



SAN DEFENSION TO A

NI' N--

ť



JHU/APL TG 1360 DECEMBER 1986

Copy No.

AD-A179 908



Technical Memorandum

# WIDE AREA GUIDANCE AND CONTROL PROGRAM: INVESTIGATION OF SCANNING IR SEEKER PERFORMANCE IN BACKGROUND CLUTTER

DTIC FILE COPY

L.M. HOWSER



20

THE JOHNS HOPKINS UNIVERSITY . APPLIED PHYSICS LABORATORY

87

Approved for public release: Distribution is unlimited.

JHU/APL TG 1360 DECEMBER 1986

Technical Memorandum

# WIDE AREA GUIDANCE AND CONTROL PROGRAM: INVESTIGATION OF SCANNING IR SEEKER PERFORMANCE IN BACKGROUND CLUTTER

L.M. HOWSER

THE JOHNS HOPKINS UNIVERSITY 
APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20707
Operating under Contract N00024-35-C-5301 with the Department of the Navy

Approved for public release: Distribution is unlimited.

## UNCLASSIFIED SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED 28. SECURITY CLASSIFICATION AUTHORITY			1b. RESTRICTIVE MARKINGS				
			3. DISTRIBUTION/A	VAILABILITY OF REPOR	т		
DECLASSIFICAT	TION/DOWNGRADIN	G SCHEDULE		- Approved for	public release; distri	bution unlimited.	
. PERFORMING OF	RGANIZATION NUM	BER(S)		5. MONITORING OR	GANIZATION REPORT N	UMBER(S)	
JHU/APL TG 1360			JHU/APL TO	G 1360			
A NAME OF PERF	ORMING ORGANIZ	ATION	6b. OFFICE SYMBOL	7a. NAME OF MONI	TORING ORGANIZATION		
The Johns Ho Applied Phys	opkins University sics Laboratory	,	TIR	NAVPRO, La	urel, Maryland		
IC. ADDRESS (City	, State, and ZIP Cod	e)	<u> </u>	7b. ADDRESS (City,	State, and ZIP Code)		
Johns Hopkin Laurel, Mary	ns Road land 20707			Johns Hopkin Laurel, Maryl	s Road and 20707		
A. NAME OF FUND	DING/SPONSORING	ORGANIZATION	8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT I	NSTRUMENT IDENTIFIC	ATION NUMBER	
Naval Surface	e Weapons Cente	r	G06	N00024-85-C-5	5301		
Ic. ADDRESS (City	, State, and ZIP Cod	e)		10. SOURCE OF FUN	DING NUMBERS		
Dahlgren, VA	22448			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. A3D0	WORK UNIT ACCESSION NO.
	Security Classificatio						
Wide Area G	iuidance and Con	itrol Program: Invest	igation of Scanning IR S	eeker Performance	in Background Clutt	er	
	THOR(S)						
E. I ENOUTHE AU							
Howser, L. N	М.						
Howser, L. N	M.	13b. TIME COVE	RED	14. DATE OF REPOR	RT (Year, Month. Day)	15. PAGE COUNT	
Howser, L. N 13a. TYPE OF REPO Technical M	M. DRT femorandum	13b. TIME COVE	RED TO	14. DATE OF REPOR	NT (Year, Month. Day) CT	15. PAGE COUNT 72	
Howser, L. N Isa. TYPE OF REPC Technical M IS. SUPPLEMENTAL	M. DRT Jemorandum RY NOTATION	13b. TIME COVE	:RED TO	14. DATE OF REPOR	NT (Year, Month. Day) Pr	15. PAGE COUNT 72	
Howser, L. N I3a. TYPE OF REPC Technical M 16. SUPPLEMENTA 17.	M. DRT femorandum RY NOTATION COSATI CODES	13b. TIME COVE FROM	TO TO	14. DATE OF REPOR	NT (Year, Month. Day) PT	15. PAGE COUNT 72	
Howser, L. N I3a. TYPE OF REPC Technical M I8. SUPPLEMENTA I7. FIELD	M. DRT Iemorandum RY NOTATION COSATI CODES GROUP	13b. TIME COVE FROM S SUB-GROUP	TO	14. DATE OF REPOR 1986, Novembe	RT (Year, Month. Day) er ulse discrimination	15. PAGE COUNT 72	
Howser, L. N I3a TYPE OF REPC Technical M I6. SUPPLEMENTA I7. FIELD	M. DRT Iemorandum RY NOTATION COSATI CODES GROUP	13b. TIME COVE FROM SUB-GROUP	TO	14. DATE OF REPOR 1986, Novembe	IT (Year, Month. Day) Er ulse discrimination oint target detection	15. PAGE COUNT 72	
Howser, L. N 13a. TYPE OF REPC Technical M 16. SUPPLEMENTA 17. FIELD 19. ABSTRACT (Co	M. DRT Jemorandum RY NOTATION COSATI CODE: GROUP	13b. TIME COVE FROM S SUB-GROUP necessery and identify by	TO TO 18. SUBJECT TERMS Advanced, scannir Clutter-limited per Digital filtering	14. DATE OF REPOR 1986, Novembe	RT (Year, Month. Day) er ulse discrimination oint target detection	15. PAGE COUNT 72	
Howser, L. N Howser, L. N I3a. TYPE OF REP( Technical M I6. SUPPLEMENTA I7. FIELD I9. ABSTRACT (Co The clut tigation. R used. Artif spectral de Seeker p alarm rate one-dimen compariso algorithm	M. DRT femorandum RY NOTATION COSATI CODES GROUP Intinue on reverse if ter-limited perfor Requirements of the facts in the selected ensities. Detailed performance is det produced by the isional digital filted in between the out in a missile seekee	13b. TIME COVE FROM	TO         18. SUBJECT TERMS         Advanced, scannir         Clutter-limited per         Digital filtering         block number)         4, scanning infrared seeke         hoice of imagery; three t         and correction technique         lat collection instrumen         ber of techniques. Perform         the matched filter, and t         tels is shown to be useful	14. DATE OF REPOR 1986, November 1986, Novem	T (Year, Month. Day) T ulse discrimination oint target detection urvey of infrared i.na ita sets from Ai: i-or images are character at a presented in a oth in terms of the re -filter analysis using wed by a pulse-widtl xtended background	15. PAGE COUNT 72 gery lists data availa ce and Navy collect ized by radiance sta ppendixes. quired target irradia the image power sp o discriminator. Fin features. Implement	ble for this inves- ion programs are atistics and power nce and the false- ectral densities, a ally, a cross-scan lation of the final
Howser, L. N Howser, L. N 13a. TYPE OF REPC Technical M 16. SUPPLEMENTA 17. FIELD 19. ABSTRACT (Co The clut tigation. R used. Artif spectral de Seeker p alarm rate one-dimen compariso algorithm	M. DRT femorandum RY NOTATION COSATI CODES GROUP Intinue on reverse if ter-limited perfor Requirements of the facts in the selecter ensities. Detailed performance is det produced by the isional digital filte in between the out in a missile seeke	13b. TIME COVE FROM	IB. SUBJECT TERMS         Advanced, scannir         Clutter-limited per         Digital filtering         block number)         d, scanning infrared seeke         hoice of imagery; three b         and correction technique         lata collection instrumen         ber of techniques. Perfor         the three techniques com         the matched filter, and t         nels is shown to be useful	14. DATE OF REPOR 1986, Novembe 1986, Novembe ag IR seeker P formance P tr is investigated. A sub background-image da s are developed. The ts and the scenes use mance is measured be pared are a matched he digital filter follo in further rejecting e	ulse discrimination oint target detection urvey of infrared i.na ata sets from Ai: bor images are character cd are presented in a oth in terms of the re -filter analysis using wed by a pulse-widtl xtended background	15. PAGE COUNT 72 gery lists data availa ce and Navy collect ized by radiance sta ppendixes. quired target irradia the image power sp h discriminator. Fin features. Implement	ble for this inves- ion programs are tistics and power nce and the false- ectral densities, a ally, a cross-scan tation of the final
Howser, L. N Howser, L. N I3a. TYPE OF REPC Technical M I8. SUPPLEMENTA I7. FIELD I9. ABSTRACT (Co The clut tigation. R used. Artif spectral de Seeker p alarm rate one-dimen compariso algorithm	M. DRT Iemorandum RY NOTATION COSATI CODES GROUP Inter-limited perfor Requirements of the facts in the selector ensities. Detailed performance is det produced by the isional digital filten in between the out in a missile seekon	13b. TIME COVE         FROM         FROM    SUB-GROUP          necessary and identify by         mance of an advanced         he study restrict the c         ed data are examined         information on the difference         background scene. T         er that approximates         up to f adjacent changer         er is discussed.	I8. SUBJECT TERMS         Advanced, scannir         Clutter-limited per         Digital filtering <i>block number</i> )         A, scanning infrared seeke         hoice of imagery; three the         and correction technique         ata collection instrumen         ber of techniques. Perforning         the matched filter, and the         hels is shown to be useful	14. DATE OF REPOR 1986, November 1986, Novem	Use discrimination oint target detection urvey of infrared i.na ta sets from Ai. i or images are character ed are presented in a oth in terms of the re -filter analysis using wed by a pulse-widtl xtended background	15. PAGE COUNT 72 gery lists data availa ce and Navy collect rized by radiance sta ppendixes. quired target irradia the image power sp o discriminator. Fin features. Implement	ble for this inves- ion programs are utistics and power nce and the false- ectral densities, a ally, a cross-scan tation of the final
Howser, L. N Howser, L. N I3a. TYPE OF REP( Technical M I6. SUPPLEMENTA I7. FIELD I9. ABSTRACT (Co The clut tigation. R used. Artif spectral de Seeker p alarm rate one-dimen compariso algorithm I0. DISTRIBUTION//	M. DRT femorandum RY NOTATION COSATI CODES GROUP Intinue on reverse if ter-limited perfor Requirements of th facts in the selecter ensities. Detailed performance is det produced by the isional digital filter in a missile seeker AVAILABILITY OF AL FIED/UNLIMITED	13b. TIME COVE FROM	TO         18. SUBJECT TERMS         Advanced, scannir         Clutter-limited per         Digital filtering         / block number)         d, scanning infrared seekee         hoice of imagery; three termined         and correction techniques. Perform         he three techniques. Commune         ber of techniques. Commune         bet of filter, and the second filter, and the matched filter, and the second filter.         bels is shown to be useful	14. DATE OF REPOR         1986, November         198	T (Year, Month. Day) er ulse discrimination oint target detection urvey of infrared i.na ita sets from Ai: i or images are character id are presented in a oth in terms of the re- filter analysis using wed by a pulse-widtl xtended background URITY CLASSIFICATION ED	15. PAGE COUNT 72 gery lists data availa ce and Navy collect ized by radiance sta ppendixes. quired target irradia the image power sp o discriminator. Fin features. Implement	ble for this inves- ion programs are itistics and power nce and the false- ectral densities, a ally, a cross-scan lation of the final
Howser, L. N Howser, L. N I3a. TYPE OF REPO Technical M I8. SUPPLEMENTA I7. FIELD I9. ABSTRACT (Co The clut tigation. R used. Artii spectral de Seeker p alarm rate one-dimen compariso algorithm I0. DISTRIBUTION// II UNCLASSIF I2a NAME OF RES NAVPRO See	M. DRT Iemorandum RY NOTATION COSATI CODES GROUP Intinue on reverse if ter-limited perfor Requirements of the facts in the selecter ensities. Detailed performance is det produced by the isional digital filter in a missile seekee AVAILABILITY OF AL FIED/UNLIMITED SPONSIBLE INDIVIDIC curity Officer	13b. TIME COVE         FROM         FROM    S          SUB-GROUP         necessary and identify by         mance of an advanced         he study restrict the c         ed data are examined         information on the d         termined using a numl         background scene. T         er that approximates         tput of adjacent changer         r is discussed.	IB. SUBJECT TERMS         Advanced, scannir         Clutter-limited per         Digital filtering <i>block number</i> )         A, scanning infrared seeke         hoice of imagery; three b         and correction techniques         ber of techniques. Perfor         the three techniques com         the matched filter, and t         nels is shown to be useful	14. DATE OF REPOR         1986, November         1987, State         1983, State	IT (Year, Month. Day) er ulse discrimination oint target detection urvey of infrared i.na ita sets from Ai: i or images are character ed are presented in a oth in terms of the re -filter analysis using wed by a pulse-widtl xtended background	15. PAGE COUNT 72 gery lists data availa ce and Navy collect ized by radiance sta ppendixes. quired target irradia the image power sp h discriminator. Fin features. Implement	ble for this inves- ion programs are tristics and power nce and the false- ectral densities, a ally, a cross-scan lation of the final lation of the final

1







#### ABSTRACT

The clutter-limited performance of an advanced, scanning infrared seeker is investigated. A survey of infrared imagery lists data available for this investigation. Requirements of the study restrict the choice of imagery; three background-image data sets from Air Force and Navy collection programs are used. Artifacts in the selected data are examined and correction techniques are developed. The images are characterized by radiance statistics and power spectral densities. Detailed information on the data collection instruments and the scenes used are presented in appendixes.

Seeker performance is determined using a number of techniques. Performance is measured both in terms of the required target irradiance and the false-alarm rate produced by the background scene. The three techniques compared are a matched-filter analysis using the image power spectral densities, a one-dimensional digital filter that approximates the matched filter, and the digital filter followed by a pulse-width discriminator. Finally, a cross-scan comparison between the output of adjacent channels is shown to be useful in further rejecting extended background features. Implementation of the final algorithm in a missile seeker is discussed.

Acces	Accession For					
NTIS	GRA&I					
DTIC	TAB	1				
Unann	ounced					
Justi	ficatio	n				
By Distr	ibution					
AVAI		y Codes				
Dist	Spec	and/or 1al				
A-1						

QUALITY INSPECTED 1

. al Ş Ę B ŝ 10 10 ā 57 57 57 8 8 22 - 222 7

•

## CONTENTS

List of Figures
List of Tables
1.0 Introduction91.1 Background91.2 Missile Infrared Seekers91.3 Approach to Algorithm Development10
2.0 Background Data.112.1 Data Requirements.112.2 Data Survey.112.3 Selected Data.14
3.0 Characterization of Data193.1 Data Artifacts and Corrections193.2 Radiance Statistics203.3 Power Spectral Density20
4.0 Scene Clutter Processing.244.1 Approach.244.2 Matched-Filter Performance Analysis.254.3 Digital-Filter Performance Analysis.284.4 Filtering and Pulse Discrimination Performance Analysis.334.5 Cross-Scan Comparison.434.6 Comparison of Processing Techniques.434.7 Implementation of the Scanning Sensor Processing.48
5.0 Conclusions
References
Appendix A: BMAP Data Description

5

### LIST OF FIGURES

LAN BUY BUT HUS BUS

Đ

8

5

Res.

ą

E

Ĩ

53

8

Ň

22

T.

.

1.	Images from each of the sets of data used in this study17
2.	Image showing bad data in ERIM scene S23CH220
3.	Power spectral density of BMAP Montauk Point middle-
	wavelength and long-wavelength background data
4.	Power spectral density of AFGL cloud and terrain
_	Dackground scene 105
3.	to 2.6 µm spectral band (scene S23CH1)
6.	Fourier transform of point source as seen by the BMAP
	instrument
7.	Required target irradiance for detection as a function of
	seeker resolution for AFGL and BMAP data27
8.	Comparison of required target irradiance for ideal band-
	pass filters to the matched-filter result using BMAP
	data
9.	BMAP bandpass filter: second-order low-pass and first-order
	high-pass (corner = 1.5 cycles/mrad)29
10.	AFGL first-order high-pass filter (cut-on = 0.25 cycle/mrad)29
11.	ERIM first-order high-pass filter (cut-on = 0.1 cycle/mrad)30
12.	Power spectral density of BMAP Montauk Point long-wave-
	length background data after bandpass filter
13.	Power spectral density of AFGL cloud and terrain back-
	ground scene 105 after high-pass filter
14.	Power spectral density of ERIM Port Hueneme scene in 2.0
	to 2.6 µm spectral band (scene S23CH1) after high-pass
	filter
15.	Line 471 of ERIM Camp A.P. Hill morning scene in 2.0 to
	2.6 μm spectral band (scene S01CH1)31
16.	Line 471 of ERIM Camp A.P. Hill morning scene in 8.0 to
	14.0 µm spectral band (scene S01CH3)31
17.	Images after filter and threshold
18.	Pulse width discrimination algorithm for BMAP data35
19.	Line 1 of BMAP Montauk Point long-wavelength back-
	ground data
20.	Typical derived NE $\Delta$ T values for the ERIM M-7 line
• •	scanner
21.	Images after filter, pulse discrimination, and threshold42
22.	Comparison of processing techniques
23.	Histograms of BMAP mid-IR Bedford scene46
24.	Cumulative histograms showing reduction of maximum
26	irradiance and NEI from filtering and pulse discrimination40
25.	Lines of images from ERIM Port Hueneme scene in 4.5 to
	bios μη spectral band (scene 525CH3) showing bad scan
26	Implementation of the scapping sensor processing 49
A.1	Spectral response of RMAP mid, and long-wave channels 54
A.2	Point-source response of RMAP detector channels 54
B-1	= 1  only source response of  M(1/M) = M(1/
	Spectral response of AEGI FUR with 7.84 to 13.16 um
	Spectral response of AFGL FLIR with 7.84 to 13.16 µm filter

D-1. Power spectral densities of AFGL scenes, 7.84 to 13.16 $\mu$ m
spectral band (0.5 mrad sample size)65
D-2. Power spectral densities of AFGL scenes, 7.84 to 13.16 $\mu$ m
spectral band (0.1 mrad sample size)65
D-3. Power spectral densities of ERIM scenes of Camp
A.P. Hill, 2.0 to 2.6 $\mu$ m spectral band
D-4. Power spectral densities of ERIM scenes of Camp
A.P. Hill, 4.5 to 5.5 $\mu$ m spectral band
D-5. Power spectral densities of ERIM scenes of Camp
A.P. Hill, 8.0 to 14.0 $\mu$ m spectral band
D-6. Power spectral densities of ERIM scenes of Port Hueneme
(port and water)
D-7. Power spectral densities of ERIM scenes of Port Hueneme
(port, water, and sun)68
D-8. Power spectral densities of ERIM scenes of mountains near
Nellis AFB (F08)68
E-1. Power spectral density of BMAP mid-IR scene from
Montauk Point after bandpass filter69
E-2. Power spectral density of AFGL terrain scene (104) after
high-pass filter69
E-3. Power spectral densities of ERIM afternoon scene of
Camp A.P. Hill after high-pass filter70
E-4. Power spectral density of ERIM scene of Port Hueneme,
spectral band 4.5 to 5.5 $\mu$ m, after high-pass filter (scene
S23CH3)

## LIST OF TABLES

1.	Requirements for wide-area missile IR background data	12
2.	Summary of available background data	13
3.	Characteristics of instruments used to collect background data	
	used in this study	16
4.	Summary of data used in this study	18
5.	Statistics of background data in units of W/cm <sup>2</sup> /sr	21
6.	PSD noise level	23
7.	Required target irradiance for matched filter detection in	
	several AFGL cloud scenes	26
8.	Digital filters used in the performance analysis	29
9.	Statistics of background data after filtering in units of	
	W/cm <sup>2</sup> /sr	32
10.	Thresholds used in Fig. 17	35
11.	Results of processing impulses with BMAP filters	36
12.	Results of processing impulses with AFGL filter	38
13.	Thresholds of AFGL images for pulse discrimination	38
14.	Results of processing impulses with ERIM filter	39
15.	ERIM NEIs and thresholds	40
16.	Pulse discrimination parameters	40
17.	Statistics of data after filtering and pulse discrimination in	
	units of W/cm <sup>2</sup> /sr	41
18.	Filtering output-to-input ratios	43
19.	Minimum detectable signal in units of W/cm <sup>2</sup> /sr	44

McVie.

A-1. Characteristics of the BMAP dual-band IR measure-	
ment system	53
A-2. Summary of BMAP data	
B-1. Characteristics of the AFGL-FLIR	56
B-2. Summary of AFGL infrared imagery characteristics	57
B-3. Calibration and spectral band data for AFGL infrared	
imagery	
C-1. Characteristics of the ERIM M-7 scanner	60
C-2. Summary of ERIM infrared imagery characteristics	61
C-3. Calibration and spatial registration for ERIM infrared	
imagery	62
C-4. ERIM middle-infrared detector arrays	64

47...

1

Se. 484 42.

**Nace** 

ate ate ate ate ate ate states ate ate at

#### **1.0 INTRODUCTION**

#### 1.1 Background

Advanced antiair missile guidance systems will make extensive use of infrared (IR) sensors to counter radar cross-section reduction and standoff jamming, to achieve lower miss distance, and to increase highaltitude missile dynamic performance. IR sensors will also provide an added discrimination capability to defeat self-screening countermeasures and select targets from closely spaced formations. The Wide-Area Guidance and Control Program is tasked with developing guidance technology for use in advanced, long-range, surface-to-air missiles (SAM). Such missiles must be "self-targeting," that is, the missile guidance conducts wide-field angle search to compensate for poor targeting (i.e., midcourse flight) accuracy against longrange targets. While advances in detector technology potentially offer very sensitive IR seeker systems, detection performance will most likely be limited by the background clutter.

An investigation of clutter-imposed limitations to missile IR seeker performance is being conducted to determine the likely performance of a guidance sensor that could be used on long-range SAMs. The objective of this effort is to develop clutter processing algorithms and to apply those processing techniques to data in order to determine the clutter-limited performance of advanced IR seekers. The principal clutter processing technique investigated here is a combination of digital filtering followed by a pulse discrimination algorithm.

#### **1.2 Missile Infrared Seekers**

A long-range SAM with IR guidance has several unique requirements that dictate the choice of signal processing. First, an IR seeker must acquire and track the target autonomously. Potential false alarms, if not immediately rejected, result in the waste of an expensive missile. Second, an IR seeker must be capable of rapid, wide-field search to compensate for significant targeting and midcourse guidance errors that may occur when targets are engaged at long range. Third, the long-range nature of the missile requires sufficient seeker acquisition range to acquire targets from the optimum flight altitude to allow time for descent to target altitude. Hence, the capability to detect small signature targets in terrain and cloud background clutter at long range is crucial for mission success.

Achievement of high IR seeker performance will become significantly more important as enemy capabilities evolve. Autonomous IR seeker acquisition becomes more important as target radar cross section is reduced and the IR mode assumes greater initial detection responsibility. Initially, the IR seeker will have primary acquisition responsibility against high-speed, higher altitude (i.e., higher IR signature) targets with the missile seeker radar having the primary responsibility for detecting lower speed and lower altitude (i.e., lower IR signature) targets. Ultimately, an IR seeker capability against low-signature targets is desired.

Because of the severity of the targeting and midcourse guidance requirements for a long-range mission, the enemy will develop tactics and electronic countermeasures (ECM) to degrade these functions. As targeting and midcourse guidance quality is reduced, the search capability of all missile guidance modes must be increased. Increases in the size of the search field of regard, the search angular scan rate, and acquisition range are needed to offset the effects of poorer target localization. The long-range missile must have acquisition and intercept capability even in situations when target range is unknown or external communications (for midcourse guidance) are lost. Uncertainties in range also require longer search time, hence a lower false-alarm rate.

As external targeting becomes poorer, particularly when target range information is degraded or unavailable, the need for the missile to fly a propulsionefficient trajectory increases. Since propulsion-efficient trajectories result in high-altitude flight, range to potential targets is increased. The increased range requirement, coupled with the need for more search capability and the need to detect lower signature targets, results in an IR seeker requirement for significantly greater sensitivity.

Advances in detector technology offer large increases in sensor sensitivity, e.g., two orders of magnitude over current systems. Increased IR sensitivity offers the potential for the needed long-range detection of low-signature targets. However, actual capability depends on the development of satisfactory techniques for clutter suppression.

In addition to the unique long-range mission requirements discussed above, all IR seekers have common constraints that affect their clutter discrimination capability. Most important are resolution, stabilization, and high closing velocity. Typically, IR seekers have an aperture of about 5 cm resulting in a typical minimum resolution of 0.5 mrad at 5  $\mu$ m and 1.0 mrad at 10  $\mu$ m. Current IR seekers have a typical stabilization drift rate of ~0.1 degree/sec.

There are three basic techniques for point-target discrimination in clutter. The first is the use of a reticle to encode point-target data in a background scene. This approach allows continual observation of a wide field with a single detector while a spatially small target is tracked. The technique is used in most current IR seekers. Unfortunately, the reticle modulates any background structure within the field of view (FOV). This unwanted modulation can interfere with target detection, particularly if greater seeker sensitivity is required. An even greater drawback to reticle-based systems is the great difficulty in separating multiple targets or targets and decoys.

The drawbacks of the first technique are mitigated by the second technique, i.e., scanning a larger FOV with small instantaneous field-of-view (IFOV) detectors. Scanning systems can be implemented with single detectors or multiple detectors up to large arrays. Detector size is matched to optical resolution (i.e., to the size of the blur circle). Discrimination is based on the fact that most of the scene power is concentrated in large features. Small features, on the scale of the blur circle size, remain a source of clutter. As resolution increases (blur circle and detector size decrease), the clutter power entering the system is reduced. Hence detection capability is improved as resolution increases.

The third technique is the staring system. Again, small IFOV detectors are used. Discrimination is based on moving target detection. Each detector looks (stares) at a portion of the background. Successive frames are subtracted to detect the motion of a target from one pixel to the next. Ideally, all background power is removed in the subtraction process, leaving a result that is corrupted only by system noise. Unfortunately, there are practical implementation problems, including changes in background power during the stare period, caused by missile motion relative to the background (e.g., projected velocity on the threedimensional scene), by seeker stabilization (drift) errors resulting in pixel misregistration, and by temporal variations in the scene. The relatively large IFOV of a missile seeker (compared to advanced search set) requires a longer stare time for detection. The longer stare time, coupled with background changes, drift, and the need to scan a wide search field rapidly, makes implementation of staring processing unlikely in a long-range missile IR seeker.

For the reasons shown, this report concentrates on development and test of clutter suppression algorithms for scanning IR seekers.

#### 1.3 Approach to Algorithm Development

The background data used in this study are described first. A characterization of the background imagery is then provided. The processing techniques used in the analysis are then described, followed by the results of processing the data by these techniques.

The description of background data includes a summary of data requirements and a survey of available IR clutter data. Reasons for selecting the background imagery used in this study and a detailed description of that data are provided.

Background data are then characterized and artifacts in the data examined and corrected. The characterization is used to guide the implementation of signal processing algorithms. In some cases, the background characterization can be used to estimate seeker performance directly and to make a comparison between scenes and spectral bands.

Finally, the original background data are directly processed with clutter-suppression algorithms to determine the effectiveness of the algorithm and ultimate clutter-limited performance of an advanced seeker. These algorithms are described and the reasons for their selection explained. Comparisons of sensor performance are made between different spectral bands and different scene types. Conclusions are in the form of expected sensor performance

#### 2.0 BACKGROUND DATA

#### 2.1 Data Requirements

Background data needed to support a wide-area missile IR seeker are desired in the form of high spatial resolution, two-dimensional, contiguous background maps (scenes). Since the data support the evaluation of a scanning system, high relative radiometric accuracy along one of the scene dimensions (scan direction) is needed. Oversampled data in this direction are needed so filtering can be applied. Absolute radiometric accuracy, to within 20%, is required to provide a good estimate of sensor performance. Scanning background measurement sensors are most likely necessary to provide the radiometric accuracy and oversampling needed to predict performance of a scanning system.

The wide-area missile mission requires scenes with down-looking geometries. Typical seeker search is from high altitude, looking below the horizontal at depression angles of 5 to  $20^{\circ}$ . Since a representative set of all scenes of interest is an enormous quantity of data, this study concentrates on cloud scenes. Clouds present a variety of difficult clutter conditions, particularly over water.

Background data in two spectral bands are needed: middle-wavelength data and long-wavelength data. The middle-wavelength data, nominally 4 to 5  $\mu$ m, require an angular spatial resolution of approximately 0.5 mrad. Long-wavelength data, nominally 8 to 12  $\mu$ m, require an angular spatial resolution of about 1.0 mrad. Data taken at altitudes lower than typical widearea missile search altitude (60,000 to 100,000 ft) can be obtained with lower resolution instruments, i.e., instruments that have the equivalent linear spatial resolution. Acquisition of simultaneous middle- and longwavelength data is preferred to make a side-by-side comparison of performance between these two major spectral bands.

The noise in the background measurement sensor must be below that expected for advanced sensors. Sensor radiometric accuracy of 10 <sup>-</sup> W/cm<sup>2</sup>/sr (middle wavelength) and 10 <sup>-6</sup> W/cm<sup>2</sup>/sr (long wavelength) is needed. The data resolution (digital sample increment) must be less than or equal to the rms noise requirements so that the sensor noise rather than digitizing noise is the predominant noise source.

Each scene should have sufficient samples to provide an estimate of false-alarm rate. A minimum of  $10^6$  pixels is necessary;  $10^8$  pixels or more are desired.

Table 1 summarizes the requirements for background data. These requirements, while designed to support development of a scanning IR seeker for a wide-area missile, are believed to be equally applicable to scanning infrared surveillance from aircraft.

#### 2.2 Data Survey

A survey of available IR background data was conducted to gain an understanding of the available background data and to guide selection of the data for use in this study. Table 2 summarizes some of the available data sources. Comments on these sources are given below.

The Armament Laboratory at Eglin Air Force Base maintains two databases: BASES and TABILS. The BASES system is designed to support the development of missile seekers. It consists of a pod mounted on an F4 aircraft with 3 to 5 and 8 to 12  $\mu$ m imagery (1.0 mrad) capabilities. These data are collected for a specific program, or SPO, and are not well cataloged. Targets are primarily tactical aircraft (all aspects) at close range. The background data, at ranges of interest, do not have sufficient signal-to-noise ratio for use in this study.

The second source is the Target and Background Information Library System (TABILS), which is accessible through remote computer terminals to DoD agencies and contractors. This database was developed to support air-to-ground tactical battlefield programs such as Assault Breaker, Tank Breaker, etc. A user's manual is available.<sup>1</sup>

The Environmental Research Institute of Michigan (ERIM) has collected a large volume of airborne imagery with their M5 and M7 line scanners as part of the Navy Optical Signatures Program as well as for other sponsors. This work started in 1976 with an extensive survey of available background data,<sup>2</sup> followed by data collection of ground scenes from low altitude. Typical data are collected at 1000 to 2000 ft altitude in three IR spectral bands. Detector resolution of 2 to 2.5 mrad gives high spatial resolution on the ground. A summary of the data collected for

Air Force Armament Laboratory, *Target and Background Information Library System (TABILS)* User's Manual (May 1, 1982).

<sup>&</sup>lt;sup>2</sup>J. Beard, J. Braitwaite, and R. Turner, *Infrared Background* Survey and Analysis, ERIM 118000-1-F (Jun 1976).

Parameter	Requirement					
Geometry	60,000-100,000 ft a 5-20° depression at	ltitude ngle				
Scenes	Cloud: solid layers multiple layers broken clouds storms and thun	derheads				
	Land					
Spectral bands	4.0-5.0 μm	8.0-12 μm				
Angular resolution	0.5 mrad	1.0 mrad				
Sensitivity	$10^{-7}$ W/cm <sup>2</sup> /sr	$10^{-6} \text{ W/cm}^2/\text{sr}$				
Radiometric dynamic range (from zero)	12 bits	12 bits				
Radiometric accuracy	better than 20%					
Oversampling (scan direction)	2:1 or greater					
Number of pixels per scene	$\geq 10^6$					

 Table 1
 Requirements for wide-area missile IR background data.

1978-1979, as well as earlier data, is given in Ref. 3. More recently (1983), long-wavelength European terrain background data were collected.

A number of government agencies and contractors are tasked to collect data for the long-range detection of air targets. General Electric and ITT, under contract to the Air Force Weapons Laboratory, have developed middle-wavelength airborne IR search and track systems. These systems were tested at Eglin Air Force Base in the summer of 1985. Data produced by the tests were not available for this analysis. The Navy is planning to continue the development with full-scale engineering, starting in late 1986.

The Navy Background Measurements and Analysis Program (BMAP) is being conducted as a successor to the background portion of the Optical Signatures Program. The program is tasked with collecting data needed to design surface- and air-based IR search and track systems. The initial instrument is a high-spatial-resolution, high-sensitivity device with simultaneous 4 to 5  $\mu$ m and 8 to 11  $\mu$ m coverage.<sup>4,5</sup> Initial data collection began with surface measurements in 1984 (Ref. 6) and has continued with airborne (P3 aircraft) measurements. A follow-on instrument

d

27

ſ,

I,

2

S

R

8

<u>N</u>

X

Ŗ

<sup>&</sup>lt;sup>3</sup> A. J. LaRocca and D. J. Witte, Handbook of the Statistics of Various Terrain and Water (Ia) Backgrounds from Selected U.S. Locations, ERIM 139900-1-X (Jan 1980).

<sup>&</sup>lt;sup>4</sup>R. L. Lucke, et al., "The Navy's Infrared Background Measurement and Analysis Program," in *Proc. IRIS Specialty Group Meeting on Targets, Background, and Discrimination, San Diego* (Feb 11-14, 1986).

<sup>&</sup>lt;sup>5</sup>R. A. Steinberg, "Navy IR Background Measurements and Analysis Program," in *Proc. Tri-Service Infrared Backgrounds Symp.*, Oct 18-20, 1983, Mitre Corporation, pp. 216-223.

<sup>&</sup>lt;sup>6</sup>A. Hirschman, "BMAP Surface-Based Background Measurement Activities at Montauk Point, New York, August 1983," Naval Surface Weapons Center, White Oak, Silver Spring, Md., draft report (Nov 1984).

Source agency	Database	Platform	Sensors
AFATL	BASES TABILS	F4 Various	AGA 3-5, 8-12 μm Imagery
AFFTD		KC-135	Spectrometer, 3-5 μm FLIR, 8-12 μm
AFWAL			FLIR, 8-12 μm
AFGL		NKC-135	Spectrometer, 3-5 $\mu$ m NORELCO, 3-5 $\mu$ m FLIR, 8-12 $\mu$ m
NSWC/DL		Ground- based	Spectrometer, 3-5 $\mu$ m FLIR, 3-5 and 8-12 $\mu$ m
NRL	ВМАР	P-3	Radiometer, 3-5 and 8-12 $\mu$ m
NWC	Target Signatures Program		Various
DARPA/Lockheed (ERIM library)	ВМР, САМР НІСАМР	U2	Scanner; several staring imagers, 10-12 μm
General Dynamics		Ground- based	Spectrometer, 3-5 and 10-12 $\mu$ m
Block Engineering		Ground- based	Spectrometer, 3-5 $\mu$ m
General Electric Syracuse		C-54	Imager, 8-12 μm
ERIM		C-47	M-5 and M-7 multi- spectral scanner
MIT/LL			FLIR, 3-5 and 8-17 $\mu$ m
JHU/APL		P-3	Radiometer, 3-4 and 10-12 $\mu$ m

#### Table 2 Summary of available background data.

with an expanded number of detectors per spectral band (from 16 to 120) and higher spatial resolution (0.25 mrad) is under development.

General Dynamics, NSWC/DL, and Block Engineering have ground-based measurement systems. These organizations maintain excellent calibrated signature libraries of tactical aircraft flown at low altitudes. A summary of spectral background measurements made by General Dynamics is given in Ref. 7, and a compendium of their target signatures library is given in Ref. 8.

<sup>8</sup>General Dynamics/Pomona Division, Available Target Infrared Spectral Signature Data, TM6-125PH-450 (Sep 1981).

General Dynamics/Pomona Division, Background Spectral Radiance and Contrast in the Near-UV, Mid-IR, and LWIR Regions, TM6-125PH-438 (Oct 1976).

The Applied Physics Laboratory has measured the radiometric properties of sea surface with low-altitude (500 to 3000 ft) flights of a line-scanning, dual-band (3.6 to 4.1  $\mu$ m and 10.1 to 11.1  $\mu$ m radiometer. This instrument has high sensitivity (NE $\Delta$ T of 0.003 K in each band) and low spatial resolution (10 to 200 mrad). An instrument description and typical data are given in Ref. 9.

Another major source of target and background data is the DARPA Infrared Data Library located at ERIM. This library serves as the archival collection of data with secret security classification. Major programs represented in the library are the DARPAsponsored Background Measurements Program (BMP), the Calibrated Airborne Measurements Program (CAMP), and the Highly-Instrumented, Calibrated Airborne Measurements Program (both HICAMP and HICAMP-II). A report on library holdings<sup>10</sup> lists the contents of the library.

The Air Force Geophysics Laboratory (AFGL) operates an instrumented NKC-135 aircraft to acquire target and background signature data. Over the past 10 years AFGL has collected in-flight spectral and spatial data on several tactical and strategic aircraft (e.g., T-38, F4, F5, F14, F15, A4, A7, B1, B52, C140, KC135, etc.). The measurement aircraft typically flies at 6 km (20,000 ft) altitude, but is capable of acquiring data at altitudes ranging from 0.3 to 13 km (1000 to 42,000 ft). Data can be taken in the down-, side-, forward-, and rear-looking modes.

This aircraft contains a number of IR measurement instruments for various purposes. Spectral measurements are made with Michelson interferometers having spectral resolution of 0.1 (for plume) to 32 cm<sup>-1</sup>. Imagery data are taken in two broad spectral bands (3 to 5, 8 to 12  $\mu$ m) and subbands within these intervals. The mid-wave IR (MWIR) imagery data are taken at 1 mrad resolution using an AC-coupled system. Consequently, the data only provide differential radiance values. The 8 to 12  $\mu$ m forward-looking IR (FLIR) system consists of two 9-element HgCdTe detectors with serial scan at TV-compatible rates.<sup>11</sup> The IFOV is approximately 0.5 mrad, and a typical image consists of  $192 \times 256$  pixels. Individual frames can be spliced together to form a long-track mosaic on the order of 0.75 km by 40 km. Two such tracks have been constructed: one in the American West (near

Santa Cruz, California) and the other in northernlatitude ice fields.

The AFGL has not been specifically tasked to acquire data for the IR search and track (IRST) (long range detection) problem. However they have acquired data relevant to this effort in the course of scheduled missions. These include horizontal viewing, 2° above and below the horizon, cloud orbits, and cloud flythroughs. These data have not been cataloged.

#### 2.3 Selected Data

Selected data were based on criteria of (a) availability, (b) measurement with a scanning instrument, and (c) no classification restrictions. Once algorithms are developed, they will be tested on classified as well as unclassified data.

Three data sets are used in this study: images from AFGL, ERIM, and BMAP. AFGL scenes are all longwavelength scenes of clouds or clouds and terrain viewed from high altitude. ERIM scenes are short-, middle-, and long-wavelength scenes of many types of terrain as well as of water taken from low altitude. BMAP data consist of middle- and long-wavelength scenes taken from the ground. Airborne BMAP data have been taken and are expected to be used for future work. Each of these data sets is described in the following paragraphs.

Two sets of BMAP data were supplied by the Naval Research Laboratory. The BMAP instrument consists of 16 middle-wavelength and 16 long-wavelength detectors each with a 0.33 by 0.33 mrad IFOV. Data in the scan direction are sampled every 0.096 mrad resulting in an oversampling of 3.3 to 1. The data are stored as 16-bit words. To convert the data to radiance, the data were multiplied by the multiplicative factor (MF) corresponding to the correct IR band. (For the BMAP data, the MF equaled the noise equivalent irradiance (NEI) of the system.) Appendix A contains more detailed information on the BMAP instrument and imagery including the spectral response and the impulse response of the sensor.

The BMAP sensor has two modes of operation. Data can be collected in a format of 8 lines of longwavelength IR followed by 8 middle-wavelength IR lines per frame. In this 8/8 format, the data are extracted from coincident detectors. The second format is 16 lines of either middle- or long-wavelength IR data per frame. In this mode, the frames usually alternate between the spectral bands.

APL has received data in both of the formats. Fifty frames of data were collected at Montauk Point, Long Island in the 8 long-wavelength 8 middlewavelength format. The background scene for these data was overcast sky.

<sup>&</sup>lt;sup>o</sup>K. Peacock, Radiometric Temperature Characteristics of the Ocean Surface, JHU/APL STD-R-377 (Oct 1980).

<sup>&</sup>lt;sup>10</sup> A. J. LaRocca and B. A. Whaley, DARPA Infrared Data Library, ERIM 155300-24-X (Jul 1984).

<sup>&</sup>lt;sup>11</sup>J. Shumsky and J. H. Schummers, AFGL FLIR NKC-135 Aircraft Instrument, AFGL TR-82-0031 (Jan 26, 1982).

The second set of BMAP data received by APL was collected at Bedford, Massachusetts. These data were in the format of 16 lines of alternating spectral bands per frame. APL used the first 61 frames of these data. Thirty-one frames were mid IR and 30 frames were long IR. Long-wavelength IR frames only had 15 lines of data per frame. A hole in a cloud deck was the background scene for these frames. More detail on the images is included in Appendix A.

Data from AFGL were the second set used in this study. The instrument is a two-detector array, serial scan, FLIR unit with a 10-position filter wheel that can select various spectral bands. All data supplied to APL were taken with filter 19005A (7.84 to 13.16  $\mu$ m). The FOV on this seeker was 0.36 (H) × 0.43 (V) mrad, but the digitizing sample size was 0.52 (H) by 0.45 (V) mrad. Eight of the frames have an additional telescope decreasing the IFOV to less than 0.1 mrad. The sample size means that these images were slightly undersampled (as opposed to the BMAP images). Video data (EIA RS-170) are recorded and subsequently digitized before distribution to APL. A more detailed description of the AFGL data is included in Appendix B.

The AFGL scenes are stored on tape in an 8-bit format (1 pixel = 1 byte). Because of this, the data were scaled to range from 0 to 255. To recover radiance, a multiplicative factor and an additive factor (AF) were applied to the data. Each scene has a unique MF and AF. These factors are listed in Appendix B. Thirty scenes were available for analysis; the four primary AFGL scenes used in this analysis were 101R, 104R, 105R, and 109R.

The third set of data used in this study was from ERIM. The data collection instrument is a line scan-

ner flown at low altitude. Ten spectral bands were available with the ERIM scanner. At most, four bands were scanned for a scene. The size of the scenes was variable. The FOV of the scanner also varied slightly. Appendix C has more detailed information on the ERIM data.

Six ERIM scenes are used in this study. These are denoted S01, S02, S03, S23, S24, and F08. There were three or four channels for each of these scenes. The first three of these scenes are from Camp A.P. Hill, Virginia. These images provide morning, afternoon, and evening data of one scene. S23 and S24 are of Port Hueneme, California. S23 is of the port and water; sunglint is added to this in S24. The last image, F08, is of the mountains by Nellis AFB.

Table 3 compares the characteristics of the BMAP, AFGL, and ERIM data.

Figure 1 shows an image from each of the sets of data used in this study. Part A shows middlewavelength BMAP data from Bedford (31 frames of data are shown). Part B of the figure shows the AFGL scene 109R. The remainder of the images in this figure are ERIM images. Part C is S01CH2, part D is S02CH2, and part E is S03CH2. These three are middle-wavelength images from Camp A.P. Hill at different times of day. Part F of the figure is S23CH3 from Port Hueneme. Finally, part G of the figure is

F8CH1, a mountain scene from Nellis AFB. These images will be shown after each of the processing steps to show the effect of the processing.

Table 4 summarizes the data used in this study. All of the images used, IFOV, size, spectral band, and descriptive comments are included in this table.

Parameter	BMAP sensor	AFGL sensor	ERIM sensor		
Platform	Ground	NKC-135 @ 35,000 ft	C-47		
Viewing geometry	5° elevation	Typically small depression angles	90° depression (nadir) $\pm 45^{\circ}$ scan or 35° depression with $\pm 45^{\circ}$ scan		
Sensor band (µm)	3.9-4.8 7.6-11.3	7.84-13.16	various bands: 2.0-2.6 3.0-4.6 3.5-3.9 3.9-4.7 4.5-5.5 8.0-14.0 9.0-11.4		
Instantaneous field of view (mrad)	$0.33 \times 0.33$ (azimuth resolution = 0.096)	$0.36$ (H) $\times$ 0.43 (V) (digitized sample size = 0.5 $\times$ 0.5)	2.0 or 2.5 (circular)		
Sensitivity NEI (W/cm <sup>2</sup> )	Long $1.1 \times 10^{-13}$ Mid $6.1 \times 10^{-15}$	$5.5 \times 10^{-12}$	2.0-2.6 $\mu$ m 4.91 × 10 <sup>-12</sup> 3.5-3.9 $\mu$ m 8.83 × 10 <sup>-12</sup> 3.9-4.7 $\mu$ m 3.40 × 10 <sup>-12</sup> 4.5-5.5 $\mu$ m 4.47 × 10 <sup>-12</sup> 8.0-14.0 $\mu$ m 2.45 × 10 <sup>-11</sup> 9.0-11.4 $\mu$ m 4.63 × 10 <sup>-11</sup>		
NE∆T (°C)	Long 0.02 Mid 0.01	0.40	3.5-3.9 $\mu$ m 3.0 3.9-4.7 $\mu$ m 0.25 4.5-5.5 $\mu$ m 0.2 8.0-14.0 $\mu$ m 0.1 9.0-11.4 $\mu$ m 0.25		
Scene size	8 scans mid-IR and 8 scans long-IR per frame or 16 scans mid-IR per frame and 15 scans long-IR per frame	256 (H) × 192 (V) pixels	855 or 646 pixels (H); number of lines per scene varies from 700 to 2000		
	373 pixels per scan line oversampled at 3.3:1				

## Table 3 Characteristics of instruments used to collect background data used in this study.

ada, Ũ 7 E. E. Š 8 Ì 2 200  $\overline{\mathcal{D}}$ 







(c)





(a)



(f)

Figure 1 Images from each of the sets of data used in this study. (a) BMAP middle-wavelength image from Bedford. (b) AFGL scene 109 of Monument Valley. (c) Morning (scene S01CH2). (d) Afternoon (scene S02CH2). (e) Evening (scene S03CH2). (f) ERIM image of Port Hueneme (4.5-5.5 µm spectral band) (scene S23CH2). (g) ERIM image of mountains by Nellis AFB (3.9-4.7 µm spectral band) (scene F8CH1).

Contraction of the second

Data	Scan IFOV (H)	Imag	Image size		Correct	
source	(mrad)	(H)	<u>(v)</u>		Comm	
ВМАР	0.33	373	8	Montauk (50 frames); long- and mid-IR: overcast sky; sample spacing: 0.1 mrad		
вмар	0.33	372	15 16	Bedford1 Long-IR: Mid-IR: Sample s	(61 frames) hole in clo hole in clou pacing: 0.1	) ud deck d deck mrad
				File	D	escription
AFGL	AFGL 0.5		192	101R 104R 105R 109R	clouds, down viewing terrain, down viewing horizon, clouds, terrain Monument Valley, clouds	
				File	Band	Camp A.P. Hill
ERIMI	2.0	855	700	SOICHI	2.0-2.6	Morning
			700	S01CH2	4.5-5.5	*
			700	S01CH3	8.0-14.0	"
			704	S02CH1	2.0-2.6	Afternoon
			704	S02CH2	4.5-5.5	"
			704	S02CH3	8.0-14.0	
			700	SOJCHI	Bad data	Evening
			700 700	S03CH2 S03CH3	4.3-5.5 8.0-14.0	"
				File	Band	Port Hueneme
ERIM3	2.5	646	1982	S23CH1	2.0-2.6	Port/water
			1982	S23CH2	Bad data	"
			1982	S23CH3	4.5-5.5	11
			1982	S23CH4	9.0-11.4	~
			1761	S24CH1	2.0-2.6	Port/water/sun
			1761	S24CH2	3.0-4.2	*
			1761 1761	S24CH3 S24CH4	4.5-5.5 9.0-11.4	"
				File	Dand	Nollie ACD
ED1144	2.4			<u>rne</u>	Dallu	INCHIS AFD
ERIMS	2.5	646	1541	FUSCHI	3.9-4.7	Mountains
			1541	FU8CH2	5.5-5.9	
			1541	F08CH3	9.0-11.4	

#### Table 4 Summary of data used in this study.

4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.4<sup>1</sup>8.

፝ኇዾጞዹጞዹጞዹጞዀጞዹጞቚጞቚጞቚጞቚጞቚጞቚጞቚጞቚጞቚጞቚጞቚጞ

#### **3.0 CHARACTERIZATION OF DATA**

#### 3.1 Data Artifacts and Corrections

There are a number of data artifacts and characterization uncertainties that limit the usefulness of scene data to background investigations. All data used in this investigation have one or more of the following unwanted artifacts: (a) significant sensor noise, (b) data errors, (c) calibration uncertainty, (d) imprecisely known sensor characteristics, and (e) sensor-induced scene artifacts.

When the sensor noise masks part of the scene-clutter power spectrum, the high-spatial-frequency component of the background clutter is lost and the full spatial resolution of the collection sensor cannot be used in evaluating the effect of clutter. Data errors can include poorly performing detectors, recording errors, and externally produced noise (e.g., from vibration). Such errors can produce target-like signals that significantly degrade usefulness in determining the effectiveness of an algorithm that uses spatial extent as the discriminant.

Calibration errors include radiometric inaccuracy that causes a significant variation in the predicted performance in clutter and calibration imbalance between detectors that degrades the scene in the cross-channel direction. This latter effort is not especially significant if all processing is done using data from the collection instrument scan direction only. Uncertainty in the clutter processing results is also introduced by unknown or imprecise description of the instrument and its functioning. Accurate knowledge of the spectral response, and optical and electrical transfer functions are frequently imprecise or unknown.

Finally, the data collection geometry can adversely affect the data by introducing aperture vignetting (i.e., lower scene variations) or geometric distortion (such that the pixel footprint on the scene varies significantly across a scan line). These effects are particularly noteworthy in wide FOV instruments. Another geometric effect is imprecise or changing registration between detectors making simultaneous measurements in multiple spectral bands. Registration between spectral bands becomes particularly significant if multiple colors are part of the discrimination processes.

All data sets used in this investigation had artifacts and, to some extent, imprecise knowledge of the sensor characteristics. A description of the major artifacts in each data set is given below.

The BMAP data had some defective data points caused by the data acquisition system. Software creat-

ed at the Naval Research Laboratory (NRL) located the bad data points in the BMAP images and corrected them by linearly interpolating from adjacent good data points.<sup>12,13</sup> These interpolated points were identified in the data supplied to APL by assigning them a negative value. When the data are used, these negative values are changed back to positive values. (For this study, we did not need to keep track of the bad data points.) Correcting these data recording errors was all that had to be done to the BMAP data.

When the BMAP Montauk images were first received at APL some of the recording errors had not been corrected by the NRL software. The errors were detected after the images were processed through the clutter-suppression algorithm. (The clutter-suppression algorithm passed many of the bad data points as possible targets.) NRL then sent a corrected set of the images to APL. The performance of the clutter-suppression algorithm was much better on these updated images than on the original images.

Both the AFGL and some ERIM images were significantly affected by noise within the sensor. This noise masks the highest frequencies of the background clutter. The effect of this noise will be discussed when the power spectral densities (PSD) are presented. Methods of reducing the effect of this noise will also be discussed later in this report.

AFGL images were formed by a TV-like raster scan, with alternate lines produced by separate detector arrays. The two detector arrays produced alternating lighter and darker scan lines when the response of the two arrays had drifted out of calibration. Reference 14 describes how the images were corrected. First, the mean of each line was computed. Half of the difference of the mean values was then added to pixels in the darker lines and half the difference was subtracted from pixels in the lighter lines. All of the AFGL scenes shown in this study have been corrected.

There were multiple problems with the ERIM data. The main problem was that images obtained with a depression angle less than 90° suffered from vignet-

<sup>&</sup>lt;sup>12</sup>R. A. Steinberg, Elimination of Sensor Artifacts from Infrared Data, NRI Report 8861 (Dec 11, 1984).

<sup>&</sup>lt;sup>1</sup>R. A. Steinberg and M. J. McHugh, *An Error Detection and Smoothing Algorithm for Infrared Data*, JHU API, TG 1355 (Apr 1986).

<sup>&</sup>lt;sup>14</sup>A. N. Vasteck, AIGU Infrared Image Restoration, JHU APU F1D(1)83-U-079.

ting by part of the aircraft fuselage. Reference 15 describes how this problem was corrected. A downscan average of all of the lines in the scene was computed. The mean and standard deviation of the left and right edges of the scene were then adjusted to create a constant mean and standard deviation for the downscan average. This restoration improved the images but some bright and dark bands still remained on the edges of the restored images.

In addition to the vignetting problem, there were some other problems with particular scenes. These problems were found while analyzing the scenes during the study. All three channels of S01 had 10 bad scan lines. These lines were found because they had pixel values of 0 or 255. No other lines in the scene had these pixel values. This artifact (see Fig. 1c) was corrected by simply skipping the 10 bad lines.

Channel 1 of S03 was not processed. ERIM reports analyzing these data never included this scene in the analysis. A PSD plot of the scene differed from PSDs of all of the other scenes. Most likely, the sensor was not able to acquire background data because the signal-to-noise ratio was too low. The image is essentially featureless. This scene was therefore excluded from the study.

Channel 2 of S23 was also excluded from the study. While analyzing this image (shown in Fig. 2) some unexpected results were obtained. Examination of the digital data of this scene showed that the pixel values were mostly 0 and 255. Since the data showed that there was a problem with this image, it was excluded.

#### **3.2 Radiance Statistics**

Before any of the IR data were processed certain characteristics of the data were needed. A histogram of each image was computed. From this histogram the maximum and minimum in the scene were obtained. The mean and variance were also calculated for each image. Table 5 lists the radiance values (mean, variance, maximum, and minimum) for most of the images used in this investigation.

The radiance statistics are needed to assess the performance of the processing techniques used. The maximum and minimum irradiance (with mean removed) will be compared to the maximum and minimum after processing. This comparison provides a measure of the performance of the processing techniques.



Figure 2 Image showing bad data in ERIM scene S23CH2.

#### 3.3 Power Spectral Density

In addition to calculating the moments of the images, the PSDs were also computed because they were needed in selecting the appropriate filters for the images. Figure 3 shows the PSDs of the BMAP Montauk long- and mid-IR bands. Figure 4 shows the PSD of one of the AFGL scenes. Figure 5 shows the PSD of an ERIM scene. Appendix D has the PSDs of many of the remaining scenes. From Figs. 3 through 5, it is seen that all of the PSDs have approximately the same slope. The power falls off as the inverse of the square of the spatial frequency  $(1/k^2)$ . Such a frequency dependence is often observed in background data. Figures 3 through 5 also show that at the higher frequencies all of the PSDs begin to flatten.

The level at which a PSD flattens is the noise level of the system. All three figures show the flattening. These figures and the additional power spectral density data given in Appendix D show that all of the AFGL and some of the ERIM PSDs have this flattening. BMAP data also show some change in slope at high frequencies.

The flattening of BMAP PSDs occurs because of the oversampling of the scene. The BMAP detector ß

5

 $\nabla$ 

£C.

Ð

<sup>&</sup>lt;sup>14</sup> A. N. Vavreck, *ERIM Infrared Image Restoration*, JHU/APL F1D(1)84-U-003.

### THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND

Table 5	Statistics of	background	data in	units	of	W/cm <sup>2</sup>	/sr.
---------	---------------	------------	---------	-------	----	-------------------	------

Lat Sal Fat Salt Salt

			Image Statistics				
S	cene	Spectral band (µm)	Mean	Variance	Max	Min	Δ (max – min)
BMAP (long	-Montauk (IR)	7.6-11.3	$1.93 \times 10^{-3}$	$1.43 \times 10^{-9}$	$2.04 \times 10^{-3}$	$1.84 \times 10^{-3}$	$0.20 \times 10^{-3}$
BMAP (mid	-Montauk IR)	3.9-4.8	$7.35 \times 10^{-5}$	$2.17 \times 10^{-13}$	$9.10 \times 10^{-5}$	$6.41 \times 10^{-5}$	$2.69 \times 10^{-5}$
BMAP (long	-Bedford	7.6-11.3	$1.66 \times 10^{-3}$	$5.09 \times 10^{-8}$	$1.76 \times 10^{-3}$	$1.30 \times 10^{-3}$	$0.46 \times 10^{-3}$
BMAP (mid	-Bedford IR)	3.9-4.8	$1.05 \times 10^{-4}$	$3.12 \times 10^{-5}$	$1.92 \times 10^{-4}$	$7.26 \times 10^{-5}$	$1.19 \times 10^{-4}$
AFGL	101 R	7.84-13.16	$2.87 \times 10^{-3}$	$5.01 \times 10^{-8}$	$3.87 \times 10^{-3}$	$2.42 \times 10^{-3}$	$1.45 \times 10^{-3}$
AFGL	104R	7.84-13.16	$3.81 \times 10^{-3}$	$1.36 \times 10^{-7}$	$4.43 \times 10^{-3}$	$2.74 \times 10^{-3}$	$1.69 \times 10^{-3}$
AFGL	105R	7.84-13.16	$3.01 \times 10^{-3}$	2.69 - 10 <sup>-8</sup>	$3.42 \times 10^{-3}$	$2.44 \times 10^{-3}$	$0.98 \times 10^{-3}$
AFGL	109R	7.84-13.16	$2.80 \times 10^{-3}$	$3.57 \times 10^{-8}$	$3.46 \times 10^{-6}$	$2.32 \times 10^{-3}$	$1.14 \times 10^{-3}$
ERIM	F8CH1	3.9-4.7	$5.2 \times 10^{-5}$	$7.8 \times 10^{-11}$	$7.2 \times 10^{-5}$	$2.5 \times 10^{-5}$	$4.7 \times 10^{-5}$
ERIM	F8CH2	3.5-3.9	$1.2 \times 10^{-5}$	$2.0 \times 10^{-11}$	$2.8 \times 10^{-5}$	$2.3 \times 10^{-8}$	$2.8 \times 10^{-5}$
ERIM	F8CH3	9.0-11.4	$1.8 \times 10^{-3}$	$2.8 \times 10^{-8}$	$2.3 \times 10^{-3}$	$1.4 \times 10^{-3}$	$0.9 \times 10^{-3}$
ERIM	S01CH1	2.0-2.6	$3.6 \times 10^{-5}$	$2.6 \times 10^{-10}$	$1.0 \times 10^{-4}$	0.0	$1.0 \times 10^{-4}$
ERIM	S01CH2	4.5-5.5	$1.5 \times 10^{-4}$	$2.1 \times 10^{-10}$	$2.7 \times 10^{-4}$	$1.2 \times 10^{-4}$	$1.5 \times 10^{-4}$
ERIM	S01CH3	8.0-11.4	$4.2 \times 10^{-3}$	$2.8 \times 10^{-8}$	$6.0 \times 10^{-3}$	$3.1 \times 10^{-3}$	$2.9 \times 10^{-3}$
ERIM	S02CH1	2.0-2.6	$3.7 \times 10^{-5}$	$2.2 \times 10^{-10}$	$1.3 \times 10^{-4}$	0.0	$1.3 \times 10^{-4}$
ERIM	S02CH2	4.5-5.5	$1.6 \times 10^{-4}$	1.8 × 10 <sup>-10</sup>	$2.8 \times 10^{-4}$	$1.3 \times 10^{-4}$	$1.5 \times 10^{-4}$
ERIM	S02CH3	8.0-11.4	$1.9 \times 10^{-3}$	$8.1 \times 10^{-9}$	$3.1 \times 10^{-3}$	$1.5 \times 10^{-3}$	$1.6 \times 10^{-3}$
ERIM	S03CH2	4.5-5.5	$1.5 \times 10^{-4}$	5.3 × 10 <sup>11</sup>	$1.9 \times 10^{-4}$	$1.3 \times 10^{-4}$	$0.6 \times 10^{-4}$
ERIM	S03CH3	8.0-11.4	$4.0 \times 10^{-3}$	$1.4 \times 10^{-8}$	$4.9 \times 10^{-3}$	$3.6 \times 10^{-3}$	$1.3 \times 10^{-3}$
ERIM	S23CH1	2.0-2.6	$3.8 \times 10^{-5}$	$1.1 \times 10^{-9}$	$2.6 \times 10^{-4}$	0.0	$2.6 \times 10^{-4}$
ERIM	S23CH3	3.0-4.2	$2.1 \times 10^{-4}$	$1.3 \times 10^{-9}$	$4.5 \times 10^{-4}$	$1.4 \times 10^{-4}$	$3.1 \times 10^{-4}$
ERIM	S23CH4	9.0-11.4	$2.3 \times 10^{-3}$	1.0 × 10 <sup>7</sup>	$4.5 \times 10^{-3}$	$1.5 \times 10^{-3}$	$3.0 \times 10^{-3}$

21

<u>د ا</u> Š. 9Ľ P 3 E 2 -127 No. Sec. 3 Ň Ś K,

7





**Figure 3** Power spectral density of BMAP Montauk Point middle-wavelength and long-wavelength back-ground data.



Figure 4 Power spectral density of AFGL cloud and terrain background scene 105.

has a resolution of 0.33 mrad, giving a maximum spatial frequency of about 1.5 cycles/mrad. However, the scene is sampled at 0.1 mrad resolution, giving a max-



Figure 5 Power spectral density of ERIM Port Hueneme scene in 2.0-2.6  $\mu$ m spectral band (scene S23CH1).

imum Nyquist frequency of 5 cycles/mrad. Since the detector limits the frequency to 1.5 cycles/mrad, data between 1.5 cycles/mrad and 5 cycles/mrad are principally sensor noise.

All of the AFGL PSDs show the flattening because at high spatial frequencies the power of the noise within the sensor is greater than the power from the scene. Without the sensor noise, the PSDs are expected to maintain the  $1/k^2$  slope up to 1.0 cycle/mrad. Several AFGL scenes with higher spatial resolution (~0.1 mrad) were also analyzed and show that the  $1/k^2$ slope continues to at least this spatial frequency (see Appendix D).

Table 6 lists the levels at which the four PSDs flatten and the frequencies where they begin to flatten. These values are also listed for some of the PSDs given in Appendix D. Also listed in Table 6 are the cutoff frequencies of the sensors. The roll-off of the PSDs, the noise level, and the cutoff frequency are used in the analysis.

The point-source characteristic of the BMAP data is included in Appendix A. Since the BMAP scenes are oversampled, a point target in the scene will spread into many pixels in the resulting image. The Fourier transform of the point-source characteristic was computed for both the long- and mid-IR bands. Figure 6 shows the Fourier transform of the point-source

Scene	Power spectral density at noise level ((W/cm <sup>2</sup> /sr) <sup>2</sup> /(cycles/mrad))	Flattening frequency (cycles/mrad)	System cutoff frequency (cycles/mrad)		
BMAP (long IR)	$1.5 \times 10^{-13}$	3.0	1.5		
BMAP (mid IR)	$3.0 \times 10^{-15}$	3.0	1.5		
AFGL (I01R)	$3.3 \times 10^{-10}$	0.35	1.0		
AFGL (104R)	$2.0 \times 10^{-9}$	0.35	1.0		
AFGL (105R)	$3.0 \times 10^{-10}$	0.30	1.0		
AFGL (109R)	$4.0 \times 10^{-10}$	0.30	1.0		
ERIM (S01CH1)	$6.0 \times 10^{-12}$	0.15	0.25		
ERIM (S01CH2)	$1.5 \times 10^{-12}$	0.17	0.25		
ERIM (S23CH1)	$2.0 \times 10^{-11}$	0.15	0.20		





Figure 6 Fourier transform of point source as seen by the BMAP instrument.

characteristic of the long-IR band. The plot looks like a low-pass filter with a cutoff at about 1.5 cycles/mrad.

Point-source characteristics of the AFGL data were not available. Some ERIM frequency response data are included in Appendix C. Since there was no oversampling in either of these data sets, it was assumed that the point-source target is an impulse. The PSD of an impulse is a flat spectrum with a cutoff at the Nyquist frequency. Therefore, while the PSD of the BMAP point-source characteristic looks like a real lowpass filter, the PSDs of the AFGL and ERIM pointsource characteristics are assumed to be ideal low-pass filters.

 $\mathbf{E}$ 3 

THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY LAUREL, MARYLAND

#### 4.0 SCENE CLUTTER PROCESSING

#### 4.1 Approach

The first technique examined uses the PSD of the scene to give an estimate of the required target signal for detection. A signal-to-noise criterion was selected to produce a nominal false-alarm level. The target is modeled as a point source with unknown irradiance in the spectral band. A matched filter is then applied to the signal and noise spectra to estimate the required target irradiance for detection. The target irradiance required for detection and the false-alarm rate are the primary measures of performance, both in this study and for tactical sensors. This technique is well-established and often used to estimate IR sensor performance. <sup>16,17</sup>

A matched-filter approach offers a number of advantages. Foremost is that this approach allows one to make performance estimates for a scanning sensor in the presence of background clutter rather than on sensor noise alone. Since the matched-filter technique gives the maximum achievable performance, this method sets a limit (or standard) on sensor detection capability. The matched-filter approach can be used to compare clutter-limited performance in different scenes and in different spectral bands when the same scene is measured in multiple colors.

The matched-filter approach to predicting clutterlimited performance has well-known disadvantages. Results of the method are incorrect because real scenes do not meet the assumptions of the matched-filter analysis (see below). Even so, a processing filter that is approximately "matched" to the signal and ciutter spectrum approximately minimizes the clutter power into the sensor. Hence the matched-filter method "designs" a real filter that can be applied directly to the raw scene data. Directly filtering the raw scene provides a measure of false-alarm rate as a function of detection threshold. The threshold can then be used to estimate the required target irradiance.

Therefore, the second approach is directly filtering the raw scene with a digital filter that approximates a matched filter. Raw data is processed with a firstorder high-pass filter that approximately "whitens" the clutter spectrum. Results of this filtering process can be compared to that of the matched-filter analysis. Several methods of comparison are possible: one is to determine the threshold required to give no false alarms in the filtered data and then compare the results with the threshold that would be required to give no false alarms (e.g., false alarm probability of  $\leq 0.5$ ) in the matched-filter analysis.

Thresholding the filtered data at various levels gives the number of false alarms (i.e., false-alarm rate) as a function of threshold (hence, target signal). After filtering, the scene has the mean background level removed and large, low-frequency features are suppressed. Unfortunately, large features with sharp edges will also produce a significant filter output that is indistinguishable from that produced by a target. Real scenes have a number of these boundaries such as cloud edges against sky, terrain, or other cloud layers, terrain crests and valleys, and boundaries between woods and fields.

Further discrimination is obtained by examining the differences in high-pass filter response to point objects and to extended objects. Since the high-pass filter acts as a differentiator, a filtered positive point feature produces a positive pulse immediately followed by an approximately equal-amplitude negative pulse. (The reverse is true for a negative point feature.) On the other hand, a sharp edge will only produce a positive (or negative) pulse, not a pair of pulses. Therefore a pulse-width discriminator can be developed to separate small point features from edges.

Implementation of the pulse-width discriminator requires that a negative crossing of a specially set confirmation threshold will follow a positive crossing of the detection threshold. Similarly, crossings of the negative detection threshold (i.e., to detect a negative contrast target) must be followed by a crossing of the positive confirmation threshold. The confirmation thresholds are only active for a short time after a crossing of the detection threshold.

This pulse-width discriminator rejects sharp edges and therefore enhances the discrimination provided by the high-pass digital filter. Performance is again measured in terms of number of detections as a function detection threshold leve! (i.e., false-alarm rate). However, the high-pass filter plus pulse-width discriminator is still not sufficient to eliminate extended scene features totally. Linear features such as roads and sunenhanced cloud edges will pass the processing tests. If the sensor has multiple parallel detection channels, near simultaneous detections in adjacent channels can be used to reject features with extent in the cross-scan direction.

<sup>&</sup>lt;sup>17</sup> H. Samuelson, "Infrared Systems: I. Expressions for Signal and Background Induced Noise with Space Editers," *IEEE Trans. Aerosp. Electron. Syst.* AES-7, 27-33 (1971).

R. Yoshitani, "Signal Processing Theory for Linearly Scanning Rectangular Detector," Proc. IRIS 18, 117-148 (1973)

This post-detection adjacent-channel logic will allow discrimination against linear features whose length extends across three or four contiguous channels. The combination of high-pass filtering, pulse-width discrimination, and adjacent-channel logic provides a complete set of spatial-discrimination techniques that allow separation of point features from larger features with significant in-scan or cross-scan extent (or both). The nature of the scanning geometry provides better discrimination in the in-scan direction because of oversampling.

Even implementation of the above combination of techniques cannot eliminate all potential false alarms. Background features whose spatial extent is  $\leq 2$  detector widths (or pixels or resolution cells) in the scan direction and  $\leq 3$  detector widths in the cross-scan direction cannot be distinguished from targets. As sensor sensitivity is improved, the number of these small features that pass all point source discrimination tests will increase and clutter will limit the sensor performance. When this fundamental limit is encountered, other discrimination techniques such as improved spatial resolution (unlikely in a missile seeker) or color (multiple-spectral-band) tests must be investigated. Such an investigation requires a database beyond the scope of this investigation.

The following sections describe the analyses and results of these discrimination techniques as applied to the available background scenes.

#### 4.2 Matched-Filter Performance Analysis

Using the PSDs of the AFGL, BMAP, and ERIM images, a matched filter was applied to the data.<sup>18,19</sup> The signal was assumed to be an impulse (flat spectrum to the cutoff frequency), and the cutoff frequency (i.e., spatial resolution) was varied up to the sensor resolution-limited Nyquist maximum value to determine the effect of spatial resolution. A minimum target irradiance required for detection was determined as a function of the cutoff frequency assuming a target irradiance to rms clutter noise irradiance of  $\times$ 50. Hence, the detection threshold is 7.07 times the rms clutter noise. Assuming that the noise is Gaussian, the false-alarm probability is 0.5 after about 10<sup>12</sup> independent looks (resolution cell).

From the above discussion, the signal-to-noise ratio (SNR) is given as

$$SNR = \frac{|s(0)|^2}{\sigma_N^2} \qquad (1)$$

where s(0) is the peak signal output and  $\sigma_N^2$  is the variance of the noise output. For a system with a filter transfer function H(f) the peak signal and noise variance are

$$s(0) = \int_{-\infty}^{\infty} H(f) \ s(f) \ df \qquad (2a)$$

and

$$\sigma_{\rm N}^2 = \int_{-\infty}^{\infty} |H(f)|^2 N(f) df \qquad (2b)$$

where s(f) is the signal spectrum and N(f) is the noise (internal plus scene) PSD. For a matched filter

$$SNR^{2} = \int_{-\infty}^{\infty} \frac{|s(f)|^{2}}{N(f)} df$$
 (3)

and when the target is an impulse, the signal spectrum (for AFGL and ERIM data) is assumed to be generated from an impulse:

$$S(k) = E_t \Delta x \qquad (4$$

where  $E_i$  is the target irradiance (in W/cm<sup>2</sup>) and  $\Delta x$ is the sample interval. Table 7 gives seeker performance results in terms of required target irradiance for detection using the above method for all available AFGL scenes.<sup>20</sup> Three cases are given. The first uses the PSDs of the original data (background-plus-noise case that includes the collection scenes). The second performance result is the required target irradiance if only sensor noise from the forward-looking IR (FLIR) were present (FLIR-noise-only case). The AFGL FLIR internal noise is approximated by a flat PSD with a magnitude equal to the high spatial frequency portion of the PSD. Since the AFGL data always show sensor noise at high spatial frequencies, this internal noise estimate gives the sensor limitation. Finally, the third column (background-only case) gives an estimate of the background clutter limitation, assuming that the clutter PSD continues to decrease as  $1/k^2$ . Averages

<sup>&</sup>lt;sup>15</sup> J. Schroeder, J. H. Schummers, B. P. Sandford, and W. J. Tropf, "Infrared Cloud Backgrounds," in *Proc. Tri-Service Intrared Background Symposium*, AFGL-TR-84-0094 (Mar 16, 1984).

<sup>&</sup>lt;sup>19</sup>1. M. Howser and W. J. Tropf, "Investigation of Infrared Background Clutter," in *Research and Development Programs* at *The Johns Hopkins University Applied Physics Laboratory*, JHU API, Quarterly Report RQR 85-1 (Jan-Mar 1985).

<sup>&</sup>lt;sup>29</sup> W. J. Tropf, A. N. Vavreck, B. J. Sandford, J. H. Schummers, and J. Schroeder, "Infrared Cloud Backgrounds and Sensor Performance," in *Presentations at the Second Tri-Service Cloud Modeling Workshop*, 1DA Report M-9, I, pp. 199-248 (Aug 1, 1984).

			Required Target Irradiance (10 <sup>-11</sup> W/cm <sup>2</sup> )		
	TROM		Background	FLIR	Background
Image	IFOV	Scene description	plus noise	noise only	only
			3 00	2.04	
101	0.5 mrad	Down viewing cloud	3.98	2.96	1.81
102		Down viewing and water	3.40	2.67	1.53
103		Down viewing and terrain	8.36	6.46	4.80
104		Down viewing and terrain	8.67	6.82	4.67
105		Clouds and horizon	3.53	2.73	1.73
106		Cloud deck	4.97	3.68	2.95
107		Cloud structure	5.53	4.22	3.70
I08		Clouds and horizon	9.81	8.14	2.94
109		Monument Vailey	4.17	3.21	2.34
110		Monument Valley	4.09	3.12	2.23
<b>I</b> 11		Close clouds	3.39	2.71	1.50
112		Close clouds	3.38	2.72	1.63
113		Clouds and horizon	5.29	4.36	2.62
114		Clouds and horizon	5.75	4.65	3.01
I16		Horizon and clouds	6.20	4.62	3.26
117		Clouds and terrain	5.20	4.35	2.07
118		Clouds and horizon	5.95	4.57	3.02
119		Clouds and horizon	5.64	4.34	3.36
120		Down viewing clouds	3.32	2.69	1.40
I <b>3</b> 1		Clouds below horizon	4.54	3.55	3.23
132		Down viewing clouds	4.96	3.86	3.70
21-scen	e, 0.5-mrad a	verage	5.23	4.12	2.74
121	0.1 mrad	Structured clouds	0.147	0.110	0.070
122		Structured clouds	0.152	0.107	0.083
123		Structured clouds	0.175	0.131	0.106
124		Structured clouds	0.150	0.122	0.072
125		Structured clouds	0.171	0.134	0.084
126		Structured clouds	0.154	0.118	0.077
127		Structured clouds	0.165	0.125	0.084
128		Structured clouds	0.160	0.127	0.077
129		Structured clouds	0.144	0.114	0.063
9-scene	, 0.1-mrad av	erage	0.157	0.121	0.080

#### Table 7 Required target irradiance for matched filter detection in several AFGL cloud scenes.

of the results for 21 AFGL scenes sampled at 0.5 mrad and for 9 AFGL scenes sampled at 0.1 mrad are given.

Similar matched-filter estimates were made using BMAP Montauk Point and Bedford No. 1 data. Since scanning seeker performance is dependent on resolution (i.e., IFOV), a matched-filter analysis with a variable seeker IFOV was conducted. Results for AFGL and BMAP cloud scenes are given in Fig. 7. The target irradiance required for detection is proportional to the sensor instantaneous solid-angle FOV (square of linear FOV dimension). AFGL results for the 21 scenes with 0.5 mrad resolution and 9 scenes with 0.1 mrad resolution are shown as a shaded range of values. Results of two BMAP scenes are shown for comparison. Long-wavelength BMAP data are shown as thick solid lines and middle-wavelength results as thick dashed lines. The Montauk Point scene is overcast and has low contrast. The Bedford No. 1 is a hole in the LAUREL, MARYLAND



Figure 7 Required target irradiance for detection as a function of seeker resolution for AFGL and BMAP data.

clouds near the sun and has significantly higher contrasts. Note that long-wavelength clutter-limited results from both AFGL and BMAP data are comparable, although the overcast sky at Montauk Point gives lower clutter results.

A typical middle-wavelength seeker will have a spatial resolution of 0.5 to 1.0 mrad while the resolution of a long-wavelength seeker will be 1 to 2 mrad. Combining the difference in minimum detectable target signature and resolution results in approximately two orders of magnitude difference between the clutter noise of the middle- and long-wavelength bands.

An ideal bandpass filter was also applied to the Montauk data using the PSDs.<sup>20</sup> The response of an ideal bandpass filter is zero up to the cut-on of the filter. After the cut-on, the filter response is unity up to the cutoff. The cutoff of this bandpass was chosen to be the sensor-limited maximum frequency (1.5 cycles/mrad). The cut-on of the filter was varied from just above DC to the sensor-limited maximum frequency. The minimum detectable signal (or required target irradiance) was computed as a function of cuton frequency, assuming a signal-to-noise ratio of 7.07. Figure 8 shows a comparison of the matched-filter performance versus the ideal bandpass filter performance. Figure 8a is from the mid-IR data and 8b is from the long-IR data. Both parts of the figure show that the matched filter requires a lower target irradiance than the ideal bandpass filter. However, the ideal bandpass filter performance approaches the matched-filter performance for a bandpass cut-on that is approximately one-half of the cutoff frequency of the system.

Using the PSDs of some of the AFGL scenes, an ideal high-pass filter was applied to AFGL images.<sup>18</sup> A high-pass filter was used for the AFGL data because the scene was sampled at the Nyquist rate. Therefore, the sensor-limited maximum frequency equaled the sampling frequency, and the higher frequencies did not need to be rejected. The results of the procedure were the same. The matched filter performed better than the ideal high-pass filter, but the performance of the high-pass filter again approached the matched-filter performance for a cut-on frequency of about one-half the cutoff frequency of the system.



Figure 8 Comparison of required target irradiance for ideal bandpass filters to the matched-filter result using BMAP data. (a) Required target irradiance for BMAP mid-IR images. (b) Required target irradiance for BMAP long-IR images.

The matched filter and ideal high-pass or bandpass filter results give a first-order approximation to seeker performance. However, these results assume that the scene is Gaussian and stationary. The stationary assumption requires that the power spectrum and statistics of the scene are independent of the location within the scene. If the PSD is dependent on the location within the scene, then the scene average PSD is not a valid representation. Also, the PSD characterization of the scene only includes a measure of the scene mean and variance, not higher moments. If the scene is Gaussian the mean and variance of the scene totally describe the scene statistics. However, if the scene is not Gaussian (as is usually the case), higher moments are needed. A

9

3

3

រា ដៃ

**(**);;;

(70)

Ě

3

3

3

Ś

2

<u>₹</u>5

Since real scenes violate the Gaussian and stationary assumptions, actual performance (e.g., true-false alarm rate) must be determined by direct processing of the raw background data. The following sections of the report describe a procedure used to process the raw background images.

#### 4.3 Digital-Filter Performance Analysis

In theory, a matched filter applied to the IR data would maximize the signal-to-noise ratio of a point target in the scene. Since the assumptions on which matched-filter theory is based do not apply to IR clutter, direct filtering of the raw scene data with a digital filter that approximates a matched filter can be used to estimate detection system performance.

Since the signal (point-source) spectrum is approximately white, the input clutter is whitened by a digital high-pass filter that approximately whitens the clutter and therefore represents a matched filter.<sup>21</sup>

Since the BMAP frequency data extend beyond the signal (point-source) spectrum, an additional low-pass filter is needed to eliminate sensor noise. The additional filter was applied to the BMAP data to eliminate data lying between 1.5 and 5.0 cycles/mrad spatial frequency.

It was mentioned earlier that the PSDs of the pointsource characteristics of the AFGL and ERIM data collection instruments were close to flat spectrums because the data were taken at the Nyquist frequency; therefore, no filtering beyond the clutter-matched filter was needed with the AFGL and ERIM data.

The matched filters needed for these images were applied to the PSDs shown in Figs. 3 to 5. A Butterworth digital filter was selected to evaluate the IR images.<sup>22</sup> A first-order high-pass filter was used because it approximately matched the rolloff of the background PSDs and therefore approximated the matched filter of the previous section. PSDs of the AFGL and ERIM filtered images are approximately flat. The BMAP PSDs were not completely flat because of the second-order, low-pass filter that was also applied.

The cut-on of the filters was chosen on the basis of the point where the PSDs of the images began to

<sup>&</sup>lt;sup>21</sup>L. M. Howser, Analysis of Background Measurement and Analysis Program (BMAP) IR Images, JHU/APL F1F(2)85-U-035, Rev 1.

<sup>&</sup>lt;sup>22</sup>G. L. Turin, "An Introduction to Matched Filters," *IEEE Trans. Information Theory* **1T 6**, 311-329 (Jun 1960).

flatten. Table 6 lists the system cutoff frequencies for the data and the frequencies at which the PSDs begin to flatten for a number of scenes. These frequencies were used to choose the cut-on of the highpass filters. For the BMAP data, the system Nyquist sampling spatial frequency of 1.5 cycles/mrad was chosen as the cut-on frequency. Since the AFGL image flattened at 0.3 cycles/mrad, 0.25 was chosen as the filter cut-on frequency. (Since the specified cut-on frequency is 3 dB down for a first-order high-pass filter, by choosing the cut-on frequency to be slightly less than the frequency at which the PSD is flat, the output PSD should be approximately flat.) The ERIM cut-on frequencies were chosen for the same reasons. That is, knowing the frequencies where the input PSDs flattened, the cut-on frequencies were chosen to whiten the output PSD.

Table 8 lists the filters and the corner frequencies used. Figures 9 through 11 show the filters used in this analysis. Figure 9 shows the BMAP bandpass filter, Fig. 10 shows the AFGL high-pass filter, and Fig. 11 shows the ERIM high-pass filter.

٦	Table 8	Digital	filters used	d in the	performance	analysis.
a	HF	ov	Low-pas	s	High-pass	Corne

Data source	HFOV (mrad)	Low-pass filter	High-pass filter	Corner (cycles/mrad)
BMAP	0.33	2nd order	1st order	1.5
AFGL	0.5	None	1st order	0.25
ERIM	2.0	None	1st order	0.1
ERIM	2.5	None	lst order	0.07



**Figure 9** BMAP bandpass filter: second-order lowpass, and first-order high-pass (corner = 1.5 cycles/mrad).



**Figure 10** AFGL first-order high-pass filter (cut-on = 0.25 cycle/mrad).

1000



**Figure 11** ERIM first-order high-pass filter (cut-on = 0.1 cycle/mrad).

Figures 12 through 14 show the PSDs of three images after filtering. Figure 12 shows the PSD of the BMAP Montauk long-IR data after filtering with the combination of a second-order, low-pass filter and a first-order, high-pass filter. This PSD can be compared to the long-IR PSD in Fig. 3 and the PSD of the pointsource characteristic in Fig. 6. The comparison with Fig. 6 shows that the filtered PSD does look like the Fourier transform of the point-source characteristic, as expected after applying the matched filter. Figures 13 and 14 show the PSDs of the AFGL and ERIM images. These PSDs can be compared to the PSDs in Figs. 4 and 5. The two figures show that the high-pass filters did approximately flatten the background PSDs. Appendix E shows the PSDs of the remaining images.

The reason for applying the filtering was to maximize the signal-to-noise ratio by minimizing the clutter. Flattening the PSD of the background image reduces the energy of the low-frequency objects and does not affect the high-frequency objects. Point target signals, which are predominately of high-frequency content, therefore remain almost unaffected.

Figures 15 and 16 demonstrate the effect of the filtering. Figure 15a shows line 471 of ERIM scene S01CH1. This line contains no point targets. Figure 15b shows the same line after filtering, now all of the low-frequency features in the line have been attenuated. Figure 16a shows line 471 from ERIM scene



d

A

8

**Figure 12** Power spectral density of BMAP Montauk Point long-wavelength background data after bandpass filter.



Figure 13 Power spectral density of AFGL cloud and terrain background scene 105 after high-pass filter.

S01CH3. This line has some possible point targets present. Figure 16b shows the same line after filtering; most of the image features have been attenuated, but the possible point targets are almost unaffected by the filter. Figure 16c shows an enlargement of the area around the possible point targets, giving a better view of the filtered output.

The previous figures have shown that the filtering applied to the background images reduce the amplitude of image features when possible targets are not present. Also, the mean of all of the images are removed when high-pass filters are applied. Table 9 shows the maximum and minimum radiance of the scenes used in this study, after filtering. The values can be compared to the values in Table 5. A comparison of the tables shows that except for two scenes, the difference between the maximum and minimum scene radiance values before filtering is greater than the difference after filtering. Figures 15 and 16 show that this result is expected.



Figure 14 Power spectral density of ERIM Port Hueneme scene in 2.0-2.6  $\mu$ m spectral band (scene S23CH1) after high-pass filter.



**Figure 15** Line 471 of ERIM Camp A.P. Hill morning scene in 2.0-2.6  $\mu$ m spectral band (scene S01CH1). (a) Unprocessed line of scene. (b) Line of scene after highpass filter.



**Figure 16** Line 471 of ERIM Camp A.P. Hill morning scene in 8.0-14.0  $\mu$ m spectral band (scene S01CH3). (a) Unprocessed line of scene with data artifact. (b) Line of scene after high-pass filter. (c) Expanded line of scene after high-pass filter.

Scene	Maximum	Minimum	Δ (max – min)
BMAP-Montauk (long IR)	1.93 × 10 <sup>-5</sup>	$-0.94 \times 10^{-6}$	$2.87 \times 10^{-5}$
BMAP-Montauk (mid IR)	1.27 × 10 °	-1.46 × 10 <sup>6</sup>	$2.73 \times 10^{-6}$
BMAP-Bedford (long IR)	$2.46 \times 10^{-5}$	$-2.75 \times 10^{-5}$	$5.21 \times 10^{-5}$
BMAP-Bedford (mid IR)	1.18 × 10 <sup>-5</sup>	$-4.30 \times 10^{-6}$	$1.61 \times 10^{-5}$
AFGL 101R	$2.14 \times 10^{-4}$	$-3.91 \times 10^{-4}$	$6.05 \times 10^{-4}$
AFGL 104R	$6.13 \times 10^{-4}$	$-2.39 \times 10^{-4}$	$8.52 \times 10^{-4}$
AFGL 105R	$3.56 \times 10^{-4}$	$-2.76 \times 10^{-4}$	$6.32 \times 10^{-4}$
AFGL 109R	$2.48 \times 10^{-4}$	$-2.67 \times 10^{-4}$	$5.15 \times 10^{-4}$
ERIM F8CH1	$2.81 \times 10^{-5}$	$-2.88 \times 10^{-5}$	5.77 × 10 <sup>-5</sup>
ERIM F8CH2	$1.48 \times 10^{-5}$	$-1.53 \times 10^{-5}$	$3.00 \times 10^{-5}$
ERIM F8CH3	$1.86 \times 10^{-4}$	$-1.71 \times 10^{-4}$	$3.57 \times 10^{-4}$
ERIM S01CH1	$2.52 \times 10^{-5}$	$-2.92 \times 10^{-5}$	5.44 × 10 <sup>5</sup>
ERIM S01CH2	3.96 × 10 5	$-3.46 \times 10^{-5}$	$7.42 \times 10^{-5}$
ERIM S01CH3	$8.31 \times 10^{-4}$	$-8.22 \times 10^{-4}$	$1.65 \times 10^{-3}$
ERIM S02CH1	4.49 × 10 <sup>5</sup>	$-3.19 \times 10^{-5}$	7.68 × 10 <sup>5</sup>
ERIM S02CH2	4.22 × 10 <sup>4</sup>	$-3.58 \times 10^{-5}$	7.80 × 10 5
ERIM S02CH3	$3.77 \times 10^{-4}$	$-3.86 \times 10^{-4}$	$7.63 \times 10^{-4}$
ERIM S03CH2	3.01 × 10 5	$-2.34 \times 10^{-5}$	5.35 × 10 <sup>-5</sup>
ERIM S03CH3	$3.32 \times 10^{-4}$	$-2.66 \times 10^{-4}$	5.98 × 10 <sup>4</sup>
ERIM S23CH1	$1.21 \times 10^{-4}$	-8.08 × 10 <sup>°</sup>	$2.02 \times 10^{-4}$
ERIM S23CH3	$1.55 \times 10^{-4}$	-9.49 × 10 <sup>5</sup>	$2.50 \times 10^{-4}$
ERIM S23CH4	$1.11 \times 10^{-3}$	$-1.20 \times 10^{-3}$	$2.31 \times 10^{-3}$

Table 9 Statistics of background data after filtering in units of W/cm<sup>2</sup>/sr.

1

Š

-

٠

3

Ş,

8

3

3

653 689

8

8

E

8

ŝ

8) --

 $\overline{\mathcal{T}}_{i}$ 

**USSESS** 

2021

Figure 17 shows each of the images in Fig. 1 after filtering was applied. To see the results of the processing clearly, only a portion of each image is displayed. A pixel area of about  $300 \times 300$  is displayed for each image. For the AFGL scene this is the entire image.

The images were created by first taking the absolute value of the data. Each of the images was then scaled from 0 to 255 with 0 equal to 0.0 W/cm<sup>2</sup>/sr, and 255 equal to the maximum filtered radiance in the image. Each image was then thresholded to be consistent with succeeding processing. All levels below the threshold were set to black; all levels above the threshold were set to white. The thresholds for the seven scenes are shown in Table 10 in terms of the noise equivalent irradiance. This thresholding will be discussed later.

Using this thresholding, any negative or positive outputs of the filter that are greater than the threshold are white in the images. The BMAP image in Fig. 17a shows that about 50% of the figure is greater than the threshold. Figure 17b is mostly black with a much smaller percentage of pixels greater than the threshold. Figure 17c, d, and e shows the morning, afternoon, and evening scenes of Camp A.P. Hill, after filtering. Figure 17c and d shows only a small percentage of pixels above the threshold. Only a very few pixels are above the threshold in Fig. 17e.

One bad line is visible in the Port Hueneme scene of Fig. 17f. The high-pass filtering and thresholding have accented this bad line since it was not visible in Fig. 1f. Also shown in Fig. 17f are strong edges from the buildings in the scene. The ridges in the mountains of Fig. 17g also give strong edges after high-pass filtering.

#### 4.4 Filtering and Pulse Discrimination Performance Analysis

After applying the filters, the next step in the procedure is a pulse discrimination algorithm. This step adds an additional false-alarm-rejection capability to suppress sharp but extended features such as edges and boundaries.<sup>21</sup>

Figure 18 shows the pulse width discrimination algorithm for the BMAP images. The lower part of the figure shows a point targe: (a near impulse). After filtering, this target produces two pulses, one positive and one negative, which is the impulse response of the bandpass filter. The magnitude of the spikes and the delay between the maximum and minimum are functions of the order and the cutoff frequency of the filter.

The upper part of Fig. 18 shows a step input. This is used to simulate the edge of a cloud as seen by the sensor. After filtering, this artifact also produces a positive pulse but no corresponding negative pulse. Similarly, a negative step would produce a negative pulse but not a corresponding positive pulse.

Any post-filtering threshold set to detect point targets could not distinguish between the point target and the step artifact impulses. To perform an additional discrimination between point and extended features, a pulse-width measurement algorithm is used. The pulse-width discrimination algorithm searches for any local maximum above a specified threshold. (The algorithm actually searches for a maximum or minimum since a target could be hotter or colder than the surrounding background. We will focus on the maximum in this discussion.) After finding a maximum, succeeding filter output is searched to find a corresponding minimum based on a given threshold. If a maximum and a corresponding minimum are both found, the point is declared to be a target; therefore, in Fig. 18 the point target would pass the discrimination logic and the step artifact would not pass.

Three parameters are needed for the pulsediscrimination algorithm. One parameter is the minimum-to-maximum ratio. This parameter requires that the absolute value of the minimum pulse that follows the local maximum passing the detecting threshold must be of some minimum size. The second parameter is the delay between the maximum and minimum values. Since this algorithm searches for point targets, the delay is small. The final parameter that must be specified is the detection threshold. To avoid processing sensor noise as possible targets, any pixel less than the detection threshold is not processed.

As discussed earlier, the selected filter determines the theoretical maximum for an impulse response and the delay between the maximum and minimum. For this reason the thresholds and delays used in this analysis varied depending on the filters used. In order to determine the appropriate thresholds and delays, various inputs were processed through the filters. The response of the filters to these inputs was used to determine the thresholds and delays. Since each set of data (BMAP, AFGL, and ERIM) had different filters this selection had to be performed for each data set.

Since the BMAP data were oversampled by the seeker, simply putting an impulse into the filtering would not be correct. Before filtering, the impulse was convolved with the point-source characteristic of the sensor, spreading the input into more than one output

<sup>&</sup>lt;sup>24</sup> L. M. Howser, "Investigation of Infrared Background Clutter," in *Research and Development Programs at The Johns Hopkins University Applied Physics Laboratory*, JHU API Quarterly Report RQR/85-2 (Apr-Jun 1985).




(b)







A 8 8 8 4

23

N

 $\mathbf{\Sigma}$ 

8

3

3

3

3

Ś

<u>دم</u>

Ś

3

iş.

ŝ

ę,

Зh

 $\overline{\mathbf{v}}$ 

(c)

ERIM images of Camp A.P. Hill (4.5-5.5 µm spectral band) after high-pass filter and 3.0 NEI threshold.





**Figure 17** Images after filter and threshold. (a) BMAP middle-wave image from Bedford after bandpass filter and 1.5 NEI threshold. (b) AFGL scene I09 of Monument Valley after high-pass filter and 1.5 NEI threshold. (c) Morning (scene S01CH2). (d) Afternoon (scene S02CH2). (e) Evening (scene S03CH2). (f) ERIM image of Port Hueneme (4.5-5.5  $\mu$ m spectral band) after high-pass filter and 10.0 NEI threshold (scene S23CH3). (g) ERIM image of mountains by Nellis AFB (3.9-4.7  $\mu$ m spectral band) after high-pass filter and 3.0 NEI threshold (scene F8CH1).

Image	Maximum (W/cm <sup>2</sup> /sr)	Threshold (W/cm <sup>2</sup> /sr)	Threshold (LUT)	× NEI <sup>1</sup>
BMAP, Bedford, mid IR	1.18 × 10 <sup>-5</sup>	$1.12 \times 10^{-7}$	2	1.5
AFGL (109R)	$2.67 \times 10^{-4}$	$5.60 \times 10^{-5}$	53	1.5
ERIMI (S01CH2)	3.96 × 10 <sup>-5</sup>	$3.36 \times 10^{-6}$	22	3
(S02CH2)	$4.22 \times 10^{-5}$	$3.36 \times 10^{-6}$	20	3
(S03CH2)	$3.01 \times 10^{-5}$	$3.36 \times 10^{-6}$	29	3
ERIM3 (S23CH3)	$1.55 \times 10^{-4}$	$1.25 \times 10^{-5}$	21	10
ERIM5 (F8CH1)	$2.88 \times 10^{-5}$	$1.63 \times 10^{-6}$	14	3

Table 10 Thresholds used in Fig. 17

 $^{1}$  × NEI = times noise equivalent irradiance





point (performing a low-pass function on the impulse). The result of the convolution was filtered with the bandpass filter selected for the BMAP data. In addition to the impulse, other inputs were processed in the same way. After the inputs were processed, information on the threshold and delays was obtained. Table 11 shows the results of this process.

Table 11 shows than an impulse that has been convolved with the BMAP point-source characteristic has a magnitude of about 0.25 times its original value af-

## THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND

Input	Input max	Output	Output	Max min	Delay	Output min
signar	(convolved)			Max - mm	Delay	
Л	255.0	64.3	- 51.0	115.3	3	0.793
	468.7	125.9	- 91.2	217.0	4	0.724
	681.4	158.9	- 125.5	284.4	4	0.790
	793.6	186.7	- 145.7	332.4	4	0.780
	881.3	197.0	- 151.3	348.4	5	0.768
	921.6	200.0	- 150.7	350.7	6	0.754
ſ`	361.8	93.8	- 71.2	165.9	4	0.759
<u></u>	362.3	95.2	- 68.2	163.4	3	0.716
<b>」</b> ┦┡┓ <u></u>	469.0	110.4	- 88.4	198.8	4	0.801
_ſŢĹ_	575.4	139.8	- 105.5	245.3	3	0.755
J┥┆┝╲	631.3	156.4	- 118.6	274.9	4	0.758
	574 9	142.4	- 108 4	250.9	4	0.761

Table 11	Results of	processing	impulses	with	BMAP	filters
	nesults of	processing	impuises	WILII	DIVIAL	mera.

ter filtering with the Butterworth bandpass filter. Also the ratio of the output minimum to maximum is 0.793. There is a 3-sample delay between the output maximum and minimum for the impulse input.

The second line of Table 11 shows the results for a two-pixel-wide input. For this input, the ratio of output minimum to maximum is 0.724 and the delay between the two is 4 samples.

The logic for the pulse discrimination algorithm was determined using the results in Table 11. A value of 0.70 was chosen for the ratio of the pulse-measuring threshold to the initial detected pulse. This value means that if a local maximum is found and the corresponding minimum is less than 0.70 times the maximum, that point will not be chosen as a target.

From Table 11 a delay of 3 or 4 samples was chosen for the algorithm. Any local maximum and minimum that is found that has a delay less than 3 or greater than 4 will not be chosen as a target. This restriction will eliminate wide artifacts (like the 5-samplewide pulse in the table). With the restrictions described, all of the wide features in Table 11 will not be chosen as targets. Only inputs less than 4 samples wide will pass this logic. R

23

دے س

 $\mathbb{Z}$ 

3

2

The only parameter that still needs to be defined for the BMAP images is the noise threshold. The threshold of images was set depending on the NEI of the seeker. The NEI of the system is, by definition, the irradiance required for a signal to have a magnitude equal to the rms noise within the system. The NEI of the BMAP, AFGL, and ERIM sensors are given in Table 3.

Since the threshold is defined in terms of the standard deviation of the noise of the system, the percentage of the image expected to be greater than the threshold can be computed using statistics tables. (This calculation assumes a normal distribution of the output levels.) If the threshold is set to be 3 NEI, 0.26%of the pixels are expected to be greater than the threshold. With a threshold of 1.5 NEI, 13.4% of the pixels would be expected to be greater than the threshold. For the analysis below, the detection threshold was typically set at a low multiple of NEI to develop detection statistics in the small scenes that are available.

Figure 19 demonstrates the effect of pulse discrimination on one line of the Montauk long-IR image. Figure 19a shows the first line of the first frame of the long-IR Montauk image before any filtering. Figure 19b shows the same line of the image after the bandpass filter was applied. Notice that both axes have



Figure 19 Line 1 of BMAP Montauk Point longwavelength background data. (a) Unprocessed line of scene. (b) Line of scene after high-pass filter (with  $\pm 1.5$ NEI threshold). (c) Line of scene after high-pass filter and pulse discrimination (with  $\pm 1.5$  NEI threshold).

changed. The y-axis changed because the mean of the image was removed by the filtering. The x-axis changed because the image had to be padded with zeros to perform some of the processing. The horizontal lines in Fig. 19b show the  $\pm 1.5$  NEI threshold applied to the data, demonstrating that most of the pixels in the line are excluded from processing with a simple threshold. The pulse discrimination process is then needed to eliminate the remaining pixels. Figure 19c shows the same line of the pulses that crossed the threshold have been eliminated by using the pulse discrimination. Also, the remaining pulse barely exceeds the threshold. If the threshold were increased to  $2 \times NEI$  no pixels in this line would pass the discrimination logic.

No convolution of an input pulse with the sensor response function was needed for the AFGL data because no oversampling occurred with this seeker. Excluding this step, the same procedure was applied to the AFGL data as was applied to the BMAP data. Various inputs were processed with the AFGL high-pass filter and their results were tabulated. Table 12 shows the results.

Table 12 shows that the output minimum-tomaximum ratio was 0.586 for the impulse input. The delay between the maximum and minimum was 1 pixel (= one sample). These results show there is a large difference between the more realistic bandpass filter impulse of the oversampled BMAP data and the highpass filtered impulse of data sampled at the Nyquist rate (i.e., AFG1 and ERIM).

The parameters for the pulse discrimination algorithm were calculated from the results in Table 12. A ratio of 0.5 was selected for the minimum-tomaximum pulse height. A delay of 1 or 2 pixels was allowed between the maximum and minimum. This selection of parameters only passes 1- and 2-pixel-wide targets. No other features will pass this logic.

The threshold for the AFGL data was not as easy to pick as it was for the BMAP data. The scaling of the images was not set to the NEI of the system. The PSD of each image was needed to compute the NEI of the system. The PSD of each image flattened at the noise level of the system. The minimum value of each PSD in the flattened region was obtained from the plots. The threshold for the AFGL images was set at 3.0 NEI. Knowing the scaling of each of the images, the threshold in units of output levels was calculated. Table 13 lists the thresholds used for the AFGL images.

The filtering process was again repeated for the ERIM data. Two filters had to be applied to these images because the ERIM data had two spatial resolu-

Input signal	Input max	Output max	Output min	Max – min	Delay	Output min Output max
	256.0	181.0	- 106.0	287.0	1	0.586
	256.0	181.0	- 150.0	331.0	2	0.829
	256.0	181.0	- 168.2	349.2	3	0.928
	256.0	181.0	- 175.7	356.7	4	0.971
	256.0	181.0	- 178.8	359.8	5	0.988

Table 12 Results of processing impulses with AFGL filter.

Table 13 Thresholds of AFGL images for pulse discrimination.

Scene	NEJ (W/cm²)	MF (W/cm <sup>2</sup> /sr)	Threshold (3 × NEI) (output levels)
101R	$5.8 \times 10^{-12}$	$8.4 \times 10^{-6}$	13.35
104R	$1.4 \times 10^{-11}$	$2.1 \times 10^{-5}$	12.84
105R	$4.9 \times 10^{-12}$	$8.4 \times 10^{-6}$	11.28
109R	$5.8 \times 10^{-12}$	1.1 × 10 <sup>5</sup>	10.59

tions. Again, various inputs were processed through the filters and the results tabulated. Table 14 shows the results of the filtering. The first section of this table is for the ERIM1 data (filtered with a cut-on of 0.10); the second section is for the ERIM3 and ERIM5 data (filtered with a cut-on of 0.070).

The results in Table 14 were used to determine the parameters of the pulse-discring nation logic on the ERIM data. The ratios for ERIM3 images were slightly lower than the corresponding ratios for the ERIM1 images. For the impulse input, the ratio of the output minimum to output maximum was 0.84 for the ERIM1 filters and 0.75 for the ERIM3 and ERIM5 filters. Looking at Table 14 it can be seen that limiting the delay between maximum and minimum to 1 or 2 pixels eliminates some of the wider features from being considered a target. It would be desirable to set the minimum-to-maximum ratio to 0.70 (just below the impulse ratio); however, this high threshold would eliminate the 2-pixel-wide pulse in line 5 of both sections of the table. The minimum-to-maximum ratio was therefore set to 0.50 in order to avoid eliminating possible targets from consideration.

The last parameter to be specified is the threshold for both sets of the ERIM data. Two methods were used in computing the NEI for these images. The first method used was the same as the AFGL calculation of the NEI. The minimum of the PSD was assumed to be the noise power. The NEI was computed from the power. The second method used the noise equivalent differential temperature of the sensor. Some of the ERIM spectral bands had a noise equivalent differential temperature (NE $\Delta$ T) already computed. Figure 20 shows a plot of the NE $\Delta$ T of some of the bands of ERIM data versus temperature. An average temperature of 285 K was assumed for the ERIM im $\mathbf{D}$ 

N

Input	Input	Output	Output			Output min
signal	max	max	min	Max – min	Delay	Output max
	64.0	37.0	- 31.0	68.0	1	0.84
	64.0	37.0	- 36.0	73.0	2	0.97
	64.0	37.0	- 37.0	74.0	3	0.99
	64.0	21.0	-21.0	42.0	3	0.995
	64.0	37.0	- 20.0	57.0	2	0.55
╶┎┥┠┑	64.0	21.0	- 20.0	51.0	2	0.97
<u>i</u> [	64.0	21.0	- 33.0	54.0	1	1.57
	64.0	37.0	- 28.0	65.0	2	0.76
	64.0	37.0	- 22.0	59.0	1	0.59
	64.0	40.0	- 30.0	70.0	1	0.75
$\square$	64.0	40.0	- 37.0	77.0	2	0.93
	64.0	40.0	- 39.0	79.0	3	0.98
	64.0	25.0	- 24.0	49.0	3	0.96
	64.0	40.0	- 22.0	62.0	2	0.55

## Table 14 Results of processing impulses with ERIM filter.



Figure 20 Typical derived NE $\Delta$ T values for the ERIM M-7 line scanner.

ages. Once the NEI was calculated for each image, the thresholds were computed. Table 15 shows the thresholds used for the ERIM images. The NEIs of the scenes marked were computed from the PSDs of the images. The remaining NEIs were computed from the NE $\Delta$ T of the image.

Each of the thresholds listed in Table 15 was a first choice in processing the data. For some scenes it was necessary to raise the threshold above 3 NEI/FOV to limit the number of pixels selected as targets. These cases will be discussed later.

The final parameters used for the pulse discrimination analysis are shown in Table 16, which lists the thresholds and delays used for each of the sets of data in this study.

All of the scenes were processed through the pulsediscrimination algorithm, using the parameters listed

Scene	NEI (W/cm <sup>2</sup> )	FOV (circular) (mrad)	$3 \times \text{NEI/(FOV)}$ (W/cm <sup>2</sup> /sr)	
S01CH1		2.0	$3.68 \times 10^{-6}$	(from PSD)
S01CH2	$4.47 \times 10^{-12}$	2.0	$3.36 \times 10^{-6}$	
S01CH3		2.0	$1.84 \times 10^{-5}$	
S02CH1		2.0	$3.68 \times 10^{-6}$	(from PSD)
S02CH2	$4.47 \times 10^{-12}$	2.0	$3.36 \times 10^{-6}$	
S02CH3		2.0	$1.16 \times 10^{-5}$	(from PSD)
S03CH2	$4.47 \times 10^{-12}$	2.0	$3.36 \times 10^{-6}$	
S03CH3		2.0	$1.50 \times 10^{-5}$	(from PSD)
S23CH1		2.5	$5.36 \times 10^{-6}$	(from PSD)
S23CH3	$7.80 \times 10^{-12}$	2.5	$3.74 \times 10^{-6}$	
S23CH4	$4.63 \times 10^{-11}$	2.5	$2.20 \times 10^{-5}$	
F8CH1	$3.40 \times 10^{-12}$	2.5	$1.63 \times 10^{-6}$	
F8CH2	$8.83 \times 10^{-12}$	2.5	$4.24 \times 10^{-6}$	
F8CH3	$4.58 \times 10^{-11}$	2.5	$2.20 \times 10^{-5}$	

## Table 15 ERIM NEIs and thresholds

Tab	le 16	Pulse	discrimination	parameters
-----	-------	-------	----------------	------------

Data source	<u>Output min</u> Output max	Delay (pixels)	Threshold (× NEI)
BMAP	0.70	3 or 4	1.5
AFGL	0.50	1 or 2	3.0
ERIM	0.50	1 or 2	3.01

<sup>1</sup>Threshold started at 3.0 but had to be increased for some images.

in Table 16. The results of the processing are listed in Table 17, which lists the maximum and minimum of each of the images after this processing. Also list-

ed in Table 17 is the difference between the maximum and minimum. The threshold used (in  $W/cm^2/sr$ ) is listed in the following column. The threshold in NEI is listed in parentheses in the same column. The percentage of samples that passed this algorithm is listed in the last column.

Some of the images were processed twice through the pulse-discrimination algorithm. If too many pixels passed the logic the first time, the threshold was raised and the image was reprocessed. The results for all of these runs are also listed in Table 17.

Figure 21 shows the seven sample images after filtering and pulse discrimination. The same procedure as was used for the images in Fig. 17 was followed to threshold these images. Also, the same portion of each image was displayed to make possible direct comparisons between the images.

ኯፚዹ፟ጜኯጜኯፚኯጜኯጜኯዄኯፚኯፚኯፚኯፚኯ

			Δ	Threshold	Pixels passed
Image	Max	Min	(max – min)	(× NEI)	(%)
BMAP-Montauk (Far IR)	$3.68 \times 10^{-6}$	$-6.38 \times 10^{-6}$	1.01 × 10 <sup>-5</sup>	$1.38 \times 10^{-6} (1.5)$	0.10
BMAP-Montauk (Mid IR)	$1.23 \times 10^{-6}$	$-6.0 \times 10^{-7}$	1.83 × 10 <sup>-6</sup>	$2.75 \times 10^{-7}$ (1.5)	0.10
BMAP-Bedford (Far IR)	6.18 × 10 <sup>-6</sup>	$-5.44 \times 10^{-6}$	1.16 × 10 <sup>5</sup>	1.5 × 10 <sup>6</sup> (1.5)	0.04
BMAP-Bedford (Mid IR)	$1.25 \times 10^{-6}$	$-1.27 \times 10^{-6}$	$2.52 \times 10^{-6}$	$8.38 \times 10^{-8}$ (1.5)	0.18
AFGL I01R	$1.34 \times 10^{-4}$ $1.34 \times 10^{-4}$	$-1.19 \times 10^{-4}$ -1.19 × 10 <sup>-4</sup>	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$5.61 \times 10^{-5} (1.5)$ $1.12 \times 10^{-4} (3.0)$	1.02 0.01
AFGL 104R	$1.80 \times 10^{-4}$	$-2.43 \times 10^{-4}$	$6.78 \times 10^{-4}$	$\begin{array}{c} 1.35 \times 10^{-4} \ (1.5) \\ 2.71 \times 10^{-4} \ (3.0) \end{array}$	0.07 0
AFGL I05R	$1.69 \times 10^{-4}$ $1.69 \times 10^{-4}$	$-2.77 \times 10^{-4}$ $-2.77 \times 10^{-4}$	$\begin{array}{rrrr} 4.46 & \times & 10^{-4} \\ 4.46 & \times & 10^{-4} \end{array}$	$4.47 \times 10^{-5} (1.5)$ $0.48 \times 10^{-5} (3.0)$	2.02 0.05
AFGL 109R	$1.37 \times 10^{-4}$ $1.37 \times 10^{-4}$	$-1.29 \times 10^{-4}$ $-1.29 \times 10^{-4}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$5.61 \times 10^{-5}$ (1.5) 1.12 × 10 <sup>-4</sup> (3.0)	1.6 0.02
ERIM F8CH1	$2.89 \times 10^{-5}$	$-2.88 \times 10^{-5}$	$5.77 \times 10^{-5}$	$1.63 \times 10^{-6}$ (3)	2.95
ERIM F8CH2	$1.03 \times 10^{-5}$	$-1.38 \times 10^{-5}$	$2.41 \times 10^{-5}$	$4.4 \times 10^{-6}$ (3)	0.18
ERIM F8CH3	$1.42 \times 10^{-4}$	$-1.5 \times 10^{-4}$	$2.92 \times 10^{-4}$	$2.2 \times 10^{-5}$ (3)	4.6
ERIM SOICHI	$1.08 \times 10^{-5}$ $1.08 \times 10^{-5}$	$-2.92 \times 10^{-5}$ $-2.92 \times 10^{-5}$	$\begin{array}{rrrr} 4.0 & \times & 10 & {}^5 \\ 4.0 & \times & 10 & {}^5 \end{array}$	$3.68 \times 10^{-6}$ (3) $4.91 \times 10^{-6}$ (4)	0.8 0.14
ERIM S01CH2	$1.56 \times 10^{-5}$	$-1.07 \times 10^{-4}$	$1.23 \times 10^{-4}$	$3.36 \times 10^{-6}$ (3)	0.31
ERIM S01CH3	$8.31 \times 10^{-4}$ $8.31 \times 10^{-4}$	$-8.22 \times 10^{-4}$ $-8.22 \times 10^{-4}$	$1.65 \times 10^{-3}$ $1.65 \times 10^{-3}$	$1.84 \times 10^{-5}$ (3) 5.52 $\times 10^{-5}$ (9)	3.1 0.31
ERIM S02CH1	$4.49 \times 10^{-5}$	$-2.96 \times 10^{-5}$	7.45 × 10 <sup>-5</sup>	$3.68 \times 10^{-6}$ (3)	0.67
ERIM S02CH2	$1.68 \times 10^{-5}$	$-2.12 \times 10^{-5}$	$3.80 \times 10^{-5}$	$3.36 \times 10^{-6}$ (3)	0.57
ERIM S02CH3	$3.54 \times 10^{-4}$ $3.54 \times 10^{-4}$	$-2.37 \times 10^{-4}$ $-2.37 \times 10^{-4}$	$5.91 \times 10^{-4}$ $5.91 \times 10^{-4}$	$1.16 \times 10^{-5}$ (3) 5.0 $\times 10^{-5}$ (13)	4.5 0.11
ERIM S03CH2	$1.13 \times 10^{-5}$	$-4.08 \times 10^{-6}$	$1.534 \times 10^{-5}$	$3.36 \times 10^{-6}$ (3)	0.01
ERIM S03CH3	$2.99 \times 10^{-4}$ $2.99 \times 10^{-4}$	$-9.57 \times 10^{-5}$ $-9.57 \times 10^{-5}$	$3.95 \times 10^{-4}$ $3.95 \times 10^{-4}$	$1.5 \times 10^{-5}$ (3) 3.0 $\times 10^{-5}$ (6)	1.8 0.25
ERIM S23CH1	$1.09 \times 10^{-4}$ $1.09 \times 10^{-4}$	$-7.75 \times 10^{-5}$ $-7.75 \times 10^{-5}$	$1.86 \times 10^{-4}$ $1.86 \times 10^{-4}$	$5.36 \times 10^{-6}$ (3) 1.07 × 10^{-5} (6)	1.07 0.19
ERIM S23CH3	1.05 × 10 <sup>4</sup>	$-9.16 \times 10^{-5}$	1.97 × 10 <sup>4</sup>	$1.25 \times 10^{-5}$ (10)	0.33
ERIM S23CH4	$1.11 \times 10^{-3}$ $1.11 \times 10^{-3}$	$-1.20 \times 10^{-3}$ $-1.20 \times 10^{-3}$	$2.31 \times 10^{-3}$ $2.31 \times 10^{-3}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	3.8 0.39

 Table 17
 Statistics of data after filtering and pulse discrimination in units of W/cm<sup>2</sup>/sr.







œ

S.S.

8

3

B

Ë

23

2

8

8

ų,

<u>7</u>

ERIM images of Camp A.P. Hill (4.5-5.5  $\mu$ m band) after high-pass filter, pulse discrimination, and 3.0 NEI threshold.



(c)



**Figure 21** Images after filter, pulse discrimination, and threshold. (a) BMAP middle-wave image from Bedford after bandpass filter, pulse discrimination, and 1.5 NEI threshold. (b) AFGL scene I09 of Monument Valley after high-pass filter, pulse discrimination, and 1.5 NEI threshold. (c) Morning (scene S01CH2). (d) Afternoon (scene S02CH2). (e) Evening (scene S03CH2). (f) ERIM image of Port Hueneme (4.5-5.5  $\mu$ m spectral band) after high-pass filter, pulse discrimination, and 10.0 NEI threshold (scene S23CH3). (g) ERIM image of mountains by Nellis AFB (3.9-4.7  $\mu$ m spectral band) after high-pass filter, pulse discrimination, and 3.0 NEI threshold (scene F8CH1).

The image in Fig. 21a shows that a very small percentage of the points passed the pulse-discrimination logic. The AFGL image (Fig. 21b) does not show a large reduction in the number of detected pixels; however, a reduction in the number of detected pixels is still evident. Figure 21c and d shows a large decrease in the number of pixels above the threshold. Only a very few pixels in Fig. 21e passed the threshold.

Figure 21f shows the same area as Fig. 17f. Only one or two of the building outlines passed the pulse discrimination. Many of the smaller points also passed the logic. The bad scan line is still visible in this figure.

Finally, Fig. 21g shows the mountains in the ERIM5 image. A comparison with Fig. 17g shows that some of the mountain ridges have been removed from the image. However, many of the single pulses were not removed from the image, a condition that would cause many false alarms with this algorithm.

## 4.5 Cross-Scan Comparison

The pulse-discrimination algorithm discussed in the previous section reduces the required target irradiance by analyzing the pulse shapes along the scan direction. A cross-scan comparison checks neighboring scan lines to find features that extend across several scan lines. If this analysis were performed, the number of false alarms could be reduced further.

A cross-scan comparison is more difficult to perform than the pulse-discrimination algorithm because the extended features could be at any angle relative to the scan direction. Only checking pixels perpendicular to the scan direction would not be sufficient. A method to recognize extended features at any angle would need to be developed.

No cross-scan algorithm was implemented for this analysis. The thresholded images in Fig. 21 were checked visually for any extended features. The inspection can tell qualitatively whether the required target irradiance would be reduced further by applying a cross-scan comparison after the pulse-discrimination algorithm.

For Fig. 21a through e, it is doubtful that a crossscan comparison would further reduce the number of pixels that passed the discrimination logic. Few, if any, of the pixels in these images form a continuous line. However, in the port and mountain scenes in Fig. 21f and g the cross-scan comparison could eliminate some of the false alarms.

In Fig. 21f, one edge of each of two buildings is roughly outlined by false alarms. A cross-scan comparison could find these outlines and eliminate those samples from being considered possible targets.

A cross-scan comparison would also be useful in

Fig. 21g. Many short vertical lines are visible in this image. Also, a long, continuous feature is found on the right edge of the image. If these features could be removed from being considered possible targets, many of the false alarms in this image would be removed.

## 4.6 Comparison of Processing Techniques

The filtering and pulse discrimination logic were applied to these images to reduce the noise level of the background, thereby improving the signal-to-clutter ratio. One measure of the improvement is the minimum detectable signal. For the unprocessed images, the smallest signal that could be detected above the clutter would have to be greater than the maximum pixel in the image (or less than the minimum pixel if both a maximum and minimum threshold were set).

The minimum detectable signal for the images processed through only the filtering or processed through the filtering and pulse discrimination can be calculated from the maximum and minimum values of these images. It is shown in Tables 11, 12, and 14 that the maximum value of an impulse is reduced by the filtering. For example, in Table 11 the maximum of the input is 255.0 while the maximum of the output is 64.3. This gives an output-to-input ratio of about 0.25. Because of this effect, the minimum detectable signal for images that have been filtered is calculated by dividing the maximum (and minimum) values of the images by the ratio of maximum output to maximum input. This calculation produces the required signal into the filtering to produce the given maximum or minimum after filtering. Table 18 shows the factors used to calculate the minimum detectable signal. These values were computed from the impulse results in Tables 11, 12, and 14.

Table 19 lists the minimum detectable signal for each of the images in the study before any processing, af-

 Table 18
 Filtering output-to-input ratios.

Data	Quitant (insut
source	
BMAP	0.252
AFGL	0.707
ERIM1	0.578
ERIM3, ERIM5	0.625

## THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

and the second sec

5

LAUREL, MARYLAND

	Before	Before processing After fi		r filter	Afte and discrit	er filter pulse mination
Image	Max – µ	Min $-\mu$	Max	Min	Max	Min
BMAP-Montauk (Far IR)	$1.1 \times 10^{-4}$	$-9.0 \times 10^{-5}$	$7.66 \times 10^{-5}$	$-3.72 \times 10^{-5}$	$1.46 \times 10^{-5}$	$-2.53 \times 10^{-5}$
BMAP-Montauk (Mid IR)	$1.75 \times 10^{-5}$	$-9.4 \times 10^{-6}$	$5.04 \times 10^{-6}$	$-5.79 \times 10^{-6}$	$4.88 \times 10^{-6}$	$-2.39 \times 10^{-6}$
BMAP-Bedford (Far IR)	$1.0 \times 10^{-4}$	$-3.6 \times 10^{-4}$	$9.76 \times 10^{-5}$	$-1.09 \times 10^{-4}$	$2.45 \times 10^{-5}$	$-2.16 \times 10^{-5}$
BMAP-Bedford (Mid IR)	$8.7 \times 10^{-5}$	$-3.24 \times 10^{-5}$	$4.68 \times 10^{-5}$	$-1.71 \times 10^{-5}$	$4.96 \times 10^{-6}$	$-5.04 \times 10^{-6}$
AFGL I01R	$1.0 \times 10^{-3}$	$-4.5 \times 10^{-4}$	$3.03 \times 10^{-4}$	$-5.53 \times 10^{-4}$	$1.90 \times 10^{-4}$	$-1.68 \times 10^{-4}$
AFGL 104R	$6.2 \times 10^{-4}$	$-1.07 \times 10^{-3}$	$8.67 \times 10^{-4}$	$-3.44 \times 10^{-4}$	$2.55 \times 10^{-4}$	$-3.44 \times 10^{-4}$
AFGL 105R	$4.1 \times 10^{-4}$	$-5.7 \times 10^{-4}$	$5.04 \times 10^{-4}$	$-3.91 \times 10^{-4}$	$2.39 \times 10^{-4}$	$-3.91 \times 10^{-4}$
AFGL 109R	$6.60 \times 10^{-4}$	$-4.8 \times 10^{-4}$	$3.51 \times 10^{-4}$	$-3.78 \times 10^{-4}$	$1.93 \times 10^{-4}$	$-1.82 \times 10^{-4}$
ERIM F8CH1	$1.99 \times 10^{-5}$	$-2.67 \times 10^{-5}$	$4.62 \times 10^{-5}$	$-4.61 \times 10^{-5}$	$4.62 \times 10^{-5}$	$-4.61 \times 10^{-5}$
ERIM F8CH2	$1.59 \times 10^{-5}$	$-1.27 \times 10^{-5}$	$2.32 \times 10^{-5}$	$-2.21 \times 10^{-5}$	$1.65 \times 10^{-5}$	$-2.21 \times 10^{-5}$
ERIM F8CH3	$4.59 \times 10^{-4}$	$-4.3 \times 10^{-4}$	$2.98 \times 10^{-4}$	$-2.74 \times 10^{-4}$	$2.27 \times 10^{-4}$	$-2.40 \times 10^{-4}$
ERIM SOICHI	$6.4 \times 10^{-5}$	$-3.6 \times 10^{-5}$	$4.36 \times 10^{-5}$	$-5.05 \times 10^{-5}$	$1.87 \times 10^{-5}$	$-5.05 \times 10^{-5}$
ERIM S01CH2	$1.2 \times 10^{-4}$	$-3.0 \times 10^{-5}$	$6.85 \times 10^{-5}$	$-5.99 \times 10^{-5}$	$2.70 \times 10^{-5}$	$-1.85 \times 10^{-5}$
ERIM S01CH3	$1.8 \times 10^{-3}$	$-1.1 \times 10^{-3}$	$1.44 \times 10^{-3}$	$-1.42 \times 10^{-3}$	$1.44 \times 10^{-3}$	$-1.42 \times 10^{-3}$
ERIM S02CH1	9.3 × 10 <sup>-5</sup>	$-3.7 \times 10^{-5}$	$7.77 \times 10^{-5}$	$-5.25 \times 10^{-5}$	$7.77 \times 10^{-5}$	$-5.12 \times 10^{-5}$
ERIM S02CH2	$1.2 \times 10^{-4}$	$-3.0 \times 10^{-5}$	$7.30 \times 10^{-5}$	$-6.19 \times 10^{-5}$	$2.91 \times 10^{-5}$	$-3.67 \times 10^{-5}$
ERIM S02CH3	$1.2 \times 10^{-3}$	$-4.0 \times 10^{-4}$	$6.52 \times 10^{-4}$	$-6.68 \times 10^{-4}$	$6.12 \times 10^{-4}$	$-4.10 \times 10^{-4}$
ERIM S03CH2	$3.8 \times 10^{-5}$	-1.9 × 10 <sup>5</sup>	5.21 × 10 <sup>-5</sup>	$-4.04 \times 10^{-5}$	1.96 × 10 <sup>-5</sup>	$-7.06 \times 10^{-6}$
ERIM S03CH3	$9.0 \times 10^{-4}$	$-4.0 \times 10^{-4}$	$5.74 \times 10^{-4}$	$-4.60 \times 10^{-4}$	5.17 × 10 <sup>-4</sup>	~1.66 × 10 <sup>~4</sup>
ERIM S23CH1	$2.22 \times 10^{-4}$	$-3.8 \times 10^{-5}$	$1.94 \times 10^{-4}$	$-1.29 \times 10^{-4}$	1.74 × 10 <sup>-4</sup>	$-1.24 \times 10^{-4}$
ERIM S23CH3	$2.4 \times 10^{-4}$	$-6.8 \times 10^{-5}$	$2.48 \times 10^{-4}$	$-1.5 \times 10^{-4}$	1.68 × 10 <sup>-4</sup>	-1.46 × 10 <sup>-4</sup>
ERIM S23CH4	$2.2 \times 10^{-3}$	$-7.5 \times 10^{-4}$	1.78 × 10 <sup>-3</sup>	$-1.92 \times 10^{-3}$	1.78 × 10 <sup>-3</sup>	$-1.92 \times 10^{-3}$

## Table 19 Minimum detectable signal in units of W/cm<sup>2</sup>/sr.

44

As a ball to ball and the ball dat the

Ű.

3

3

3

S

3

ц Т Т

í.

3

ŝ

Ĩ

ter filtering, and after filtering and pulse discrimination. Since the means of the images are removed by the filtering the means of the before-processing images have been subtracted from the maximum and minimum values. Therefore, this table shows the spread about the mean radiance in the before-processing column and the spread about 0.0 in the remaining columns.

Figure 16 shows the relationship between the beforeprocessing results and the after-filtering results. Since the low-frequency features are present in the original images, any spike present in the image might be hidden by the low-frequency features. Therefore, the maximum and minimum values in this column might not relate to spikes in the images. On the other hand, the low-frequency features are removed from the filtered images. The maximum and minimum values are necessarily from spikes in the image. For these reasons the maximum or minimum after filtering could be greater than in the original image.

Figure 22 displays the results of Table 19. The figure shows only the positive minimum required irradi-

ance values for the BMAP, AFGL, and ERIM images. The required irradiance before processing, after filtering, and after filtering and pulse discrimination are plotted with different symbols. Also plotted on this figure are the minimum required irradiance values from the application of the matched filter to the PSDs of the BMAP and AFGL images.

To analyze the results in Table 19 and Fig. 22 the data must first be broken into subsets. The BMAP images were all of cloud backgrounds. Table 19 shows that the minimum detectable signal of these images was reduced by the filtering. For all four of these images the pulse discrimination algorithm further reduced the required signal. Figure 23 shows a histogram of these results. Three histograms of the Bedford mid-IR data are presented in this figure-the original image (with the mean subtracted), the image after filtering with a first-order high-pass and a second-order low-pass filter, and the image after filtering and pulse discrimination. The figure shows a large reduction in the maximum and minimum owing to the filtering. The smaller reduction owing to the pulse discrimination is also seen.





THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND



Figure 23 Histograms of BMAP mid-IR Bedford scene.

Figure 24a and b further demonstrates the effect of the pulse discrimination and filtering on the IR scenes. This figure shows a cumulative histogram for the unprocessed image, the image after filtering, and after filtering and pulse discrimination. Figure 24a shows these histograms for AFGL scene I09R and Fig. 24b shows the histograms for ERIM (S01CH2). The ordinate of these plots is the cumulative frequency of occurrence. Two scales are drawn along the abscissa--the irradiance and the NEI. This plot indicates where the NEI or irradiance threshold must be set to get no false alarms for these two scenes. These plots again show the decrease in the required irradiance owing to filtering and filtering with pulse discrimination.

Figure 22 shows that for the BMAP scenes the matched filter usually requires a lower target irradiance than is required by the Butterworth filter. However, the Butterworth filter followed by the pulsediscrimination algorithm usually performs better (i.e., requires a lower target irradiance) than the matched filter. This unexpected result is probably attributable to the higher threshold used in the matched filter analysis. The matched-filter threshold was much higher than needed to climinate all false alarms in these small scenes.

Scene I01R was the only processed AFGL image that contained only clouds. The results in Table 19 show that the filtering and pulse discrimination did reduce the minimum detectable signal. The remaining AFGL



Legend

······· Filtered

-----Filtered and pulse discrimination

**Figure 24** Cumulative histograms showing reduction of maximum irradiance and NEI from filtering and pulse discrimination. (a) Histograms of AFGL Monument Valley and cloud scene (I09). (b) Histograms of ERIM Camp A.P. Hill morning scene 4.5-5.5  $\mu$ m spectral band) (scene S01CH2).

scenes had clouds and terrain in the images. Scene I09R shows a decrease in the required signal for the filtering and the pulse discrimination. Scenes I04R and I05R show a reduction owing to the filtering, but the pulse discrimination does not further reduce the negative required signal. This result means that there were large negative pulses in the images that passed the filtering and the pulse discrimination. This result is expected to be more common for terrain images than for cloud images.

For all four of the AFGL scenes, the Butterworth filter followed by the pulse discrimination performed better than the matched filter applied to the PSD.

The ERIM data must be broken into many parts for analysis. The ERIM5 images used in this analysis (F8CH1, F8CH2, and F8CH3) were of mountains. The results in Table 19 show that in some cases the pulse discrimination further reduced the minimum required signal, but the value often remained almost the same.

The set of images from ERIM1 (S01 through S03) can be discussed by band. One of the channel 1 images shows very little decrease in the minimum detectable signal when pulse discrimination is added. Channel 2 images, on the other hand, all show a significant decrease in false alarms when the pulse discrimination is added. Some of the channel 3 images show a decrease in the maximum or minimum clutter pulses but other images show little or no change because of the pulse discrimination.

Scene 23 from ERIM3 had two bad lines in the image. Figure 25 shows three lines of the image. Figure 25a shows a normal line in channel 3 (line 1) of the image. Figure 25b and c shows lines 18 and 641 of channel 3. These plots show that there is something wrong with these two lines of data, a problem that was not found until after the pulse discrimination algorithm was applied and hundreds of points from each of these lines passed the discrimination logic. Channels 3 and 4 of scene 23 had bad data in both of these lines. Channel 1 had bad data in only line 641. Because of these bad data, the results in Table 19 and Fig. 22 are not expected to show a significant decrease resulting from the pulse discrimination.

The results from Table 19 can be related to the results from Table 17. In Table 19 the BMAP data (clouds) showed a large decrease in the minimum detectable signal owing to filtering and pulse discrimination. The results in Table 17 agree with these results in that less than 0.2% of the pixels in the images passed the discrimination logic with the threshold set at 1.5 NEI. Many more of the AFGL pixels passed the logic. This result can again be associated with the scene content.

Fewer points passed the pulse discrimination logic for channel 2 of ERIM scenes S01, S02, and S03 than



**Figure 25** Lines of images from ERIM Port Hueneme scene in 4.5-5.5  $\mu$ m spectral band (scene S23CH3) showing bad scan lines. (a) Line 1 of scene with no bad data. (b) Line 18 of scene with entire line of bad data. (c) Line 641 of scene with partial line of bad data.

for channels 1 and 3, consistent with the results in Table 19.

The bad scan lines in scene S23 affect the results in Table 17. To get about 0.3% of the points to pass

the logic, the threshold had to be raised to 20 NEI for one of the channels, agreeing with the results in Table 19 where little to no improvement was gained with the pulse discrimination. This result shows that most of the bad points passed the filtering and the pulse discrimination.

## 4.7 Implementation of the Scanning Sensor Processing

The previous sections of this report described the applications of clutter suppression algorithms to digital infrared images. This section briefly summarizes implementation of the algorithms in a missile guidance system.

Figure 26 shows a block diagram of one potential seeker-processing configuration that implements the scanning-sensor algorithms developed in this report. The detected scene (plus target) is preamplified and prefiltered. The prefilter suppresses high frequency (out of the seeker bandpass) and may also be used to suppress the detector DC output. The resultant video signal from each channel is then digitized in an A/D converter. The converter has a dynamic range of 14 to 16 bits (or as few as 8 bits for AC-coupled longwavelength sensors), and samples at two to three times the Nyquist rate. The output digital signal is then available for clutter suppression algorithm implementation.

The digital signal is first processed with a bandpass filter that is matched to the clutter spectrum and the spatial filter at the scanning detector. Filtered output is then thresholded at approximately five to ten times the sensor NEI to eliminate most of the internal noise. Data above threshold are a detection. Data below threshold are perserved for use in the pulse-width discrimination algorithm. In general, both positive and negative thresholds are implemented to detect targets of both contrasts.

After thresholding, each detection is pulse-width tested by looking for the corresponding pulse of the opposite sign, appropriate magnitude, and appropriate delay. The exact implementation of this pulse-width discriminator is dependent on the filtering and noise level. Tolerance on the magnitude of the second pulse for point-target confirmation can be computed readily from the measured first pulse magnitude and the known (or real-time measured) system noise. At this point the data are compressed and only detections are preserved.

The final step in the discrimination algorithm is comparison of the detected output at adjacent detector channels. Detections (passing threshold and pulsewidth discrimination) that span typically three or more adjacent channels within two or three time samples of one another are declared false targets. If the detectors are offset and if they overlap across the scan direction, the detection of false targets is made easier. With this configuration, a false target would be detected in three or more contiguous channels. This would eliminate the necessity for checking channels two or three time samples apart.

Outputs of all the detector channels may also be used to raise the detection threshold adaptively, on the basis of occurrence of many false alarms within a scan frame (or segment thereof). When the number of detections per frame becomes large, a momentary increase in detection threshold may be necessary to



discriminate against clutter patches during search. Once in track, different algorithms would be used to discriminate against the appearance of decoys so as to avoid the raising of the threshold while tracking a valid target.

## **5.0 CONCLUSIONS**

The performance of a scanning sensor in background clutter has been investigated. A number of background scenes, supplied by three separate measurement programs, have been characterized in terms of artifacts, imagery, scene radiance statistics, and power spectral density.

Available scene data were processed in several ways to determine the minimum target signature that can be detected in particular scenes. Two techniques were used to derive performance. The first used the scene power spectral density to estimate required target irradiance as a function of sensor resolution (IFOV) assuming a fixed threshold based on a matched-filter (maximum signal-to-noise) analysis.

Since the matched-filter results are based on assumptions that are not met by real scenes, direct processing of the scenes is also done. The analysis includes three levels of scene processing in much the same way as a sensor signal processor detection system. These three levels are:

 A high-pass, first-order digital filter that whitens the clutter power spectral density and approximately maximizes the target signal-to-clutter ratio. The result is directly comparable to the matched-filter results but gives a better estimate of false-alarm rate. The filter provides good discrimination against large, low-frequency scene features.

- 2. A high-pass filter, as above, but in addition there is a pulse-width discriminator. The discriminator rejects the high-frequency output of filtered edges while passing the high-frequency output of a target or smaller feature. This technique is shown to reduce significantly the false alarms produced by a scene.
- 3. A high-pass filter, pulse-width discriminator, and cross-scan, multiple channel logic. Multiplechannel logic enhances the point-discrimination capability of the system by determining the crossscan spatial extent of linear features and by rejecting those that are significantly greater in cross-scan extent than is expected of point targets. This feature was particularly useful in improving performance against certain terrain scenes that had significant linear feature content.

The results of the direct-processing methods are illustrated in images, graphs, and tables that compare performance of these techniques as well as the effects of spectral bands, scene types, and data spatial resolution. The analysis is concluded with a discussion of the implementation of the background processing in a missile guidance system. LAUREL, MARYLAND

## REFERENCES

- <sup>1</sup>Air Force Armament Laboratory, Target and Background Information Library System (TABILS) User's Manual (May 1, 1982).
- <sup>2</sup>J. Beard, J. Braitwaite, and R. Turner, *Infrared Background Survey and Analysis*, ERIM 118000-1-F (Jun 1976).
- <sup>3</sup>A. J. LaRocca and D. J. Witte, Handbook of the Statistics of Various Terrain and Water (Ia) Backgrounds from Selected U.S. Locations, ERIM 139900-1-X (Jan 1980).
- <sup>4</sup>R. L. Lucke, et al., "The Navy's Infrared Background Measurement and Analysis Program," in *Proc. IRIS Specialty Group Meeting on Targets, Background, and Discrimination, San Diego* (Feb 11-14, 1986).
- <sup>6</sup>R. A. Steinberg, "Navy IR Background Measurements and Analysis Program," in *Proc. Tri-Service Infrared Backgrounds Symp.*, Oct 18-20, 1983, Mitre Corporation, pp. 216-223.
- <sup>6</sup>A. Hirschman, "BMAP Surface-Based Background Measurement Activities at Montauk Point, New York, August 1983," Naval Surface Weapons Center, White Oak, Silver Spring, Md., draft report (Nov 1984).
- <sup>7</sup>General Dynamics/Pomona Division, Background Spectral Radiance and Contrast in the Near-UV, Mid-IR, and LWIR Regions, TM6-125PH-438 (Oct 1976).
- <sup>8</sup>General Dynamics/Pomona Division, Available Target Infrared Spectral Signature Data, TM6-125PH-450 (Sep 1981).
- <sup>9</sup>K. Peacock, Radiometric Temperature Characteristics of the Ocean Surface, JHU/APL STD-R-377 (Oct 1980).
- <sup>10</sup>A. J. LaRocca and B. A. Whaley, DARPA Infrared Data Library, ERIM 155300-24-X (Jul 1984).
- <sup>11</sup>J. Shumsky and J. H. Schummers, AFGL-FLIR NKC-135 Aircraft Instrument, AFGL TR-82-0031 (Jan 26, 1982).
- <sup>12</sup>R. A. Steinberg, Elimination of Sensor Artifacts from Infrared Data, NRL Report 8861 (Dec 11, 1984).

- <sup>13</sup> R. A. Steinberg and M. J. McHugh, An Error Detection and Smoothing Algorithm for Infrared Data, JHU/APL TG 1355 (Apr 1986).
- <sup>14</sup> A. N. Vavreck, AFGL Infrared Image Restoration, JHU/APL F1D(1)83-U-079.
- <sup>15</sup> A. N. Vavreck, ERIM Infrared Image Restoration, JHU/APL F1D(1)84-U-003.
- <sup>16</sup> H. Samuelson, "Infrared Systems: I. Expressions for Signal and Background Induced Noise with Space Filters," *IEEE Trans. Aerosp. Electron. Syst.* AES-7, 27-33 (1971).
- <sup>17</sup> R. Yoshitani, "Signal Processing Theory for Linearly Scanning Rectangular Detector," *Proc. IRIS* 18, 117-148 (1973).
- <sup>18</sup> J. Schroeder, J. H. Schummers, B. P. Sandford, and W. J. Tropf, "Infrared Cloud Backgrounds," in *Proc. Tri-Service Infrared Background Symposium*, AFGL-TR-84-0094 (Mar 16, 1984).
- <sup>19</sup>L. M. Howser and W. J. Tropf, "Investigation of Infrared Background Clutter," in *Research and Development Programs* at The Johns Hopkins University Applied Physics Laboratory, JHU/APL Quarterly Report RQR/85-1 (Jan-Mar 1985).
- <sup>20</sup> W. J. Tropf, A. N. Vavreck, B. J. Sandford, J. H. Schummers, and J. Schroeder, "Infrared Cloud Backgrounds and Sensor Performance," in *Presentations at the Second Tri-Service Cloud Modeling Workshop*, IDA Report M-9, I, pp. 199-248 (Aug 1, 1984).
- <sup>21</sup>L. M. Howser, Analysis of Background Measurement and Analysis Program (BMAP) IR Images, JHU/APL F1F(2)85-U-035, Rev 1.
- <sup>22</sup>G. L. Turin, "An Introduction to Matched Filters," *IEEE Trans. Information Theory* **IT 6**, 311-329 (Jun 1960).
- <sup>23</sup>L. M. Howser, "Investigation of Infrared Background Clutter," in Research and Development Programs at The Johns Hopkins University Applied Physics Laboratory, JHU/APL Quarterly Report RQR/85-2 (Apr-Jun 1985).

Appendix A

## **BMAP Data Description**

Additional information on the Navy Backgrounds Measurement and Analysis Program (BMAP) data are contained in this appendix. Included is a list of the characteristics of the sensor, the long- and mid-wave spectral responses, and curves showing the long- and mid-wave point-source characteristics.

The objective of the BMAP program is to obtain clutter data for design of air- and surface-based IR search and track sensors. The data obtained by APL were the initial surface-based measurements obtained with a Raytheon-owned instrument. Currently, the described instrument is collecting data from a P-3 aircraft. An advanced instrument, with significantly more detector channels, smaller IFOV, and a more capable data acquisition system is being developed to support future measurements.

Primary characteristics of the BMAP sensor of interest to this study are the high-sensitivity, simultaneous dual-band capability, and the availability of oversampled data. Table A-1 gives the basic characteristics of the BMAP sensor. Figure A-1 gives the spectral response of the mid-IR and long-IR spectral bands. Figure A-2 gives the point-source response of typical mid-IR and far-IR detector channels. Two data sets were available. The first measurement series was conducted at Montauk Point, Long Island, on August 9-19, 1983. These data are primarily overcast sky and have less contrast than the later Bedford data. Fifty frames of data taken in the 8/8 (8 lines of mid-IR and the corresponding 8 lines of far-IR data) format on August 10, 1983 were provided. The second set of data was taken on September 13, 1984 at Bedford, Massachusetts. Seven scenes of a hole in a cloud deck were taken. Table A-2 summarizes the BMAP data.

Calibration constants to convert digital data counts to radiance are as follows:

Montauk Po Long-IR Mid-IR	oint ~9.2 > ~1.8 >	< 10 <sup>7</sup> < 10 <sup>-7</sup>	W/cm <sup>2</sup> /sr W/cm <sup>2</sup> /sr	per count per count
Bedford Long-IR Mid-IR	1.000 > 5.587 >	< 10 <sup>- 6</sup> < 10 <sup>- 8</sup>	W/cm <sup>2</sup> /sr W/cm <sup>2</sup> /sr	per count per count

Multiplying the recorded data by these factors recovers the measured radiance.

Parameter	Value
Collecting area (3.9-4.8 μm) (7.6-11.3 μm)	80 cm <sup>2</sup>
Optical transmission (3.9-4.8 μm) (7.6-11.3 μm)	85% 80%
Detector collecting efficiency (3.9-4.8 $\mu$ m) (7.6-11.3 $\mu$ m)	80%
Total optical efficiency (3.9-4.8 $\mu$ m) (7.6-11.3 $\mu$ m)	68% 64%
Detector area (3.9-4.8 µm)	$2.58 \times 10^{-5} \text{ cm}^2$
Detector $D_{AV}^{*}$ (1 Hz - 1 kHz) (3.9-4.8 $\mu$ m) (1 Hz - 1 kHz) (7.6-11.3 $\mu$ m)	$2 \times 10^{11} \text{ cm Hz}^{\frac{1}{2}}/\text{W}$ 1.5 × 10 <sup>10</sup> cm Hz <sup><math>\frac{1}{2}/\text{W}</math></sup>
Electronic 3 dB bandwidth (3.9-4.8 μm) (7.6-11.3 μm)	0.0 Hz - 1 kHz 0.5 Hz - 1 kHz
Number of channels single color Two-color (per color)	16 <sup>(1)</sup> 8
Total FOV <sup>2</sup> elevation azimuth	5.33 mrad or 0.31° 2.8°
Instantaneous FOV	$0.33 \times 0.33 \text{ mrad}$
NEI (3.9-4.8 μm) (PV InSb) (7.6-11.3 μm) (PC HgCdTe)	$2.0 \times 10^{-14} \text{ W/cm}^2$ $1.0 \times 10^{-13} \text{ W/cm}^2$
Frame rate	2 forward scans/sec
Scanning speed during data acquisition	36°/sec
Detector element dwell time	520 µsec
Azimuth position resolution	0.096 mrad
Mirror shaft angle encoder	16 bits
Total incremental count (2.8° in azimuth)	512 samples
Dynamic range	12 bits/sample
Sample factor	3.44 samples/dwell
Internal reference cold hot	Narcissus, 77K precision, temp. controlled

Table A-1 Characteristics of the BMAP dual-band IR measurement system.

<sup>1</sup>Channel 1 of the 7.6-11.3  $\mu$ m band is inactive. <sup>2</sup>Internal reference source occupies ~0.6° of the azimuth FOV, leaving ~2.2°.

THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND



1.0 (a) Mid-IR 0.8 0.6 0.4 0.2 0 5.0 10.0 20.0 0 15.0 1.0 (b) Long-IR 0.8 0.6 0.4 0.2 0 5.0 10.0 15.0 20.0 0

Figure A-1 Spectral response of BMAP mid- and long-wave channels.

Figure A-2 Point-source response of BMAP detector channels.

and an and an an and

8.

8

1.1

	Scene	Line-of	-sight <sup>1</sup>	Scan	IRIG local	Frame	Temp.	RH	Visibility	Wind		Su	
No.	description	Az	El	mode <sup>2</sup>	time <sup>3</sup>	(No.)	(°F)	(%)	(mi)	Speed	Dir	Az	El
				Monta	uk Point	, Aug 10	, 1983						
1	Overcast sky	227	05	8/8		1-50	75	59		10,000 feet/sec	N	110	44
				Be	dford, Se	p 13, 19	34						
1	Hole in cloud deck	108	12	Α	3,8,52, 21.3	1- 61	66	48	>31	calm	-	112	28
2	Hole in cloud deck	112	15	Α	3,8,55, 36.8	62- 163	66	48	>31	calm	-	112	28
3	Hole in cloud deck	109	19	Α	3,8,58, 39.8	164- 265	66	48	>31	calm	-	113	29
4	Hole in cloud deck	130	11	Α	3,9,07, 51.3	266- 347	66	48	> 31	calm	-	115	30
5	Hole in cloud deck	113	09	8/8	3,9,11, 47.8	348- 389	66	48	>31	calm	-	116	31
6	Hole in cloud deck	93	08	Α	3,9,18, 57.8	390- 461	67	53	>31	calm	-	117	32
7	Hole in cloud deck	120	14	8/8	3,9,38, 38.8	521- 551	67	53	> 31	calm	_	121	35

## Table A-2 Summary of BMAP data.

 $^{1}Az$  = degrees clockwise from geographic north; El = degrees above horizontal.

<sup>2</sup>Scan mode: A = alternate mid-IR and long-IR frames; 8/8 = long-IR channels (5-12) in data channels (1-8) together with mid-IR channels (5-12) in data channels (9-16).

<sup>3</sup>IRIG time: Day, hour, minute, seconds.

## **Appendix B**

## **AFGL Data Description**

The information provided here is on the Air Force Geophysics Laboratory (AFGL) scenes. These scenes were collected from an IR FLIR Laboratory. The Honeywell IR FLIR is intended primarily for collecting signature data but has also been applied to collecting background data. The principal characteristics of these measurements are high spatial resolution, moderately large images, and a wide variety of available scenes. A description of the instrument is given in Table B-1. Characteristics of AFGL data are given in Table B-2. All scenes contain clouds and are taken with filter #9 (7.84 to 13.16  $\mu$ m). Table B-3 gives calibration data for all scenes. Note that scenes designated I21-I29 have a smaller FOV from typical AFGL FLIR data. This higher resolution is achieved by using an objective lens with longer focal length to increase spatial resolution. The system spectral response is given in Fig. B-1; overall response is approximately 80% of that achieved without a filter within the spectral bandpass.

Description	Value
Collecting aperture	25.2 cm <sup>2</sup>
Effective focal length	7.67 cm
System <i>f</i> /#	1.22
Detectors	Two 9-element, serially scanned PC HgCdTe arrays
Detector D* (11.5 μm, 10 kHz)	$7.6 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$
Noise-equivalent differential temperature	~0.2 K
Spectral bands	10-position filter wheel (APL data are all 7.84-13.16 μm)
Scanner	10-facet mirror (horizontal), galvanometer (vertical)
Dynamic range	100:1
Instantaneous FOV	0.43 mrad (V) $\times$ 0.36 mrad (H)
Total FOV	4.93° (V) × 7.62° (H)
Field rate	60 Hz
Active scan lines	192
Video output	EIA RS-170

## Table B-1 Characteristics of the AFGL-FLIR.

## Table B-2 Summary of AFGL infrared imagery characteristics. (footnotes for this table follow Table B-3)

10.00

	:	i				Scene Size	-	l	Flight			Pixel S	ize <sup>(1)</sup>		
lmage	Date	lime	Mission/	Scene description		Pixels/	:		Conditions			FLIR	Digitized	Notes	lmage
\$	даммүү	SSMMHH	run			scan line,	:		Position	-	Amb.	Resol.	sample		I
		(GMT)				Number of scan lines	Alt. ft × 1000	Vel.	Lat/Long	Look Dep. Dir. Ang.	C) C)	(H/V) (mrad)	sıze (mrad)		
	810518	164841 354	105/4	Clouds, down viewing	(10504A)	256. 192	33.1	0.68	39°24/ 67°41		- 42	0.36/0.43 (	0.50/0.50		10
102	810518	175500.792	105/10	Clouds, water below	(10510A)	256, 192	39.3	0.66	39°24/ 67°41		- 57	0.36/0.43	0.50/0.50		102
501	810821	182620.7	108/4	Overcast, down viewing	(10804A)	256, 192	31.1	0.76	42°17/ 99°55		- 33	0.36/0.43	0.50/0.50		102
5	810821	182621.359	108/4	Terrain, down viewing	(10804B)	256, 192	31.1	0.76	42°17/ 99°55		- 33	0.36/0.43 (	0.50/0.50		104
105	811118	164642.379	201/1	Horizon, clouds, terrain	(I0101A)	256, 192	31.0	0.79	40°01/ 81°48		- 41	0.36/0.43 (	0.50/0.50		105
901	811111	164926.145	201/1	Overcast cloud deck	(I0101B)	256, 192	31.0	0.79	40°01/ 81°48		- 41	0.36/0.43 (	0.50/0.50		<u>10</u>
107	811111	165045.409	201/1	Cloud structure	(10101C)	256, 192	31.0	0.79	40°01/ 81°48		- 41	0.36/0.43 (	0.50/0.50		107
108	811118	200735.559	201/3	Cloud tops, horizon	(I0103A)	256, 192	31.0	0.80	36°02/110°01		- 38	0.36/0.43	0.50/0.50		108
<u>8</u>	811111	201713.679	201/3	Monument Valley, clouds	(10103B)	256, 192	31.0	0.80	36°02/110°01		- 38	0.36/0.43 (	0.50/0.50		601
110	811111	201729.528	201/3	Monument Valley, clouds	(10103C)	256, 192	31.0	0.80	36/02/110°01		- 38	0.36/0.43 (	0.50/0.50		110
		•													-
Ш	820317	163706.484	209/1	Clouds	(Z10601)	256, 192	33.2	0.80	43°42/ 97°12		- 47	0.36/0.43 (	0.50/0.50		Ш
112	820317	164310.070	209/2	Clouds	(I0902A)	256, 192	33.2	0.82	43°35/ 96°25		- 48	0.36/0.43 (	0.50/0.50		112
113	821101	190200.296	301/3	Cloud tops, horizon	(10103Z)	256, 192	35.0	0.80	36°33/104°26		- 39	0.36/0.43 (	0.50/0.50		113
=	821101	190454.857	301/4	Cloud tops, horizon	(I0104A)	256, 192	35.0	0.81	36°29/104°49		- 40	0.36/0.43	0.50/0.50		114
115	821101	190623.029	301/4	Cloud tops, horizon	(B0104B)	256, 192	35.0	0.81	36°29/104°49		- 40	0.36/0.43 (	0.50/0.50	<del>(</del> 4)	115
116	821120	182719.501	312/1	Horizon, clouds	(I1201A)	256, 192	29.2	0.80	37°23/104°29		- 34	0.36/0.43 (	0.50/0.50		116
117	821120	182911.381	312/1	Clouds, terrain backgnd	([1201B)	256, 192	29.2	0.80	37°23/104°29		- 34	0.36/0.43 (	0.50/0.50		117
811	821120	182938.926	312/1	Cloud tops, horizon	(I1201C)	256, 192	29.2	0.80	37°23/104°29		- 34	0.36/0.43 (	0.50/0.50		118
611	821120	182938.375	312/1	Cloud tops, horizon	(11201D)	256, 192	29.2	0.80	37°23/104°29		- 34	0.36/0.43 (	0.50/0.50		119
120	821120	183915.495	312/1A	Clouds, down viewing	(I1201E)	256, 192	29.2	0.80	37°23/104°29		- 34	0.36/0.43 (	0.50/0.50		120
	1														
121	830327	182554.301	320/3	Structured clouds	(I2003A)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		121
122	830327	182600.023	320/3	Structured clouds	([2003B)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		122
123	830327	182606.246	320/3	Structured clouds	(12003C)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		123
124	830327	182617.191	320/3	Structured clouds	(I2003D)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		124
125	830327	182625.132	320/3	Structured clouds	(I2003E)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		125
126	830327	182629.420	320/3	Structured clouds	(I2003F)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		126
127	830327	182637.762	320/3	Structured clouds	(I2003G)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		127
128	830327	182650.775	320/3	Structured clouds	(I2003H)	256, 192	37.	0.76	42°13/ 88°33		- 39	0.08/0.09 (	0.10/0.10		128
129	830327	182917.624	320/3	Structured clouds	(120031)	256, 192	37.	0.76	42°13/ 88•33		- 39	0.08/0.09	0.10/0.10		129
130	830723	174721.655	325/3	Clouds below horizon	(I2503A)	256, 192	29.1	0.76	38°26/ 81°50		- 25	0.36/0.43 (	0.50/0.50		130
131	830723	175010.243	325/3	Clouds, down viewing	(I2503B)	256, 192	29.1	0.76	38°26/ 81°50		- 25	0.36/0.43 (	0.50/0.50		131

## THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY LAUREL, MARYLAND

Image	Filter	Spectral Band <sup>(3)</sup> (µm)	Conversion to Ra (µW/c	n Factors <sup>(2)</sup> diance cm <sup>2</sup> /sr)	Image
			Multiplicative	Additive	
101	19005A	7.84-13.16	8.4088 · 10 <sup>-6</sup>	$1.8064 \cdot 10^{-3}$	101
102	19005A	7.84-13.16	5.3056 · 10 <sup>-6</sup>	$2.9287 \cdot 10^{-3}$	102
I03	19005A	7.84-13.16	$2.1122 \cdot 10^{-5}$	1.4909 · 10 <sup>- 3</sup>	103
I04	19005A	7.84-13.16	$2.1122 \cdot 10^{-5}$	1.4909 · 10 <sup>- 3</sup>	I04
105	19005A	7.84-13.16	8.4088 · 10 <sup>-6</sup>	1.9456 · 10 <sup>-3</sup>	105
106	19005A	7.84-13.16	1.3327 · 10 <sup>-5</sup>	1.4152 · 10 <sup>-3</sup>	I06
<b>I07</b>	19005A	7.84-13.16	1.3327 · 10 <sup>-5</sup>	1.4126 · 10 <sup>-3</sup>	107
108	19005A	7.84-13.16	3.3476 · 10 <sup>-5</sup>	$-2.4370 \cdot 10^{-3}$	108
109	19005A	7.84-13.16	1.0586 · 10 - 5	$2.0466 \cdot 10^{-3}$	109
I10	19005A	7.84-13.16	1.0586 · 10 <sup>-5</sup>	$2.5241 \cdot 10^{-3}$	I10
 III	19005A	7.84-13.16	$8.4088 \cdot 10^{-6}$	$1.0573 \cdot 10^{-3}$	 I11
112	19005A	7.84-13.16	$8.4088 \cdot 10^{-6}$	$1.3923 \cdot 10^{-3}$	I12
I13	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	$2.9420 \cdot 10^{-4}$	I13
I14	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	4.1807 · 10 <sup>- 4</sup>	I14
115	B2180A	7.96-11.39	(4)	(4)	I15
I16	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	- 1.3316 · 10 <sup>-5</sup>	I16
117	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	5.6492 · 10 <sup>- 4</sup>	I17
118	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	9.6727 · 10 <sup>-4</sup>	I18
I19	19005A	7.84-13.16	1.6778 · 10 <sup>-5</sup>	9.6727 · 10 <sup>- 4</sup>	I19
120	19005A	7.84-13.16	$8.4088 \cdot 10^{-6}$	$1.4649 \cdot 10^{-3}$	120
121	I9005A	7.84-13.16	6.6793 · 10 <sup>-6</sup>	$3.2448 \cdot 10^{-3}$	121
122	19005A	7.84-13.16	6.6793 · 10 <sup>-6</sup>	3.2414 · 10 <sup>-3</sup>	122
123	I9005A	7.84-13.16	6.6793 · 10 <sup>-6</sup>	3.2414 · 10 <sup>- 3</sup>	I23
124	19005A	7.84-13.16	8.4088 · 10 <sup>-6</sup>	2.9607 · 10 <sup>-3</sup>	I24
125	19005A	7.84-13.16	8.4088 · 10 <sup>-6</sup>	$2.8066 \cdot 10^{-3}$	125
126	19005A	7.84-13.16	8.4088 · 10 <sup>-6</sup>	$3.2804 \cdot 10^{-3}$	126
127	19005A	7.84-13.16	8.4088 · 10 <sup>- 6</sup>	$3.2804 \cdot 10^{-3}$	127
128	I9005A	7.84-13.16	8.4088 · 10 <sup>- 6</sup>	$2.9684 \cdot 10^{-3}$	128
129	19005A	7.84-13.16	8.4088 · 10 <sup>- 6</sup>	$3.1648 \cdot 10^{-3}$	129
130	19005A	7.84-13.16	1.0586 · 10 <sup>- 5</sup>	- 1.1037 · 10 <sup>- 3</sup>	130
I31	19005A	7.84-13.16	1.0586 · 10 <sup>- 5</sup>	- 6.1401 · 10 <sup>-4</sup>	I31

## Table B-3 Calibration and spectral band data for AFGL infrared imagery. (footnotes for this table and Table B-2 follow)

## Footnotes for AFGL background data description, Tables B2 and B3

<sup>1</sup>FLIR angular resolution and digitized sample size are given as value in the horizontal (scan) direction followed by value in vertical direction. The images are formed by combining the (delayed) outputs of two serially scanning detector arrays.

<sup>2</sup>The digital values (0-255) describing the brightness of each pixel are converted to actual scene radiance  $(\mu W/cm^2/sr/\mu m)$  by multiplying the digital value (DV) of the data by the multiplicative factor (MF) and adding the additive factor (AF):

## Brightness = $MF \times DV + AF$ .

The scene has a maximum of 64 gray levels at multiples of 4 (i.e., 0, 4, 8,..., 248, 252). Therefore the quantization level is 4  $\times$  MF.

12

L.

1.1

ij

2

<u>}</u>

••••

Ęĝ.

8

8

S

8

N.

R

Ŝ,

5

<sup>3</sup>The spectral band is described by the 50% spectral response points. The AFGL FLIR has a 10-position filter wheel. Reference 11 gives spectral response data for all the filters.
 <sup>4</sup>Calibration data supplied for image 115 are not correct.



Figure B-1 Spectral response of AFGL FLIR with 7.84-13.16  $\mu m$  filter.







COSTAN STREET CARACTERISTICS

Appendix C

## **ERIM Data Description**

Information on the Environmental Research Institute of Michigan (ERIM) scenes is provided in this appendix.

Data provided by ERIM consist of surface scenes collected by the M-7 multispectral line scanner or its similar predecessor the M-5. A typical collection run is made at low altitude from a C-47 aircraft. The scanner looks downward (or tilted forward) and is scanned (with a mirror) in the cross-track direction over a 90° sector. Down-track data are gathered as the aircraft flies over the scene. The principal benefit of the ERIM data is the large number of available spectral bands per scene and the large size of some scenes (>1,000,000 pixels).

Table C-1 gives the characteristics of the M-7 scanner. Table C-2 summarizes the scene data provided to APL. Calibration constants to convert digital counts to radiance or apparent temperature (depending on spectral band) are provided in Table C-3. Spectral characteristics of the major detector channels are given in Fig. C-1. There are two infrared detector positions in the M-7 scanner. One is devoted to the long wavelength band and the other to the mid-IR detectors. Several mid-IR detector arrays were used to collect the data. Table C-4 gives the relative geometry of the four detector arrays used to collect these data and data shifts required to bring pixels of different spectral channels into approximate alignment in the center of a scan line. Note that geometric effects will not allow registration across an entire (single) scan line.

10

Ņ

9

22

3

改

506) 1717

7

83

S

55

R.

Parameter	Value
Collecting aperture	5-inch
Spatial resolution Scan rate	2 mrad 60/sec
ΝΕΔΤ	0.1°C nominal
Spectral bands (µm)	1.0-1.4 2.0-2.6 3.0-4.2 3.5-3.9 3.9-4.7 4.5-5.5 5.1-5.7 8.0-13.5 8.0-14.0

Table C-1 Characteristics of the ERIM M-7	scanner.
---	----------

9

1. T. . . . .

5

R B B

12.00

E

**K**RC

501

1223

 Table C-2
 Summary of ERIM infrared imagery characteristics.
 (footnotes for this table follow Table C-3)
 (footnotes footnotes for this table follow Table C-3)
 (footnotes footnotes foot

	Date	Time		Spec	tral Bands (μm)	S	ene Size		Fligh	1	Ē	xel Size <sup>(1)</sup>		
Image			Scene Description	6 7 9 7	0" 5" (5)L 5"	s	Pixels/ an line	1		500	Scanne	r Nadir grnd./ Samnle	Notes	Image
				2-3 0-7 0-5	ÞI-0 E1-0 S -1 S -5 Þ -6	* Ź 11-0	umber of	Alt. V	'el. [	Dir. De	b.	distance		
				E E Z	2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	3 	an lines	(IJ)	۲/5	Ar	g. (mrad)	(ij)		
ŝ		000	and a sub-	- -		ă	200	800	N N N	ýect O	. 20/2	1 60/ 1 60		195
5	C2CU0/	0011	Camp AF THE HOLINER, LICELY - JUNIE				56 704		. A 89		0 0 0 0	091/091		202
700	52508/	0001	Callip AF 1110, alternooli, ettai Cama AD Hill attaning lidht have		* ~	o od	2002	800	N 89	Ved 9	2 0/2 (	091/091		SOS
33	180373		Camp AP Hill midnicht, clear	•		) de	55.1000	800	89	Vest 9	2.0/2.0	09.1.60		Š
Ś	790403	0000	N.M. city, bredawn, snow, cloudy	•		ود . ۲	46. 385	1750 2	Z 20	S NZ	. 2.5/2.	4.38/ 4.38		<b>S05</b>
ŝ	790403	1230	N.MI. city, noon, snow, clear	1	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	4	46, 385	1750 2	N 200	MN 9	* 2.5/2,5	4.38/ 4.38		806
202	790403	0061	N.MI, city, sunset, snow, 15% clouds	-	2	9 9	46, 385	1750 2	02 N	5 NN	2.5/2.5	4.38/ 4.38		<b>S</b> 07
808	790403	0030	N.Ml, city, midnight, snow, 60-70% clouds		_	2.3 6	46, 385	1750 2	Z 20	8 32	° 2.5/2.5	4.38/ 4.38	Ī	S08
<b>5</b>	790403	0090	N.MI, conifers, predawn, snow, - 2°C		-	6 17	46, 385	1750 2	Z 20	8 MN	2.5/2.5	4.38/ 4.38		60S
<b>S10</b>	790403	1230	N.MI, coniters, noon, snow, 5°C	1	e.	4	46, 383	1750 2	N 202	8 82	2.5/2.5	4.38/ 4.38		<b>S1</b> 0
SII	790403	0061	N.MI, conifers, sunset, snow, 4°C	-	~	9 9	46, 385	1750 2	202 N	8 82	. 2.5/2.5	4.38/ 4.38	ŧ	SII
S12	790403	0030	N.MI, conifers, midnight, snow - 2°C		-	2.3 6	46, 385	1750 2	02 N	8 82	2.5/2.5	4.38/ 4.38	Î	S12
<b>SI</b> 3	790403	0090	N.MI, farms, predawn, snow, cloudy		_	6 7	46, 385	1750 2	202 Z	8 82	° 2.5/2.5	4.38/ 4.38		SI3
<b>SI4</b>	790403	1230	N.MI, farms, noon, snow, clear	1 2	£	4	46, 383	1750 2	02 N	8 82	2.5/2.5	4.38/ 4.38		S14
S15	790403	0061	N.MI, farms, sunset, snow, 15% clouds	-	~1	3	46, 385	1750 2	202 Z	8 82	2.5/2.5	4.38/ 4.38	:	S15
S16	790403	0030	N.MI, farms, midnight, snow, 60-95% clouds		-	2,3 6	46, 385	1750 2	N 20	NN 9	° 2.5/2.5	4.38/ 4.38	£	S16
S17	190403	0090	N.MI, land/water, predawn, snow, - 2°C		-	5 (¢	46, 385	1750 2	202 Z	8 80	2.5/2.5	4.38/ 4.38		S17
<b>S18</b>	790403	1230	N.MI, land/water, noon, snow, 5°C	-	•	4 6	46, 383	1750 2	Z 200	6 MN	° 2.5/2.5	4.38/ 4.38		S18
S19	790403	1900	N.MI, land/water, sunset, snow, 4°C	-	~	3	46, 385	1750 2	202 Z	8 80	2.5/2.5	4.38/ 4.38	ł	61S
<b>S20</b>	790403	0030	N.MI, land/water, midnight, snow, 2°C		-	2.3 6	46, 385	1750 2	202 N	8 MN	° 2.5/2.5	4.38/ 4.38	<b>:</b>	S20
521	690722	1340	Black Hills-1 (M-5 scanner)		<b>4</b>	•	11, 732	1500	300	East 91	° 3.5/6.6	3.75/ 9.90	5	\$2I
S22	626089	0952	Mono Lake (M-5 scanner)	(%)	1 1	۳ ا	11, 265	4000	00 S	outh 9	• 3.5/6.6	10.00/26.40	Ē	S22
		I												
S23	780307	1215	Port Hueneme (HUMI), port/water	1 2	e.	4	46,1982	1750 2	202	Vest 9	2.5/2.5	4.38/ 4.38	Ę	S23
524 S24	780307	1420	Port Hueneme (HUM2), port/water/sun	1 2	•	4	46,1761	000	202	Vest 3.	2.5/2.5	4.36/ 7.60	2	S24
SIS	780225	0926	Nellis AFB (NVG1), mountains		m, 1	4 ·	46,1535 ** 883	1750 2	00 00 00	Vest 9	2.5/2.5	4.38/ 4.38	6	22 Z
<b>9</b> 7	<7Z08/		Nellis AFB (NVHL), desert	7 - 7	•• •	4	40, 362			e last		9.7 /00.4	6	876
175	C7708/	8701	Nettis AFB (NEVJ), mountains Natis AFD (NEVY) mountains	n n		с v3	40, 00.) 16, 823		n z n c	nun on o		4.36/7.60	£	No.
525	78025	1554	Nellis AFR (NEV1), desert	, r.	eri 	o de	46. 883	1000	05 E	ast	2.5/2	4.36/ 7.60	(5)(7)	S29
<b>S</b> 30	780226	1022	Nellis AFB (NEVM), mountains	3 2		۰.	46, 883	1000	02 E	ast 3.	. 2.5/2.5	4.36/ 7.60	Ę	0ES
									1					
F03	780307	1130	Pt Mugu (NEVA1), water/sun	1 (%)	2 3	¢	46, 271	2000 2	02 SV	V-SE 90	2.5/2.5	5.00/ 5.00	(SNOKS)	F03
F04	780307	1156	Pt Mugu (NEVA4), water, sun	2	1	3 6	46, 215	2000 2	02 SV	V-SE 9(	• 2.5/2.5	5.00/ 5.00	(9)	F04
F05	780225	1151	Nellis AFB (NEVB), mountains	7	1 3	¢	46, 899	1000	302 E	ast 3.	2.5/2.5	4.36/ 7.60	(2)(2)	FOS
F06	780225	1424	Netlis AFB (NEVE), mountains	7	1 3	¢	46, 179	5000 2	02 E	cast 3.	2.5/2.5	21.79/38.00	(2)(2)	F06
F07	780225	1056	Nellis AFB (NEVC), desert	2	-	3 6	46, 898	1000	02 V	Vest 32	2.5/2.5	4.36/ 7.60	(2N3)	F07
F08	780225	0914	Nellis AFB (NEVD), mountains	2	1	3 9	46,1541	1750 2	02 V	Vest 9	2.5/2.5	4.38/ 4.38	(	F08
F09	780225	1034	Nellis AFB (NEVF), mountains	2	-	9	46, 899	1000	02 E	ast 32	. 2.5/2.5	4.36/ 7.60	ε	F09
1		1 1 1 1 1 1 1 1 1 1		Without the second seco										

# Table C-3 Calibration and spatial registration for ERIM infrared imagery. (footnotes for this table and Table C-2 follow) (footnotes for this table C-2 follow)

	1			Spe	xtral Chanr	iel Scal	ing Constants	ā					Spectra	al Ban	шт) spi	-		. S	oatial	-	
lmage	Ch	tannel 1 sion factors		Ch	annel 2 sion factors		Ch	unnel 3 ion factors		Channel 4 conversion factors	<b>Þ.</b> I .	9.2	6.6	5.8	1512.2	0.14.0	<b>\$</b> '11-	Spect	ral ban		Image
	Multipl.	Additive	Unit	Multipl.	Additive	Unit	Multipl.	Additive	Unit	Multipl. Additive U	-0'1	-0.2	·S·E	·S'7	-1.2	0.8	-0.6	- 7	-	-	
19	1.48649	- 65.405	rad	0.109412	272.368	¥	0.153566	266.193	×			-		7		~		i - 2			IOS
S S	1.12245	- 35.9184	rad	0.125966	269.518	: 2	0.187140	270.335	×			_		1		-		i - 2			23
ŝ	0.88000	- 26.4000	rad	0.0465351	277.899	¥	0.0724006	273.729	×			-		7		m		i i-2	. <b></b>		ŝ
<b>1</b> 05	0.758621	- 48.5517	rad	0.0895737	270.923	¥	0.0946701	270.911	¥			-		7		e		i i2	· <b>-</b>		5
<b>S</b> 03	0.0216759	273.283	×	0.0161324	273.498	¥								-			2	÷2 i			Sõ
808	7.23158	- 435.394	rad	0.420110	206.309	×	0.0432885	273.730	×	0.0675130 273.266 1	¥	-	7	~			4	i i-2	i+2	· <b>-</b>	ŝ
20J	0.115987	254.821	¥	0.0215169	222.672	×	0.0164292	273.567	×				-	~				-2 i+2	· <b></b> -		20
808 X	0.0214671	273.277	×	0.0485744	269.979	¥	0.0163306	273.144	¥					-				 			Ŝ.
5	0.0208554	273.815	×	0.0162540	273.779	<b>×</b> :			:					- •					•		§ 3
S10	7.25525	- 532.456	rad	0.424625	204.173	¥	0.0437711	273.310	*	0.0675915 273.184 1	¥		2	m, i			4		1+7	-	S10
SII	0.118226	254.210	×	0.0215993	273.150	×	0.0164120	273.519	×				-	~				-2 :+2	<b></b> .		IS
S12	0.0215332	273.216	2	0.0488683	269.839	¥	0.0164120	273.054	¥								Z'3	 	-		S12
S13	0.0216452	273.175	¥	0.0162578	273.333	¥								-			5	+ 2			SI3
S14	7.24848	- 586.506	rad	0.462976	194.149	¥	0.0441579	272.913	¥	0.0677925 272.808 1	¥	-	4	~			4	i - 2	i+2	•	S14
SIS	0.120342	253.514	×	0.0222503	271.750	×	0.0165231	273.345	×				-	2			-	-2 i+2	. <b>_</b>		S15
S16	0.0215734	273.139	¥	0.0491603	269.634	¥	0.0165250	272.875	×					-			2.3 i	+2 i	· <b></b>		S16
S17	0.0209377	273.666	×	0.0164407	273.644	¥								-			7	+ 7			S17
S18	7.23321	- 493.026	rad	0.459405	195.496	×	0.0438113	273.153	¥	0.0677830 272.719 1	×	-	ы	~			4	i i-2	i + 2		<b>S18</b>
<b>S19</b>	0.119521	253.896	¥	0.0215725	273.117	X	0.0165116	273.416	×				-	7			~	-2 i+2	••••		<b>S</b> 19
S20	0.0215725	273.226	×	0.0488549	269.852	¥	0.0164225	273.053	×					-			2,3 i	+2 i			S20
S21	27.9646	- 27.9646	rad	1.58301	- 3.16601	rad	0.0816904	288.893	¥	0.0832039 288.905	- ×	3		m	4				6		<b>S2I</b>
S22	0.111804	276.747	¥								(g)	(8)		-	8			· <b>_</b>			S22
			•	1,01000 0	000 001				:					•			.				1
35	7.22000	000.021 -		- 0.021	000 00C	2 :	0.141202	100.202	<	001.012 200010.0				•			•	7 + ·	7		570
S24	1.73522	- 113.347	rad	0.696934	169.417	¥	0.157527	277.397	×	0.263796 275.817	¥	1		~			4	i i+2	- 7	-	S24
S25	1.06352	- 28.9010	rad	0.491094	199.472	¥	0.0998831	270.780	¥	0.131600 270.794 1	×	- 7		~			4	i - 1 - 2	1-2	-	S2S
S26	2.89031	- 26.8297	rad	0.526944	209.378	×	0.137019	276.542	¥	0.149853 278.723	¥	1		~			4	i i+2	i - 2		S26
S27	0.124586	269.122	¥	0.521030	191.812	×	00000	- 56.7006	rad			<b>~</b>	-	_			· <u> </u>	-2 i+2	-		S27
S28	0.102839	269.941	¥	0.495677	190.411	¥	1.00000	- 56.8537	rad			•	~				-	-2 i+2	-		S28
S29	0.0878207	276.758	¥	0.436174	208.743	¥	- 0.090196	300.000	×				~	_	~		·	-2 i+2			S29
S30	0.0504308	275.229	×	0.492889	195.697	×	00000.1	- 129.555	rad			•	~	_				-2 i+2			S30
F03	3.0932	- 14.9566	rad	0.0316129	283.956	Х	0.255415	261.200	×			(8)		2	~			i - 2			FOI
	0110110	177 604	5	011111	023 244	: 2	0244020 0	201 167	: 2				-	•	•				• •		
	0260/1.0		2 3	0.494020	CUE 100	< >	6/500/0.0	100 100	< >				 		-		 n		<b></b>		
2	7000000	0/4-1/7	<b>e</b> :	0.404070	201.102	2 :	600/1C'0	CU1.441	4 :					_	<b>n</b> (		<u> </u>	+ -	-		2
ŝ	0.127561	268.445	<b>×</b> :	0.644889	916.671	<b>×</b> :	0.55/182	002.641	∠:				~ ~		•		 •	-2 +1 2-	<b>.</b> .		ŝ
è	0.120006	2/0.012	∡ ;	0.204/202	224.004	∠ :	0.141/2	26.612	<b>×</b> :				2	_			 	-2 +1 2	-		5
F08	0.0966366	267.812	¥	0.469730	193.632	¥	0.127765	269.867	¥				~				÷.	-2 1+2	-		<u>108</u>
F09	0.111736	270.111	¥	0.538573	193.809	×	0.139151	273.470	¥				7	_			÷	-2 i+2			F09

62

## THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY LAUREL, MARYLAND

1

Q

-

and such a standard and shared

## Footnotes for ERIM background data description, Tables C-2 and C-3

<sup>1</sup>Angular resolution and ground sample distance given as value in scan (cross-track) direction followed by value in flight (in-track) direction. Resolutions given are for middle-infrared bands; specifically the resolution of long-wavelength bands that differ from values in the table are:

File	Channel	Spectral band	Resolution
S21	4	8.0-13.5	3.5 mrad
S23-S26	4	9.0-11.4	2.9 mrad
S29,F03, F05-F06	3	5.1-5.7	2.9 mrad
F04, F07-F09	3	9.0-11.4	2.9 mrad

<sup>2</sup>The digital values (0-255) describing the brightness of each pixel is converted to actual scene radiance ( $\mu W/cm^2/sr/\mu m$ ) or apparent temperature (K) by multiplying the digital value (DV) by the multiplicative factor (MF) and adding the additive factor (AF):

## Brightness = $MF \times DV + AF$ .

The units of the brightness result are given in the units column. MF is the data quantization increment.

<sup>3</sup>Spatial registration is given as the relative pixel number in a scan line that brings the images of different channels into approximate spatial alignment. Alignment is a function of the scan angle: best alignment is achieved in the center of scan. See Table 3, Fig. 4, and Ref. 10 for more information.

<sup>4</sup>Channel 3 data are preferred to channel 2 data for the 9.0-11.4  $\mu$ m spectral band. <sup>5</sup>Data for the 5.1-5.7  $\mu$ m channel are noisy and may not be

usable.

<sup>6</sup>Data file contains discontinuous images:

F03 and F04 contain small segments (approximately 15 scan lines per segment) of a much larger image.

F07 has two subimages of 449 scan lines each. <sup>7</sup>Tilted scanner images have vignetting on the edges of the image.

Only center 400 pixels are completely free of vignetting effects. <sup>8</sup>Original channel 2 (3.0-4.3  $\mu$ m) of image F03 has been dropped (bad data); other channels were renumbered. Data available for 1.0-1.4, 2.0-2.6, and 8.0-13.5  $\mu$ m channels were not provided to APL.

<sup>9</sup>Long-wavelength channels of M-5 scanner cannot be easily brought into spatial alignment with other channels.



Figure C-1 Spectral characteristics of ERIM M-7 detector channels.

Arrav <sup>(1)</sup>		Spectral Bands <sup>(2)</sup>		Images
	Detector 1	Detector 2	Detector 3	
InSb 3-3	2.0-2.6 μm	1.0-1.4 μm	4.5-5.5 μm	S21-S22
InSb 3-7	3.9-4.7 μm	2.0-2.6 $\mu m^{(3)}$	3.5-3.9 μm	S27-S30, F04-F09
InSb 3-8	3.0-4.2 μm	2.0-2.6 μm	4.5-5.5 μm	S01-S04, S23-S26, F03
InSb 3-9	3.5-3.9 μm	2.0-2.6 μm	4.5-5.5 μm	S05-S20

Table C-4	ERIM	middle-infrared	detector	arrays.
-----------	------	-----------------	----------	---------

<sup>1</sup>Detectors are circular with center-to-center spacing of 2.5 times the detector diameter. <sup>2</sup>5.1-5.7  $\mu$ m and long-wavelength detectors are at a different focal plane of the M-7 scanner and are in spatial registration with the center detector of the above arrays. <sup>3</sup>Detector inoperative.

Illustration of detector shifting to achieve spatial coincidence



,e

## **Appendix D**

## **Power Spectral Density of Background Data**

PSDs of many of the scenes used in this analysis are shown in this appendix. It is evident that the AFGL scenes flatten far before the cutoff of the system. This flattening shows the level of the internal noise of the sensor. Some of the ERIM scenes show this flattening to a degree, while other scenes continue straight with no flattening trend.



**Figure D-1** Power spectral densities of AFGL scenes, 7.84-13.16  $\mu$ m spectral band (0.5 mrad sample size). (a) Clouds, down viewing (101). (b) Terrain, down viewing (104). (c) Monument Valley, clouds (109).





THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND



Figure D-3 Power spectral densities of ERIM scenes of Camp A.P. Hill, 2.0-2.6  $\mu$ m spectral band. (a) Morning (S01CH1). (b) Afternoon (S02CH1).



وأعاد فعاكر قوف قعا رقوا

Ø

-

8

50

e S

3

Nie XX

23

39 28 28

83

Š

53

ž

 $\overline{\mathbf{S}}$ 

**Figure D-4** Power spectral densities of ERIM scenes of Camp A.P. Hill, 4.5-5.5  $\mu$ m spectral band. (a) Morning (S01CH2). (b) Afternoon (S02CH2). (c) Evening (S03CH2).

10-5 110 1111 1 (11) (a) 10-6 10-7 10-8 10-9 10-10 10-6 THE (b) 10-7 Power spectral density 10-8 10<sup>-9</sup> 10-10 10-11 10-5 111 (c) 10-6 10-7 10<sup>-8</sup> 10-9 10-10 10-4 10-3 10-2 10-1 100 Spatial frequency (cycles/mrad)

Figure D-5 Power spectral densities of ERIM scenes of Camp A.P. Hill, 8.0-14.0  $\mu$ m spectral band. (a) Morning (S01CH3). (b) Afternoon (S02CH3). (c) Evening (S03CH3).



**Figure D-6** Power spectral densities of ERIM scenes of Port Hueneme (port and water). (a) 4.5-5.5  $\mu$ m spectral band (S23CH3). (b) 9.0-11.4  $\mu$ m spectral band (S23CH4).

THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

LAUREL, MARYLAND







**Figure D-8** Power spectral densities of ERIM scenes of mountains near Nellis AFB (F08). (a) Channel 1 (3.9-4.7  $\mu$ m). (b) Channel 2 (3.5-3.9  $\mu$ m). (c) Channel 3 (9.0-11.4  $\mu$ m).

68

10

10-10-

1.00

ŝ

8

104

.....

44

 $\mathbb{C}$ 

2

3

0

10 m - 10 m

ġ

## **Appendix E**

## **Power Spectral Density of Filtered Scenes**

PSDs of many of the filtered scenes are included in this appendix. The BMAP plot is of the scene after a bandpass filter was applied. This PSD looks like a low-pass filter.

The AFGL and ERIM scenes have been filtered with

a high-pass filter. These plots show that the AFGL PSDs were approximately flattened by the filtering. The ERIM1 scenes are not nearly as flat as the AFGL PSDs. The ERIM3 and ERIM5 PSDs, however, were flattened by the filtering.











Figure E-3 Power spectral densities of ERIM afternoon scene of Camp A.P. Hill after high-pass filter. (a) 2.0-2.6  $\mu$ m spectral band (S02CH1). (b) 4.5-5.5  $\mu$ m spectral band (S02CH2). (c) 8.0-14.0  $\mu$ m spectral band (S02CH3).



**Figure E-4** Power spectral density of ERIM scene of Port Hueneme, spectral band 4.5-5.5  $\mu$ m, after high-pass filter (scene S23CH3).

٥Z
2

234

577

i.

ģ

ß

AND NAME A

## INITIAL DISTRIBUTION EXTERNAL TO THE APPLIED PHYSICS LABORATORY\*

The work reported in TG 1360 was done under Navy Contract N00024-85-C-5301 and is related to Task A3DO, supported by Naval Surface Weapons Center.

LOCATION	ATTENTION	No. of Copies
Washington, DC 20301 Alexandria, VA 22314	G. C. Kopesak, OUSDRE (ET) Accessions	1 12
Washington, DC 20350	OP 98 OP 983 OP 987 OP 987B OP 355 OP 35E OP 352 OP 352L OP 355 OP 355 OP 355 OP 355 OP 355 OP 355 OP 355W	
Washington, DC 20350	Edward Donalson Charles Kincaid J. R. Whalen R. L. Rumpf Ann Berman T. A. Jacobs	       
Washington, DC 22202	SEA 06 SEA 06A SEA 06AT SEA 06AT SEA 06AT SEA 06P SEA 06R SEA 62 SEA 62D SEA 62D SEA 62D1 SEA 62D2 SEA 62D2 SEA 62D2 SEA 62D3 SEA 62D3 SEA 62D4 SEA 62D52 SEA 62Z3 SEA 62Z3 SEA 62Z3 SEA 62Z31 SEA 6	1 1 1 1 1 2 2 2 1 1 1 1 1 1 1 1 1 1 2 2 1 1 1
Washington, DC 22202	AIR 320 AIR 320B AIR 320D AIR 320R AIR 06 AIR 0623 Lib., AIR 7226	               
Laurel, MD 20707		ı
Dahlgren, VA 22448 White Oak, MD 20903-5000	NSWC/DL D2W NSWC/DL G06 NSWC/DL G21 NSWC/DL G22 NSWC/DL G24 Library NSWC/WO G40 NSWC/WO K22 NSWC/WO N12 Library	[ ] ] ] ] ] ] ] ] ]
	LOCATION Washington, DC 20301 Alexandria, VA 22314 Washington, DC 20350 Washington, DC 20350 Washington, DC 22202 Washington, DC 22202 Laurel, MD 20707 Dahlgren, VA 22448 White Oak, MD 20903-5000	LOCATIONATTENTIONWashington, DC 20301 Alexandria, VA 22314G. C. Kopesak, OUSDRE (ET) AccessionsWashington, DC 20350OP 98 OP 987 OP 987 OP 315 OP 3152 OP 3122 OP 3122 O

Initial distribution of this document within the Applied Physics Laboratory has been made in accordance with a list on file in the APL Technical Publications Group.

## INITIAL DISTRIBUTION EXTERNAL TO THE APPLIED PHYSICS LABORATORY

ORGANIZATION	LOCATION	ATTENTION	No. of Copies
Navai Weapons Center	China Lake, CA 93555-6001	3906 3921 3941 3942 3854 Library	2 f 1 1 1
Office of Naval Technology	Arlington, VA 22209	ONT 07C ONT 0712 ONT 0713	1 1 1
Pacific Missile Test Center	Pt. Mugu, CA 93042	4045	1
U.S. Naval Academy	Annapolis, MD 21402	Dir. Research	2
DEPARTMENT OF THE ARMY			
Missile Command	Redstone Arsenal, Huntsville, AL 35898	DRSMI OD DRSMI RR	1
Ballistic Missile Defense Advanced Technology Center	Huntsville, AL 35807	ATC-0 Gene Tidwell, SDC-HEDI Claud E. Martin, DASD- H-4B Tony Street, DASD- H-WK Price Boyd, DASD-H-WK	1 1 1
DEPARTMENT OF THE AIR FORCE			
Air Force Armament Division	Eglin AFB, FL 32542	AD/XRG	1
Aeronautical Systems Division	Wright-Patterson AFB, Dayton, OH 45433	ҮҮМ	1
CONTRACTORS			
Acurex Corporation Aerojet Electro Systems Co. Coors Porcelain Co. General Dynamics	Huntsville, AL 35806 Azusa, CA 91702 Golden, CO 80401 Pomona, CA 91766	F. Strobel Irwin Weiss D. Roy H. J. Meltzer R. M. Pietrasz R. Parker J. Stamper	1 1 2 1 1
GTE Laboratories, Inc. Hughes Aircraft Co.	Waltham, MA 02254 Canoga Park, CA 91304	W. H. Rhodes R. R. Miller A. V. Funari Dennis Quan R. L. Sendall	1 2 1 1 1 1 1
Martin Marietta Corp.	Orlando, FL 32805	John Sura	2
McDonnell Douglas Aircraft Co. MIT Lincoln Laboratories Raytheon Corporation Raytheon Corporation Research Div.	St. Louis, MO 63166 Lexington, MA 02173 Bedford, MA 01730 Lexington, MA 02173	A. E. Davidori J. F. Reilly L. B. Anderson A. E. Franz R. L. Gentilman	1 2 1 2 1

-

3

**7** 

-----

