	CLUTTER -general background augmentation (mostly radar)	DECOYS -deliberately deceitful false targets	HEAT SHIELDS & DISSIPATORS -for engine generators -for vehicles, etc.
I motorized, airmobile/airborne forward area combat unit, hq. auxiliary support	n_1	yes	no	L yes V-IR-R ?	no	R	no	maybe
II armored/mechanized forward area combat unit, hq. auxiliary support	n_1	yes	mm, perhaps	L yes V-IR-R ?	some H.V. units	R	a few T&R	for a few
III self-propelled/towed cannon, rocket artillery, AA, FC & TA support	n_2	yes	mm, perhaps	L yes V-IR-R ?	some H.V. units	R	some T&R a few V	for a few
IV tactical bridges	n_2	yes	no	no	no	no	yes	no
VII aircraft operating bases	n_2	yes	no	no	no	perhaps	perhaps	maybe
VIII surf-to-surf missile units	n_2	yes	perhaps	perhaps	perhaps	no	some T&R	yes
IX large rear-area CCC and support installation dependent on electrical power	n_2	yes	no	no	no	perhaps	perhaps	yes
X large rear-area ammo, POL, supply and combat service support--low electr pwr needs	n_2	yes	no	no	no	perhaps	perhaps	maybe for a few
SP missiles, cannon, rocket and mortar unit vulnerable to counter-fire radar	NA	no	perhaps	no	no	no	no	no

NA=Not Applicable; R=Radar; L=Laser; mm=Millimeter-Wave Radar; T=Thermal; V=Visible; n_1 and n_2: two versions of nets (see text)

TABLE V-3

COUNTERMEASURES FOR PERIOD AFTER 1991

TARGET CLASSES	NETS - visual, IR, R -extend IR and R spectrum	THIN COATINGS -visible & IR -extend IR spectrum -reduce V & IR & mm signatures	THICK COATINGS AND BLANKETS -radar and mm anti-reflecting -thermal insulating, -etc.	SHAPE & TEXTURE -control diffuse, specular reflection -spoilers -reduce V, IR, R, L signatures	MECH/THERM/ ELECTR REDESIGN -new materials and shapes -reduce thermal, radar, laser signatures	CLUTTER -general background augmentation (mostly radar	DECOYS -deliberately deceitful false targets	HEAT SHIELDS & DISSIPATORS -for engine generators -for vehicles, etc.
I motorized, airmobile/airborne forward area combat unit, hq. auxiliary support	n_1	yes	some built in	L, some V, IR & R	yes	R	no	(redesign) or yes
II armored/mechanized forward area combat unit, hq. auxiliary support	n_1	yes	some built in	L, some V, IR & R	yes	R	maybe T&R	(redesign) or yes
III self-propelled/towed cannon, rocket artillery, AA, FC & TA support	n_2	yes	some built in	L	yes	R	T&R	(redesign) or yes
IV tactical bridges	n_2	yes	some built in	perhaps	perhaps	no	yes	no
VII aircraft operating bases	n_2	yes	no	no	doubtful	perhaps	perhaps	no
VIII surf-to-surf missile units	n_2	yes	some built in	no	yes	no	R&T, perhaps	no
IX large rear-area CCC and support installation dependent on electrical power	n_2	yes	some	no	yes	perhaps	T, perhaps	(redesign) or yes
X large rear-area ammo, POL, supply and combat service support--low elect. pwr needs	n_2	yes	no	no	no	perhaps	perhaps	no
SP missiles, cannon, rocket and mortar unit vulnerable to counter-fire radar	NA	no	perhaps	no	perhaps	no	no	no

NA=Not Applicable; R=Radar; L=Laser; MM=Millimeter Wave Radar; T=Thermal; V=Visible; n_1 and n_2: two versions of nets. (see text)

Nets will be used from time to time by targets in Classes I, II, III, IV, VII, VIII, IX and X, that is, by all targets except aircraft and shells in flight. Two varieties are called for. In the first, camouflage effectiveness is sacrificed for simplicity, light weight, and ease of erection and removal. It will be used mainly by targets in Classes I and II near FEBA that move often and are under frequent threat of attack. The other seeks the maximum camouflage protection even at the cost of being heavy and difficult to put up and take down. It will be used by targets in Classes III, IV, VII, VIII, IX and X, that normally stay put for longer than targets in Classes I and II.

The long-range goal is to develop two modular net systems that are as effective in the LWIR, MWIR, and SWIR as present nets are in the visible and VSWIR, and that have radar absorption and blending built in. Systems of erection, support, and removal will be required also. In one system, camouflage performance may be sacrificed for operational and logistic simplicity. In the other, maximum camouflage efficiency will be demanded. The two net systems may have common elements.

In the period before 1986, the objective is either one or two net systems combining incremental improvements in erection and support with new net materials with broadened spectral coverage and built-in radar protection. During this period it may be discovered that a single two-sided net material does not provide enough variety to blend with natural backgrounds in the infra-red and radar as well as the current system does in the visible. A system of modular substitution or modular modification must then be devised to meet the broadened spectral requirement. At the same time, the needs for means to achieve compatibility with heat dissipators must be anticipated.

For the period 1986 to 1991, a compromise light weight, simplified net system is specified which is no heavier and requires one-third less installation effort than the visual camouflage net now in use, and that achieves a good compromise of camouflage effectiveness across all spectral bands including radar and millimeter waves, with performance in the visible equal to that of present nets or as close to it as permitted by the other constraints. (Installation effort may be measured by the number of men in the installation crew and the time they take to put up the net.) Parts of this system, such as some of the net material, may be disposable if this greatly simplifies their use. The other system may be heavier and require as much as twice the effort to install as nets of today. The second net system is intended for larger, higher value targets and for targets that stay put for longer than typical targets in Classes I and II. It will be provided with modules compatible with heat dissipators and for items of materiel such as communication antennas, radars, and guns that are not fully compatible with being covered by a net.

For the period after 1991, developers will continue to exploit incremental improvements and may be required to solve problems unanticipated at this time.

2. Paints and Thin Coatings

The second widely used component of a general-purpose camouflage system is paints and thin coatings to be used for pattern painting. As shown on all three charts, paints and thin coatings will be used on target Classes I, II, III, IV, VII, VIII and IX, that is, on all classes except aircraft and missile and shells in flight. (Camouflage paints may be applied to aircraft and missiles also, but for the purpose of camouflage when they are on the ground, not when they are in flight.) They may also be used, along with other measures, to control surface scattering to reduce the laser signature of some targets, especially in Class II.

The long-range goal is to develop paints and thin coatings and combinations of colors, textures, and patterns that blend targets with background in the visible, VSWIR, SWIR, MWIR, and LWIR as effectively as today's pattern-painting does in the visual and VSWIR. If paints and thin coatings are used at all for radar camouflage, they will be used selectively to protect high-value targets against millimeter wave devices.

Before 1986, paints or coatings that match environmental spectra through the LWIR should be developed.

By 1991, patterns and textures using these new paints and coatings should be developed that reduce LWIR and MWIR detection to the level presently achieved in the visible and VSWIR, without degrading currently achieved levels of visual and VSWIR camouflage. In cooperation with a parallel effort of heat dissipation and suppression, the compatability of these paints and coatings with thermal IR signature suppression efforts must also be assessed. The feasibility of improvements in the laser operating ranges (but especially in the SWIR where few imaging sensors are expected except very-hot-target seekers) to greatly reduce reflectance at one or more popular operating frequencies should be investigated. This feature should be added to the paints and coatings if it can be done without degrading their other qualities.

After 1991, continuing efforts should be made to:

- Improve the effectiveness of pattern painting to all wavelengths by making colors, textures, and patterns that provide improved blends.
- Extending effectiveness to additional spectral regions, if any, where new sensor systems are anticipated and, conversely, relaxing specifications in spectral regions where experience proves that sensor systems are ineffective or where the enemy does not have any.

For all three time periods, the everyday complements of pattern painting, e.g., camouflage clothing, should be available with performance keeping pace with that of pattern painting.

It is anticipated that ways to suppress laser signatures may continue to be developed outside of the scope of a general-purpose camouflage effort. If continued review of the use of laser instruments shows that they are a growing threat, further laser signature reduction should be developed combining absorbing coatings and control of diffuse and specular reflection with shape alteration and other methods outside of paint and coating development. However, it should be recognized that the goals of reducing the scatter to zero for laser signature control and blending the scatterer with the background for imaging sensor signature control are incompatible in any frequency common to the two systems. At present, it appears that the imaging systems are the greatest threat, and should be responded to at the expense of neglecting the laser threat. If a decision is made to paint all targets dead black in the SWIR, where many lasers now operate and almost no imaging detection systems are used except very-hot-target seekers, it would be a tempting invitation to the enemy to develop ambient-illumination systems in this spectral band.

3. Heat Suppressors and Dissipators and Thermal Redesign

Because of the rapidly growing importance of surveillance and target acquisition sensors sensitive to thermal self-emission in the SWIR, MWIR, and LWIR, we consider heat suppressors and dissipators and thermal redesign next. A number of high-value targets glow bright from thermal self-emission in the SWIR, MWIR, and LWIR; and the technology for surveillance, target acquisition, and missile homing guidance on these "hot-spots" is at hand. The fastest action in all-purpose camouflage will center around the threat to hot targets.

Targets with primary power plants are particularly vulnerable to surveillance and target acquisition by sensor systems detecting thermal self-emission in the LWIR, MWIR, and SWIR spectral regions. Items in target Classes II and IX are particularly susceptible, and targets in Classes I, III, VII, VIII, and X are also susceptible. All of these items will require a way to harmlessly dissipate the heat they generate into a column of warm gas and also a system for suppressing the thermal signature. Many of the items in these classes contain other heat sources like electrical equipment and air conditioners. The thermal signature due to the diurnal heating and cooling cycle, although it is less pronounced, threatens all units to some extent.

An important intermediate range goal is to develop a family of dissipators, heat suppressors, and heat shields for all motor generators and other large stationary heat sources that dissipate the internally generated heat into a harmless column of warm gas and reduce the visible thermal signature to the equivalent of a 4°C temperature increase or less. The same should be undertaken for vehicular engines and mobile large heat sources, and this will almost certainly require modification of the engine, vehicle and platform design itself as well as an add-on dissipator and heat suppressor kit. A similar goal is to dissipate the heat from and control the thermal signature of other heat sources like air conditioners with the same 4° limit. Another goal is a combination of thermal redesign, heat flow control, and surface treatment to give each target exposed to MWIR and LWIR sensor systems a combination of thermal conductivity, heat capacity and reflectivity or emissivity so that its combined scattered and self-emitted radiation blends with that of the environment.

A more limited goal would be a material for use in thermal screens and coatings whose surface heating characteristics match those of some common environmental materials like rock or earth. This relates to the heading "thick coatings and blankets" on the three charts.

For the period before 1986, dissipators, heat suppressors, and heat shields should be designed for motor generator and other large heat sources in target Class IX. Although each design may be tailored to some extent, some degree of modular commonality is expected, and no engine or heat source redesign should be contemplated. Also, thermal suppressor coats should be designed with a combination of thermal insulating, and emitting properties to hold the thermal signature of a massive metallic object subject to the diurnal heating cycle within the equivalent of 4° of the background radiation.

During the period 1986-1991, the technology developed for heat dissipation and suppression in large stationary engines should be adapted for engines in equipment and vehicles in the forward area, in target Classes I, II, and some in Class III. Dissipators and suppressors should be developed for other heat sources also, in particular electric and electronic equipment and air conditioners.

By 1991, all stationary and automotive engines should have heat suppression and dissipation included as an integral part of the engine design so that the raw thermal signature is 10 to 15 dB below that of untreated engines of the present day, without any substantial degradation in performance. All new materiel and equipment that is likely to find its way onto the battlefield, especially items in target Classes I, II and III, should be designed to reduce this effective thermal signature to ±4°C of the surrounding environment, or as close to that ideal as possible without degrading this mission performance. Then a somewhat scaled down family of additional heat dissipators and suppressors should be developed to provide additional signature reduction to the 4°C threshold for those targets that are particularly exposed.

4. Artificial Augmentation of Background Noise (Clutter)

In any sensor system, discrimination of signal from noise is degraded as much (in principle) by raising the noise level as by decreasing the signal level. This leads to the concept of camouflage by artificially increasing background noise. The case for this camouflage method is presented in Reference 23.

When the discrimination of the sensor is very high, artificial background noise is recognized as such and ignored by the sensor. The net effect is to degrade sensor performance only in those pixels when noise is actually added. The visual field-of-view contain comprises many million pixels, and it is impossible to cloud them all except with a countermeasure that naturally distributes itself uniformly, like smoke. Smoke and its functional analogs can be effective, but for reasons already discussed, we believe it should be a special-purpose rather than a general-purpose camouflage element.

Radar resolves and discriminates much more crudely than vision, and hence there is some hope for camouflage by artificial radar clutter enhancement. Several classes of targets are vulnerable: shells and missiles in flight (Class SP) are vulnerable to counter-fire radar; large ground targets vulnerable to airborne surveillance radar, like Classes VII, X, and to a lesser extent, IX, VIII, and IV; and targets in the forward area visible by both ground and airborne surveillance and target acquisition radar, like Class IV and somewhat less Classes III, II, and I.

The radar threat is not usually very high except for the special target Class SP and tactical bridges (Class IV). (The other two "high susceptibility" entries on Table III-6 refer only to surveillance, not acquisition.) However, for occasions when forward area operations of targets in Classes I and II (and III while in the forward area) warrant large-scale camouflage cover, we should be prepared for area saturation with clutter. The long-range goal is to develop resonant or coherent radar scatterers and dispensing systems capable of creating 200,000 square meters of ground clutter per ton of material, or the equivalent of more than 1000 point targets of scattering cross-section of over 100 square meters each, distributed over an area of 1 square kilometer or larger. Another long-range goal is to develop chaff shells so that clouds of radar chaff can be deployed with field artillery to give temporary protection to missiles and shells susceptible to counter-fire radar detection. This latter is a special-purpose, rather than a general-purpose, measure and will not be considered further here.

Clutter against certain laser instruments appears technically possible, but present evaluation of the urgency of this threat does not warrant inclusion of such a countermeasure in a general-purpose camouflage system.

The development of artificial radar ground clutter and dispensing systems is probably not urgent enough to command the all-out effort needed to put it in operation by 1986. However, development and deployment by 1991 should present no problems.

5. Blankets and Thick Coatings

The development of thermal blankets will be a part of that of heat suppressors and dissipators, both add-on and built-in. Radar anti-reflective coatings are not expected to find a place in a general-purpose camouflage system.

6. Decoys

To be effective, a decoy must be matched to a particular archetype. We believe that it belongs to special-purpose rather than general-purpose camouflage.

7. Mechanical, Thermal, and Electrical Redesign and the Control of Shape and Texture

To defeat radar, visual, IR imaging and probably laser sensor systems, a target strength reduction of the order of 100:1 (20 dB) is typically called for. Such a target strength reduction is usually not possible by measures compatible with the continued undegraded operation of the target. However, the fact that 20 dB of target strength reduction is needed to defeat a sensor system should not obscure the fact that even a few dB will reduce the sensor's probability of success and accuracy. Very often, a substantial amount of target strength reduction can be designed into the target.

The most urgent need is to design all targets containing heat-sources so they do not show hot-spots. This is analogous to designing all shelters so they do not have light-leaks at night, all motors so their noise is reduced by mufflers, and so forth. Whereas an emission level within 4°C of the environment may not be achieved, any heat radiation reduction decreases the vulnerability to sensors and makes the work of the next level of camouflage easier.

Similarly shape and texture control will reduce laser retro-reflection, and control of shape, choice of materials, and redesign of high-reflectivity features will reduce radar signatures. Noise and vibration can be reduced as well.

It is unreasonable to expect newly designed equipment in the field before 1991. However, for the period beyond 1991, all high-value materiel with heat sources should be redesigned to reduce their thermal signature 5 to 10 dB, and designed to be compatible with additional heat suppression and dissipation camouflage measures. All high-value targets likely to be found in the forward area should be designed and treated to reduce their radar scattering cross-section by 3 to 6 dB on the average, with greatest attention to suppressing highlights; and to reduce laser retro-reflection by a similar amount. However, these requirements should be relaxed where incompatible with the equipment's primary purpose.

8. Tactical Siting

Where natural cover is available, it can be highly effective, and it is free. However, knowledge of how much camouflage the terrain and vegetation provide and how human activity degrades it is needed to make effective use of tactical siting. As far as visual camouflage is concerned, the operator can be taught with texts, training sessions, photographs and examples to use his own eyes. However, outside of the visual spectrum, information is considerably less accessible. Information about radar clutter, radar foliage penetration, radar rain attenuation, and so forth, is fairly easy to find, but information about effects of other invisible radiation is harder to find.

By 1986, information about the characteristics of the environment as seen by all types of threat sensors should be collected and codified. At the same time or soon after, it should be disseminated in manuals and training programs with particular attention to teaching and helping troops in the field to use vegetation, terrain, and other environmental features for SWIR, MWIR, LWIR, radar, and laser camouflage.

9. Sensory Feedback

Imagine a blind person trying to avoid light leaks or a deaf person trying to muffle a source of noise. Lack of a sensor to detect the phenomenon they are trying to control makes the task very difficult. It is now recognized that the withering of extremities characteristic of advanced untreated Hansen's disease (leprosy) is simply due to the repeated wounds and bruises people inflict on themselves when their senses of touch and pain are numbed by the disease. It would be a pity if our army units in the field were exposing themselves to damage from surveillance and target acquisition through inability to perceive when they are in danger, yet this is probably what will happen.

An essential part of any broad-spectrum general-purpose camouflage system is a system of sensing and measurement to determine the threat and verify the camouflage. After a net is erected, an overflight in the Commander's helicopter, or even a tour on foot around the unit, gives a good synoptic idea of whether the target is well hidden from view, but how does one determine whether the radar or thermal signature is reduced, or the MWIR and LWIR blend is effective?

The long-range goal should be to give all potential camouflage users access to instruments that will show them what equipment is vulnerable to surveillance and target acquisition sensing, what the nature of the background is, and how effective a particular camouflage installation is likely to be.

Many viewers, cameras, weapon sights, and other sensors in the field could be turned on our own equipment at short range to determine camouflage deficiencies and effectiveness. By 1986, a handbook on how to use existing sensors for this purpose should be developed and the need for additional instrumentation, if any, should be determined. By 1991, and possibly earlier, new equipment could be developed or existing sensors adapted to this use.

D. ALTERNATIVE EXPOSITION OF CAMOUFLAGE SYSTEM SPECIFICATIONS

1. Introduction

The program of development described in Section C above can be described in an alternative exposition that more nearly resembles system specifications, as follows. This is not a different development program, but simply an alternative way of describing the same program.

The multipurpose camouflage system comprises materials and equipment, a methodology for using them, and some sources of information. Specifications for the materials and equipment are found in Section 2. Some of the materials and equipment will be built into other equipment, some will be applied to or used on other equipment, and some are free-standing. The built-in features of the multipurpose camouflage system will be, of course, beyond the control of the user. However, in most instances, use of the applied and free-standing elements will depend to some extent on the judgment and discretion of the user. A methodology for determining what options should be put into use, when, and how, is required to transform the list of materials and equipment into a camouflage system. The general characteristics of such a methodology are summarized in Section 3, although it appears that the responsibility for drawing up methodology specifications lies outside of MERADCOM. To use this methodology, the user must have information, or a way of getting information, to base his action on. Some of this information can be provided in reference documents, but some requires instruments to make real-time on-the-spot observations. Specifications for meeting this and other particular information needs are outlined in Section 4.

The equipment and materials comprise:

- a light-weight modular net system
- a heavy-duty modular net system
- pattern-painting with paints and thin coatings
- heat-suppressors and dissipators

- artificial augmentation of radar clutter
- mechanical, thermal and electrical redesign of many types of equipment
- control of shape and texture
- equipment for making certain essential measurements.

Many useful and valuable techniques for camouflage are not mentioned explicitly, mainly because their implementation makes them special-purpose rather than general-purpose camouflage. For example, for a decoy to be effective, it must mimic a particular target, and each species of decoy will most likely be deployed by one type of operating unit (tank decoys by tank companies, missile-launcher decoys by missile units, etc.)--a special purpose rather than a general-purpose camouflage application. Similarly, radar anti-reflective materials (RAM) and isolation materials (RIM) do not achieve their full potential--in fact, they perform rather poorly--when applied as blankets or add-ons to existing materiel, but they have a place in the reduction of radar signature by redesign that combines control of shape, structural materials and substrate with use of RAM and RIM. Thick coatings and blankets are therefore implicitly included under "redesign" and "control of shape and texture."

The methodology comprises:

- doctrine and manuals explaining whether, when and how to use each type of camouflage equipment and material, to be developed concurrently with the equipment and material itself
- an updated methodology for the exploitation of natural cover for camouflage purposes (tactical siting, etc.) that is responsive to all surveillance and target acquisition sensor system threats.

The necessary information comprises:

- information about the vulnerability of each specific type of target to each type of sensor, both in general and at the time and place that a decision to use elements of the multipurpose camouflage system must be made; and
- information about the environment and background that is relevant to camouflage, both in general and at the time and place that a decision to use elements of the multipurpose camouflage system must be made; and

- direct observations and measurements of the vulnerability of each type of target to every anticipated type of surveillance and target acquisition sensor and of the degree to which camouflage measures undertaken in the field reduce their vulnerability.

2. Camouflage Equipment and Material Specifications

a. Net System

(1) Heavy-Duty Modular Net System, 1986-91 Time Period. The heavy-duty modular net system is intended primarily for targets in Classes III, IV, VII, VIII, IX and X (V.C.1.*). Its size, weight and configuration shall be such that it will require no more than twice the installation effort of present nets (V.C.1., V.B.4.). In the visual range, it will be as effective as present nets in concealing targets (V.C.1.). A suitable measure of effectiveness is the ratio of the distance at which an unprotected target or target cluster is detected with 50% cumulative detection probability to the distance at which a target covered by a net is detected (reference 1, page 247), but any measure that correlates adequately with field experience may be substituted. The performance of the net in all other wavelength regimes in which photographic and visual imaging or scanning systems are used, including multi-spectral photography, at all wavelengths from visual through infrared from very short to long wave (Table II-1) shall be the same or better (V.C.1., V.B.4.).

Against radar (microwave and millimeter wave), the two-way transmission loss of the net shall exceed 20 dB in all bands (II.F.4.). The radar backscatter shall be in the neighborhood of the median backscatter σ_m for the distribution of terrain types for which the net is certified (taking into account the relation between actual and projected area) in all operational bands (including millimeter wave) and not more than one standard deviation above that of the most reflective terrain type (or 8 decibels above the median, if the standard deviation is not known) in any one band.

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*References are to chapter, section, subsection, etc., in the body of this report, i.e., Chapter V, Section C, Subsection 1, etc.

It is not anticipated that a general multipurpose net can be made immune to the threat of laser target designators or range finders after the net-covered target has been detected by some other primary sensor-system (V.B.2.).

The heavy-duty net system shall be made compatible with heat-shields and dissipators required for the camouflage of targets containing heat-sources, but the net system itself shall not be required to redistribute heat or shield against infrared emission due to the target's having a surface temperature above the ambient temperature (V.C.1., V.B.4.).

(2) Light-Weight Modular Net System, 1986-91, Time Period. The light-weight system shall require no more than two-thirds the effort to install than present net systems (V.C.1., V.B.4.). It is intended primarily for targets in Classes I and II. It should have as many components in common with the heavy-duty net as feasible (V.C.1.), and the components should be mutually compatible in case interfacing or juxtaposition is desired (V.C.1.). It may have some disposable components (V.C.4.). Otherwise, the light-weight net system should have performance characteristics as close to those of the heavy-duty net system as can be achieved within the constraint of installation effort (V.C.1., V.B.4.).

(3) Net Systems in the Period Before 1986. In the period before 1986, principal reliance will be placed on the present net system. Development should be undertaken of components of the heavy-duty and light-weight net systems of the 1986-91 time period that can be developed and are compatible with the present net system (V.B.4., V.C.1.).

(4) Net System for the Period After 1991. Achieve the same performance specified for the 1986-91 period against imaging and scanning sensors of electromagnetic emission and against radars including sensor systems in spectral bands whose use is expected after 1991 but not before.

b. Pattern Paints and Thin Coatings

Pattern painting is intended for most targets in Classes I, II, III, VII, VIII, and IX (V.C.2.).

(1) Paints and Thin Coatings in the Period 1986-91. In this (and all time periods), the effectiveness of pattern painting should be maintained at or above the level achieved today with visual observation (naked eye, binoculars, etc.). Visual camouflage is an old art, and after the amount of effort that has been expended during and since WW II, it is unrealistic to expect large or rapid improvement. An acceptable measure of effectiveness is the ratio of the range at which an unprotected target is detected with a cumulative detection probability of 50% and the range at which the pattern-painted target is detected (reference 1, page 247).

Without reducing the visual effectiveness, the same effectiveness is required in all infrared spectrum ranges where enemy imaging and scanning sensor systems operate (see Table II-1, II.B.). This effectiveness is required against all visual, photographic, iconoscopic, image-intensifier, and other systems that present an analog picture to a human viewer, including narrow-band, black and white, color, pseudocolor and multispectral narrow band systems (V.C.2. V.B.2.). Paints and thin coatings are not expected to contribute to the thermal signature suppression in the medium and long infrared, but should reduce the contrast for that part of the total image due to scattered and reflected light, and infrared should be compatible with measures taken to achieve thermal IR camouflage.

Paints that have very low reflectance (below 0.01 if possible, as low as possible otherwise) at one or more discrete frequencies most suitable for fixed-tuned lasers in lidars and designators and range finders are required (e.g., 1.064 μm - see II.D.2.), but broad-band performance must not be sacrificed (V.B.2., V.C.2., II.D.2.).

Paints should not be expected to contribute to radar camouflage, and thin coatings will contribute little at frequencies below 30 GHz. In the millimeter-wave spectrum, thin coatings may contribute to radar target strength reduction.

(2) Paints and Thin Coatings in the Period before 1986. Without degrading pattern-paint performance in the visual or any other spectral region where comparable performance has been achieved, the spectral range over which paints match environmental reflectivity should be extended through the LWIR (V.C.2.), and, to the extent possible, their reflectance reduced at the commonest frequencies of fixed-tuned lasers expected to be used (II.D.2.).

(3) Paints and Thin Coatings in the Period after 1991. During this period, tunable lasers may be generally capable of performing all of the functions prescribed for fixed-frequency lasers (II.D.). If so, the nuisance value of interdicting the frequencies of fixed frequency lasers must be reassessed, and the requirement for paints with low reflectance at these frequencies may be relaxed. On the other hand, if these fixed lasers are still widely used in, for example, missile homing devices, the requirement should be retained.

Also, the operating frequency range over which photographic, scanning and visual imaging devices are expected must be reassessed. Otherwise, the requirement for the 1986-91 time frame, as modified to include spectral bands where new sensors are expected to be used, are reaffirmed.

c. Heat-Suppressors and Dissipators and Thermal Redesign

Heat-suppressors and dissipators and thermal redesign are required to reduce the infrared thermal emission signatures of major heat sources in target Classes II and IX especially, and for other heat sources in those target classes and heat sources in target Classes I, III, VII, VIII and X (V.C.3.). The outstanding heat sources are primary engines powering engine-generator sets and propelling vehicles, but there are many others (Tables III-3, III-6). The thermal signature due to the diurnal heating and cooling cycle, although less pronounced, makes all massive metal targets and many others vulnerable to thermal infrared sensors (IV.C.1.).

There are many different ways to ameliorate a thermal IR signature (Table IV-1). Because they function in different ways, it is hard to write a specification that applies uniformly to all of them (Table IV-1).

(1) Heat Suppressors and Dissipators and Thermal Redesign in the Period Before 1986. In this period a family of heat dissipators, suppressors and shields are required that reduce the thermal IR signature of engine-generators and other large stationary heat sources in target Class IX to a level within ±4°C of the ambient background (V.C.3.). This means control the sum of the target's scattered and self-emission to match the sum of the background's scattered and self-emission, or more precisely, the emission that the background would emit at some temperature within 4°C of the actual ambient temperature of the environment (IV.C.1.). (Practically speaking, this means keeping most of the exposed surfaces within ±4° of ambient temperature, and controlling the scattered infrared by control of the surface reflectivity, but that is not the whole story--see Subsections IV.C.1. and IV.C.2.) Similarly, thermal signature suppressor coats are required with a combination of thermal insulation and emitting properties to hold the thermal signature of massive metallic targets subject to the diurnal heating cycle within the equivalent of ±4° of the background radiation, interpreted in the same sense as above (V.C.3.).

Dissipation of substantial amounts of heat to the atmosphere is allowable, provided the exhaust plume is not warmer than 300°C and is not allowed to warm objects that irradiate in the transparent atmospheric windows (IV.C.2.). Such an exhaust plume may necessarily be accompanied by a narrow cone of radiation due to the exhaust port. If so, that cone should be made as narrow as possible (0.1 steradian or less) and directed upward onto the rear (IV.C.2., V.B.5.).

(2) Heat Suppressors and Dissipators and Thermal Redesign in the Period 1986-91. In this period, the same degree of thermal signature control prescribed for large stationary heat sources in target Class IX before 1986 shall be available for targets in Classes I, II, III, VII, VIII and X as well (V.C.3.). All newly designed stationary and automotive engines

coming into use in this period should have heat suppression and dissipation included as an integral part of the engine design, as prescribed below for all engines in the period after 1991.

(3) Heat Suppressors and Dissipators and Thermal Redesign in the Period after 1991. By 1991 all stationary and automotive engines should have heat suppression and dissipation included as an integral part of the engine design. The raw thermal IR signature should be reduced 10 to 15 dB below that of a comparable engine of today (V.C.3., V.B.5.). This thermal IR signature reduction should be achieved with no more loss in engine efficiency or effectiveness than that imposed on civil aircraft jet engines by today's noise abatement regulations or on civil automobile engines by mufflers (V.B.5.).

At the same time, equipment shall be developed to reduce the residual signature of all equipment to the ±4°C level defined above. Because most of the major heat sources (large engines) will have some thermal IR signature suppression built in, the functional requirements for this equipment will be less than for equipment serving the same function on engines without built-in thermal signature suppression, and the material can be correspondingly lighter, simpler and cheaper (V.C.3.).

d. Artificial Augmentation of Radar Clutter

This countermeasure will be used to protect concentrations of targets in target Classes I and II operating over a considerable area (several square kilometers) and vulnerable to airborne radar surveillance, radar and millimeter-wave target acquisition and ground radar surveillance and target acquisition. It may also be used to protect targets in other classes, particularly VII, IX and X and possibly III and VIII (noting that targets far behind FEBA are relatively safe from ground radar). A unique but important application for one variant will be used to protect the special target class of shells and missiles in flight.

(1) Artificial Augmentation of Radar Clutter before 1986. By the end of this period, simple spatially coherent or frequency resonant structures like corner reflectors and dipoles capable of creating 200,000 square meters of aggregate clutter or the equivalent of more than 1,000 compact targets each with a scattering cross-section greater than 100 square meters with one ton of material when distributed over an area of one square kilometer or larger are required. Distribution means shall be developed also (V.C.4., V.B.7.). During this period, it is not anticipated that phase-shifting scatterers capable of confusing moving-target indicator (MTI) circuitry will be available, although the mere amplitude of the clutter signal will degrade MTI to some degree (reference 23).

(2) Artificial Augmentation of Radar Clutter in the Period 1986 to 1991. During this period, material is required that meets the same requirements as specified for the period before 1986 and also has frequency-shifting, to simulate the doppler shift of return from typical moving ground targets. A fractional frequency shift of 10^{-7} (100 Hz at 1 GHz, 1 KHz at 10 GHz, 10 KHz at 100 GHz) simulates the dopper shift of a target with a radial velocity component of 15 meters per second or 54 km per hour).

(3) Artificial Augmentation of Radar Clutter in the Period after 1991. The same performance required in the period 1986 to 1991 is required, extended to those radar and millimeter wave frequencies that extrapolation or intelligence leads us to expect will be in use at the time.

e. Mechanical, Electrical and Thermal Redesign

All new high-value targets in all classes fielded in the period 1986 to 1991 and all high-value targets fielded after 1991 should be designed or redesigned as follows:

All targets containing heat-sources should be designed so they do not show radiative "hot-spots." A reduction of all thermal infrared signature by 5 to 10 decibels, and of the thermal infrared signatures of targets with large primary engines (self-propelled vehicles, engine-generators, etc.) by 10 to 15 decibels, or to within ±4°C of the ambient thermal IR radiation level, is required (see Section V.D.2.d. above).

Noise and vibration of machines of all kinds should be reduced also. Further analysis is required to determine how large a reduction is needed to produce a worthwhile beneficial effect (V.C.7.).

f. Control of Shape and Texture

All high-value targets, especially those in target Classes I, II, III and IV and including also those in Classes VII, VIII, IX and X, should be redesigned with a modification of surface shape, texture, materials, and optical and radar reflectivity control to reduce their median (or average) radar scattering cross-section by 3 to 6 dB, with particular emphasis on suppressing highlights (V.C.7.). Achievement of this goal may also require some structural and electrical design constraints (see V.D.2.e. above). The retro-reflection coefficient at frequencies expected in laser instruments (particularly the 1.0 to 2.9 μm band, but also others--see Chapters II.D., IV.B.) should be reduced 3 to 6 dB by controlling angle of reflection (shape), reflectivity, and glossiness (see Chapter II D and Table II-13). It should be recognized that reductions of laser and radar signatures by 3 to 6 dB can in no sense be considered effective camouflage (reference 23; II.F.4., IV.B.2.). Reductions of 20 dB or more are required truly to defeat the sensor systems. However, any signature reduction degrades the sensor system performance, and it is expected that the cost of small signature reductions (3 to 6 dB) measured both in target performance degradation and in development and manufacturing cost will be very small.

In the operating spectra of visual and imaging and scanning infrared systems, control of shape and texture (by spoilers, etc.) should be considered as an adjunct to pattern painting to help achieve the goals of Section 2 above.

3. Methodology Specifications

In addition to specific manuals of instruction for the use of each of the types of camouflage equipment, expository material and field manuals are required to teach and show users how to use the whole collection of camouflage resources and techniques as an integrated system. We believe that the development and dissemination of such a methodology is outside of MERADCOM's mission as presently defined, and have limited ourselves to a brief general description of features rather than specifications. However, the value of the equipment to be developed at or under the guidance of MERADCOM will not be fully realized unless development of methods to use it effectively is supported somewhere.

One major feature is doctrine and manuals explaining whether, when and how to use each type of camouflage equipment and materiel. These will probably be developed concurrently with the equipment and materiel itself. A second feature is an improved exposition of how to use tactical siting for camouflage, both by itself and interactively with other camouflage equipment and materials. The use of tactical siting for visual camouflage is well understood, and considerable information is also available about siting for radar camouflage. Equivalent material should be developed about tactical siting to reduce vulnerability to all kinds of IR and laser systems and to radar in the extended spectral ranges anticipated in the future.

4. Information Specifications

In order to make effective use of a multipurpose, multi-component camouflage system, the user must have

- information about the vulnerability of each type of target to each type of sensor
- information about the characteristics of the environment that are relevant to blending and concealment.

In the visible spectrum, the impressions of the human eye supported by experience, analysis and instruction, are an adequate basis for implementing camouflage measures in the field. To the extent that imaging non-thermal IR sensor systems are analogous to the eye, everyday human experience can be extrapolated. However, with respect to thermal IR, radar, laser, multi-spectral narrow band photography, and other systems that do not work in a way analogous to the human eye, experience in the visual spectrum may be irrelevant or misleading.

The same is true in the acoustic spectrum: recognition and perception of characteristic transients and tones such as gun-blasts and engine whine are analogous to unaided human hearing, and every person can use that experience to form an idea of what is loud and what is quiet, and what kind of natural background wuch as wind noise will mask what target noise. However, when acoustic arrival times are used for triangulation or seismic vibrations are used for detection, the experience of the human ear is no longer a reasonable basis for action.

In all of these cases there is a need for:

- instruments for field use to measure or observe vulnerability to sensors and camouflage effectiveness.

a. Information Specifications before 1986

Handbooks are required to tell non-specialist users what kind of information can be collected by battlefield sensor systems, how environmental conditions contribute to or inhibit observation, and what features and characteristics of targets make them vulnerable to detection, target acquisition and homing (Chapter V.C.9., Chapter V.B.9.). There is a requirement for adaptions and methods of use of sensor systems already in the inventory--night viewing devices, infrared detectors, gun sights, etc.--to turn them on our own equipment and the local environment at short range and so determine camouflage deficiencies and effectiveness (Chapter V.C.9., V.B.9.).

b. Information Specifications between 1986 and 1991, and after 1991

By 1991, a set of sensors should be developed that when used by our own personnel, at short range and under battlefield conditions, to observe our own equipment and the local environment, will enable the observer to determine:

- whether a given uncamouflaged target is showing a substantial scattered IR, thermal IR, multi-spectrum narrow-band IR, radar, acoustic, or laser-instrument signature or potential signal return;
- whether camouflage applied to the target has been effective in reducing the signature or potential return, and by how much;
- the effective reflection, scattering, emission and transmission loss of natural objects in the environment.

The sensitivity of this instrument or set of instruments must be such that, properly handled, a qualified user can determine with reasonable confidence (84% or more) by making before and after measurements in the field, whether the performance of nets, thermal signature reduction, radar clutter, and radar signature reduction required in Section 2 above have been achieved, and to estimate with comparable precision whether the level of the scattered and thermal IR, multi-spectral narrow-band IR, laser, and radar signature, contrast, or scattering cross-section, as the case may be, of targets camouflaged before going into the field is below the design level dictated by the requirements of Section 2.

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