Small Craft Identification Discrimination Criteria for Maritime Anti-Terrorism and Force Protection

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ABSTRACT

The new emphasis on Anti-Terrorism and Force Protection (AT/FP), for both shore and sea platform protection, has resulted in a need for infrared imager design and evaluation tools which demonstrate field performance against U.S. Navy AT/FP requirements. In the design of infrared imaging systems for target acquisition, a discrimination criterion is required for successful sensor realization. It characterizes the difficulty of the task being performed by the observer and varies for different target sets. This criterion is used in both assessment of existing infrared sensor and in the design of new conceptual sensors.

In this experiment, we collected 12 small craft signatures (military and civilian) in the visible band during the day and the LWIR and MWIR spectra in both the day and the night environments. These signatures were processed to determine the targets' characteristic dimension and contrast. They were also processed to bandlimit the signature's spatial information content (simulating longer range) and a perception experiment was performed to determine the task difficulty (N_{50} and V_{50}). The results are presented in this paper and can be used for Navy and Coast Guard imaging infrared sensor design and evaluation.

INTRODUCTION

The development of a credible asymmetric threat to maritime and Naval forces has been a relatively recent occurrence. The bombing of the USS Cole and the attacks on the World Trade Center in New York significantly altered our threat paradigm. As the Navy and the Coast Guard adapt to this change, we need to develop the tools to enable the community as a whole to make informed decisions and plans with regard to sensor performance and hence the development of requirements and then investment in resources.

We met with the acquisition program managers for Coast Guard and to discuss modeling needs and to develop the target set for this experiment. Additionally, we planned out a series of experiments to develop the

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capability to model EO/IR sensors in the performance of typical tasks required in the maritime security environment. This experiment is the first, and most straightforward in that series.

As an initial effort, we teamed with the US Army Night Vision and Electronic Sensors Directorate's (NVESD) Modeling and Simulation Division (MSD) to apply the existing validated models (for example, NVTherm the infrared imager performance model) to new target sets and classes. Initial efforts applied the methodology to the identification of small arms, side arms and various handheld threat objects.[1-3] NVESD has conducted numerous experiments to extend the models' performance to the urban environment also.[4,5] As this effort was very successful, we elected to continue the collaboration and develop the criteria for identifying maritime small craft.

2.0 TARGET ACQUISITION MODELING BACKGROUND

The field performance of an imager is currently described by the system contrast threshold function (CTF). This is the human eye CTF while the human is looking through the imager. The CTF is the visual threshold at which a sinusoidal input can be seen, where the sinusoid extends across the field-of-view. The system CTF is still too difficult to measure in the laboratory, but can be related to the currently measured Minimum Resolvable Temperature Difference (MRTD) measurement. The sensor CTF has been shown to be effective in characterizing the target acquisition performance of infrared, image intensifier, solid state television, laser range-gated imagers, and TeraHertz imagers [NVESD models are available from SENSIAC at https://www.sensiac.gatech.edu, for US government and contractor use and from NVESD for Allied government agencies]. In this paper, we focus on solid state television daytime performance and midwave infrared night performance.

The typical procedure for calculating/predicting field range performance is shown in figure 1. A military target is described by the characteristic dimension (square root of target area) in meters, source contrast, and task discrimination difficulty (N_{50} or V_{50}). The contrast is propagated through the atmosphere and an apparent contrast is determined at the sensor. The intersection of sensor system CTF and the apparent target contrast is called the "limiting frequency," or the highest frequency resolvable by the observer through the sensor at that particular contrast. In the process known as ACQUIRE, this limiting frequency in cycles per milliradian is converted to "cycles on target" through multiplying the limiting frequency by the target angular subtense (characteristic dimension divided by range). The cycles on target are compared to the N_{50}, or discrimination criterion sometimes called the Johnson criterion, to determine the probability. The N_{50} is different for detection, recognition, and identification and really depends on the target set. It is a characterization of the task difficulty. The ratio of cycles on target to N_{50} is input to the target transfer probability function (TTPF) to provide a probability. This process is performed iteratively for various ranges and the probability is plotted as a function of range.

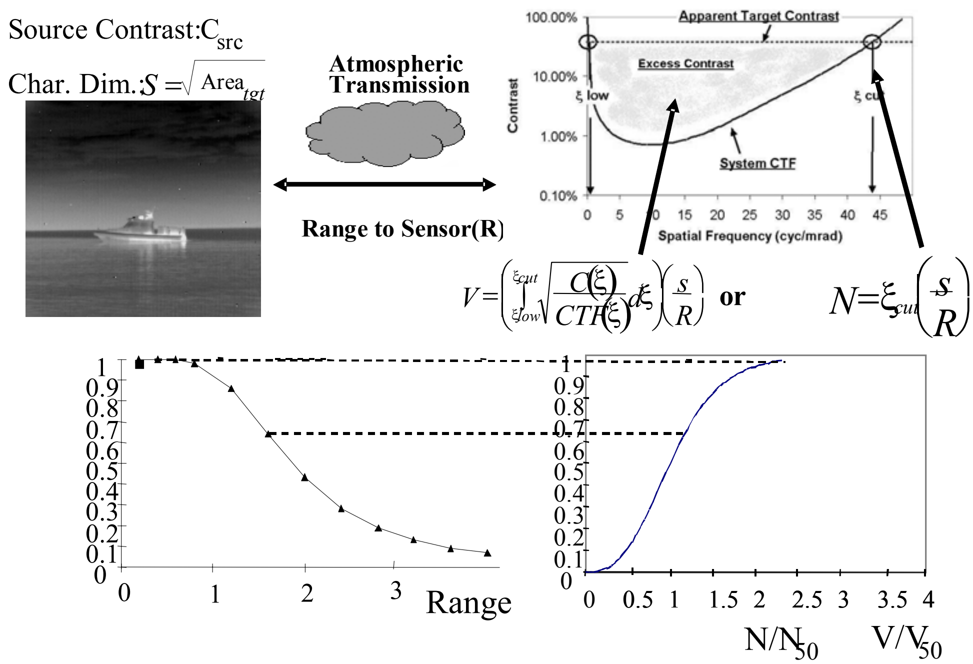


Figure 1. ACQUIRE and TTP Process.

The Target Task Performance (TTP) approach[6-9] replaces the ACQUIRE approach for most military target applications. The TTP approach varies from the ACQUIRE approach in that a system's resolution and sensitivity is accounted for by integrating the system's CTF,

$$V = \int_{\xi_{low}}^{\xi_{\lim}} \sqrt{\frac{C_{tgt}}{CTF_{sys}(\xi)}} d\xi \qquad \text{[cycles]} \qquad (1)$$

where the ratio of the target contrast to the system CTF is considered the excess contrast that the human can see on the target. The limits on the integral start and end where the target contrast intersects the system CTF. This integration is performed twice, once on the horizontal CTF of the system and then again on the vertical CTF of the system; equation 1 is assumed to be separable in spatial dimensions. The geometric mean of the horizontal and vertical results is then calculated to determine a system value. The resultant is compared to the discrimination criterion, V_{50}, to determine the probability. A different TTPF is used for the ratio of V to V_{50} than is used in the ACQUIRE process.

The TTPF is the function that converts the ratio of N to N_{50} or the ratio of V to V_{50} into a probability. The TTPF takes the form of

$$P = \frac{(\frac{N}{N50})^{\beta}}{1+(\frac{N}{N50})^{\beta}} \text{ (ACQUIRE) or } \qquad P = \frac{(\frac{V}{V50})^{\beta}}{1+(\frac{V}{V50})^{\beta}} \text{ (TTP)} \qquad (2)$$

where the coefficient, β, for the TTP is $1.51+0.24(V/V_{50})$. The coefficient for ACQUIRE traditionally is $2.7+0.7(N/N_{50})$, but a single coefficient value of 3.8 gives very close results. The traditional ACQUIRE coefficient has been used in many sensor specifications and wargames, however, a great deal of real field data has been shown to match a more gradual probability curve with coefficient equal to $1.75+0.35(N/N_{50})$ or a single coefficient of 2.7.

The TTP process provides a much more accurate prediction of field performance than the ACQUIRE process as has been demonstrated in numerous recognition and identification experiments. Search and detection is more complicated (under clutter-limited conditions) and uses a modified metric to account target acquisition in a clutter-limited realm.

3.0 DESCRIPTION OF THE EXPERIMENT

The experimental approach was to develop a representative target set for small maritime surface craft and collect signatures for creating a target identification perception experiment. The resolution of the imagery would vary in order to determine the resolution necessary to accomplish the task (identification or ID) with particular levels of certainty. An ensemble of trained observers would then participate in the ID experiment and statistical results would yield the data necessary to derive the discrimination criteria (N_{50} or V_{50}) for this task.

4.0 SIGNATURES/IMAGES COLLECTION

After discussions with the Naval Expeditionary Combat Command (NECC) personnel, a set of targets was selected which included military patrol craft, military working craft, commercial working craft and pleasure craft. These craft were assembled at Naval Surface Warfare Center Dahlgren Division (NSWC-DD) for the signature collection.

The collection site was the waterfront area looking out to the south towards the Potomac River. Data collection occurred throughout the diurnal cycle for the mid-wave infrared (MWIR), 3-5 micrometer band, and the long-wave infrared (LWIR), 8-12 micrometer band. Visible band imagery was collected during daylight hours only. The small craft were presented to the sensors with 12 different aspect angles varying from bow-on every 30^0 around the compass rose.

The sensors used included a LWIR radiometer, a MWIR radiometer and a color solid state digital camera. Specifically, the LWIR sensor was an Indigo TVS 700. The MWIR sensor was an AVIO TVS 8500. And the visible sensor was a Nikon D100.

5.0 IMAGE/SIGNATURE PROCESSING & PREPARATION

Due to resource limitations and priorities, the MWIR night imagery and monochrome visible day imagery were processed and perception experiments in DEC05. The results from this initial set of experiments were reported and presented at the Military Sensing Symposia Passive Sensors Conference in FEB06. In June of 2006, the MWIR day imagery and color imagery were processed and a further set of perception experiments conducted using all four bands/environments. The LWIR day and night imagery remain to be processed for further experimentation in the future.

A total of 576 signatures were processed for use in this research, consisting of 12 watercraft viewed at 12 aspect angles in each of two wavebands. The visible and MWIR sensors differed in field of view, focal plane array resolution, and recorded image format. The processing performed to prepare imagery for the perception experiment is described separately for each sensor. This section will also describe the target-to-background contrast and characteristic dimension calculations for each spectrum.

The MWIR imagery, captured during the day and at night with a radiometrically calibrated Avio TVS-8500 sensor, was recorded as 14-bit greyscale images in IRI format with a resolution of 256x236 pixels. Perception experiments were to be run on high resolution monitors in a larger format. This prevents the monitor pixel MTF from limiting performance. Therefore, a bilinear interpolation routine was used to increase the pixel count by a factor a two in each dimension, resulting in a 512x472 pixel image. Subsequently, the 14-bit greyscale values were contrast stretched and converted to 12-bits. The contrast stretching procedure allowed 5% saturation at the highest and lowest levels. The resulting 512x472 12-bit images were the baseline set of pristine MWIR signature imagery used for the perception experiment. These processing steps, performed using MATLAB software, are illustrated in a block diagram in Figure 2. A single aspect angle example of the baseline 12-boat image set in the MWIR spectrum is shown in Figures 3A and 3B, for the night and day respectively.

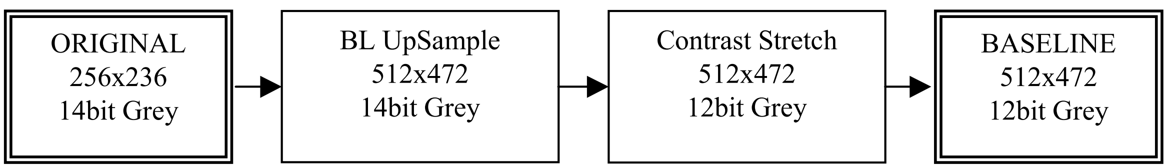


Figure 2 Image processing steps performed on MWIR imagery.

Figure 3A MWIR Night / 3B MWIR Day Baseline 12 Boat Image Set (Port Aspect Shown)

Visible Imagery

The visible imagery, captured during the daytime with a Nikon D100 digital camera, were recorded as a 24-bit color images (8 bits per color channel) in JPEG format with a resolution of 3008x2000 pixels. Images were cropped in the horizontal dimension to 2000x2000 pixels, then a bilinear down-sampling process resulted in a 1000x1000 pixel image. Image size was reduced in this manner in order to be closer to the size and format of the MW imagery presented in the experiment. The day visible imagery was presented in two perception experiments. The first series were monochrome and the second color. There is not currently a color target acquisition model (in NVESD's family of models), so only the monochrome results are analyzed quantitatively and N_{50}/V_{50}'s developed. Subsequent to down-sampling, the color image was converted to 256-level greyscale, then contrast stretched resulting in 4096 grey levels. The contrast stretching procedure allowed 5% saturation at the highest and lowest levels. These 1000x1000 pixel 12-bit images were the baseline set of pristine imagery for the visible spectrum. These processing steps, performed using MATLAB software, are illustrated in a block diagram in Figure 4. A single aspect angle example of the baseline 12-boat image set in the visible spectrum is shown in Figures 5A and 5B for monochrome and color respectively.

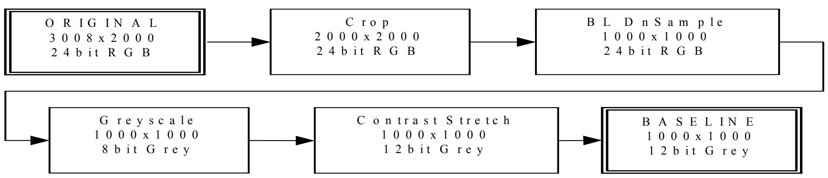


Figure 4 Image processing steps performed on monochrome visible imagery.

Figure 5A Visible Monochrome, 5B Visible Color Baseline 12 Boat Image Set (Port Aspect Shown)

Forming Images for Experimental Cells

For the day and night in both the MWIR and visible spectra, the baseline imagery was assigned to six experimental cells. The cells were balanced such that each cell contained 48 images, consisting of 12 different boats at 4 different aspects. Cells were also balanced such that target aspects were represented in equal numbers in each cell, in order to avoid any bias resulting from specific target aspects that were most easily identifiable (such as port or starboard views). Each target/aspect combination was represented twice across all six cells, resulting in an experimental database of 288 MWIR day images, 288 MWIR night, 288 monochrome visible images and 288 color images.

After assignment to an experimental cell, each baseline image was convolved with a normalized Gaussian blur filter. The Gaussian blur kernel is defined by

$$blur = \exp\left(-\pi\left(\frac{x}{b}\right)^2\right) \qquad (3)$$

The blur parameter, b, defines the width, in pixels, of the Gaussian filter. Since the resolution of the baseline imagery differed for each spectrum, two sets of blur parameters were defined in order to result in approximately the same level of perceived difficulty. The selected values of b for each experimental cell are listed in Table 1. Examples of the resultant MWIR imagery presented during the perception trial are shown in Figure 6. The top row shows the baseline imagery, while the middle and bottom rows show examples of blurred imagery for each experimental cell. The resultant imagery for the visible spectrum shows a comparable amount of blur across the experimental cells.

Table 1. Width of Gaussian Blur Kernel for Each Experimental Cell

Experimental Cell	***Visible Blur (pixels***	***MWIR Blur (pixels)***
A	15	5
B	27	11
C	39	17
D	51	23
E	63	29
F	75	35

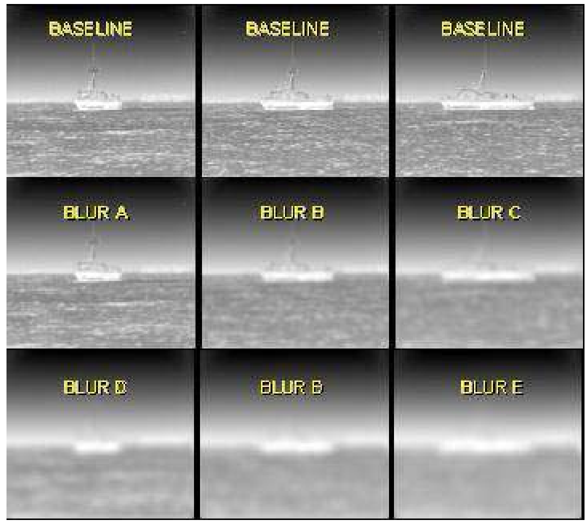


Figure 6. MWIR Experimental Imagery After Gaussian Blur Processing.

This blurring operation is a quantifiable method of systematically reducing the number of resolvable cycles on the targets in each experimental cell. Analyzed in the spatial frequency domain, the Modulation Transfer Function (MTF) of the Gaussian blur kernel is multiplied by the sensor MTF and display MTF, resulting in a modeled system MTF. As the blur parameter, b, is increased, the system MTF is contracted, limiting the spatial frequency information in the final image presented to the observer during the perception trial. The system MTF is then used in the analysis to calculate the number of resolvable cycles required to achieve a 50% probability of identification.

Target Size, Target Contrast and Delta T Calculations

For each baseline (pre-blur) image, the target was segmented from the background, creating a target mask with pixel values of 1 for all target areas and pixel values of 0 for all background areas. Target area was defined as any pixels containing any part of the boat, including masts, visible ropes, windows which contained glass, and visible operators. Disturbed water and target-related reflections on the water were not considered part of the target signature. Characteristic dimension is a one-dimensional quantity calculated as the square root of the projected target area in display pixels. Where target contrast is defined as:

$$Contrast = \frac{\sqrt{\left(\mu_{tgt} - \mu_{bkgd}\right)^2 + \left(\sigma_{tgt}\right)^2}}{2\mu_{scene}} \qquad (4)$$

where μ_{tgt} and μ_{bkgd} are the average target pixel value and the average background pixel value, respectively. The local background is defined as the area adjacent to, but not including, the target with dimensions the square root of 2 times the width and height of the target. The standard deviation of the target is accounted for by σ_{tgt} and the result is normalized by twice the average scene pixel value, μ_{scene}. The average scene value is the average of all pixels in the local background and in the target area. As shown in Table 2, the target characteristic dimension and target contrast varied by only a few percent when averaged across the watercraft in each experimental cell.

Table 2. Target Characteristic Dimension and Contrast for Each Cell

	MWIR NIGHT			VISIBLE DAY		
Blur Cell	Contrast	L scene	Tgt Size	Contrast	L scene	Tgt Size
A	0.179	8.27 fL	82 pix	0.335	4.75 fL	176 pix
B	0.181	8.44 fL	83 pix	0.338	4.78 fL	174 pix
C	0.177	8.40 fL	83 pix	0.327	4.64 fL	178 pix
D	0.179	8.27 fL	82 pix	0.335	4.75 fL	176 pix
E	0.181	8.44 fL	83 pix	0.338	4.78 fL	174 pix
F	0.177	8.40 fL	83 pix	0.327	4.64 fL	178 pix

The target thermal contrast metric (ΔT) as used to model infrared sensor performance in NVThermIP is a root-sum-square temperature value, calculated by

$$\Delta T = \sqrt{\left(\mu_{tgt} - \mu_{bkgd}\right)^2 + \left(\sigma_{tgt}\right)^2} \qquad (5)$$

where all parameters are analogous to the contrast equation, but in units of degrees Celsius, rather than greyscale pixel value. The ΔT for all aspects of the MWIR night baseline watercraft targets ranged from 0.8ºC to 4.4ºC, with an overall mean ΔT of 1.6ºC. The ΔT for all aspects of the MWIR day baseline watercraft targets ranged from 3.7ºC to 13.6ºC, with an overall mean ΔT of 7.3ºC.

6.0 OBSERVER TRAINING

A prototype trainer was developed for use in preparing the subjects to perform consistently and competently in the identification of the boats in the 12-target perception experiments. Signature training for the perception experiment subjects (Ss) is critical to achieving a low noise set of results. The training was designed to teach a robust set of cues in a tutorial format, provide interactive practice and provide exit testing to assure that, upon completion, Ss could achieve a basic ID score of at least 95% on the 12-item small boat target set.

The signatures of the boats were trained in 3 distinct training groups or “Confusion Sets,” so called because the members of each group are similar in appearance thus easily “confused.” Teaching the boat ID using this type of grouping promotes good learning of the critical cues of the signatures. Three confusion sets were established based upon the location of superstructure found on the craft. Within each confusion set, the specific distinguishing identification cues for each boat were developed based on general characteristics of boats in this 12-set class. The boats, their respective confusion sets are shown in Table 3.

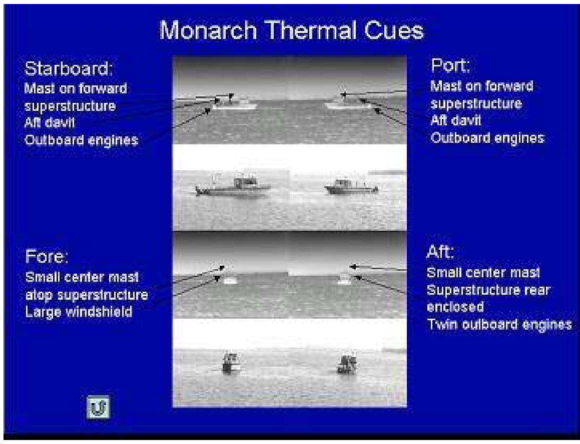
Table 3. Small Boats Test Trainer Confusion Sets

Confusion Set	Boats in the Set
#1 Superstructure Forward	Gatlin, Monarch, RCB3
#2 Superstructure Amidships	25' Patrol, 34' Patrol, H920, Yellowtail
#3 Superstructure Rear, Open or No Superstructure	F470, Fountain, LCM8, Manta, RHIB

Cues for each of the 12 boats were developed based on the cue 1) uniqueness, 2) prominence, and 3) visibility. Cues included for example location, size, numbers of superstructure, mast, windshield, out/inboard engine(s), rails, helm, etc. The same cues were used for thermal ID and visible ID. Reference images used in the trainer included both thermal and visible images, which were collected simultaneously in the field. The trainer using MS Office Powerpoint software. The curriculum was fashioned after the ROCV trainer (Recognition Of Combat Vehicles), an NVESD-developed trainer in use by the joint services to teach combat vehicle identification. The boat trainer was self-paced and automated to assist the student in navigating through the curriculum. This consisted of the student first studying the cues presented for the boats in one of the confusion sets. Second, practicing his ID of the boats using feedback quizzes provided by the trainer. The cues were studied in the context of the thermal and visible images then that study was applied through the feedback quizzes. The process involved the students testing themselves, then referring back to the cue presentations when ID errors were made. The student did the quiz routine until by his own judgment he became competent and confident in ID-ing the boats in that confusion set. The student paced through all three sets in this manner and when he felt ready to take the final exit test, the trainer ported him out of the trainer to the testing coordinator. The TC guided him thru the standard perception test interface to take the final, qualifying, exit test.

When the student received a final test score of at least 95% on the 12-boat qualifying exit test, he was qualified to participate in the experiment. If he did not pass the test then he simply returned to the trainer for more study and practice, concentrating on those boats he missed in the test. The students were also encouraged to request some cue type help from the perception test coordinator, who was always present while the students trained.

All of the students successfully qualified to take the experiments. The training time required by the group ranged from 2 hours to 10 hours, with an average of ~6 hours. Feedback on the trainer from the students indicated they felt the trainer was effective, efficient and generally enjoyable. Samples of the trainer interface showing screens from the cues section and the practice quiz section are shown below in Figures 7 and 8 respectively.



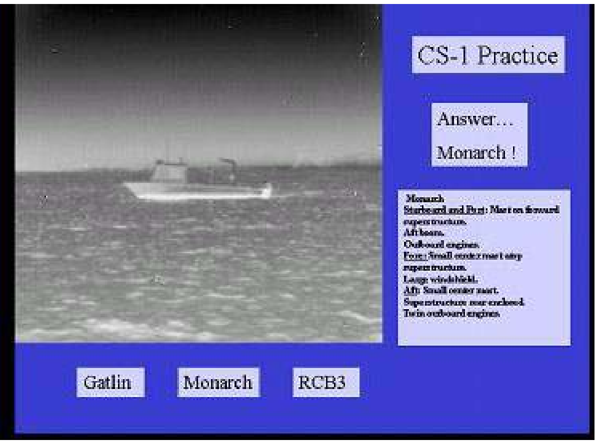


Figure 7. Small Boat Trainer Sample Screen

Figure 8 Small Boat Trainer Sample Screen for Quizzes

7.0 PERCEPTION EXPERIMENT

The form of the perception experiment was a 12 alternative fixed choice format. The fixed choice format is very is the accepted method of performing this type of perception experiment. It has been used by NVESD extensively since the mid-1990s. The imagery described in section 4.0 was presented to the observer in random order. An example of the experimental interface is shown in Figure 9.

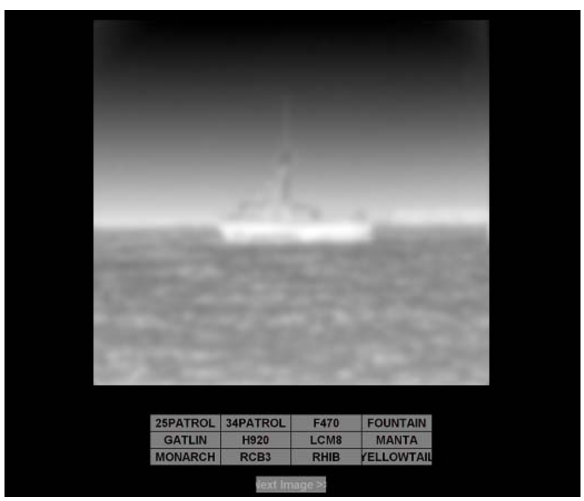


Figure 9. Observer Interface Screen Shot

Each observer participated in the visible band experiment and then took a break. After the break, the observer participated in the MWIR experiment. In all, 10 observers were trained to 95% or greater performance and then participated in the perception experiments.

8.0 RESULTS

The 12 alternative forced choice experimental results were reduced in the following way. First, the probability of identification for each level of blur was determined by taking the total correct answers divided by the total number of targets presented to all observers. That is, the average probabilities of identification for all observers were averaged to provide an overall probability of identification for the ensemble of observers. The standard error was taken as the standard deviation of the probabilities corrected for the number of observers. The number of cycles on target for the acquire methodology were determined for each level of blur and the probabilities were plotted as a function of number of resolvable cycles on target. The visible target results are shown in figure 10 and the midwave infrared results are shown in figure 11.

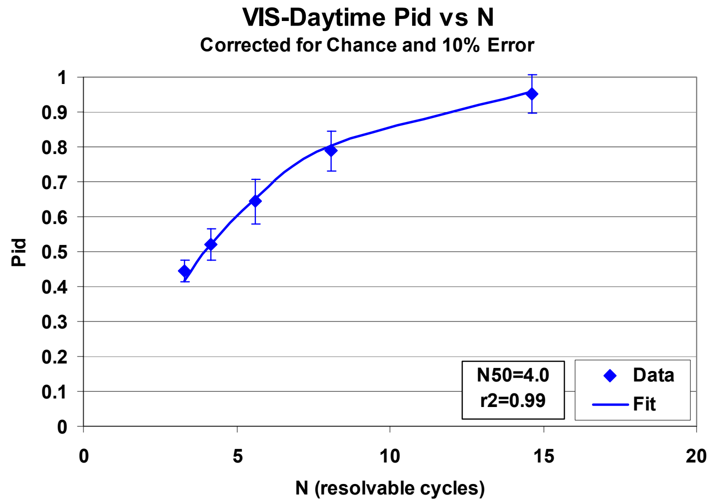


Figure 10. Visible Monochrome Day Results.

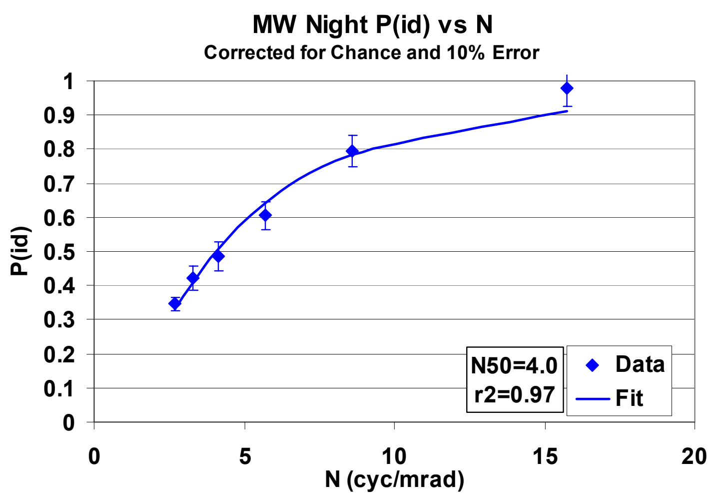


Figure 11A. MWIR Night Results.

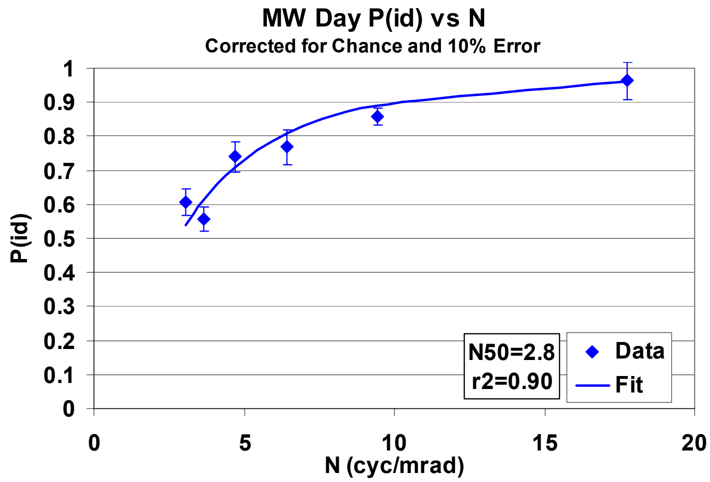


Figure 11B. MWIR Night Results.

Note that the fifty-percent probability of small boat identification (N_{50}) is 4.0 cycles on target in the visible monochrome band, 2.8 cycles on target in the MWIR day and 4.0 cycles on target in the MWIR night. The discrimination task in the visible band is about as difficult in MWIR night and visible monochrome, but significantly easier I the MWIR day case. This result of more difficulty in the visible band is different than for most other targets, such as tanks. A possible explanation is that tank ID uses hot-spot location analysis, where with boats, the locations of hot spots (engine and exhaust location) do not provide significant benefit in target identification. The overall shape and features of the boat are the primary means for discrimination.

In terms of the TTP metric (the primary metric used currently by the Army and Marine Corps), the fifty percent probabilities of boat identification (V_{50}) is 14.0 cycles on target in the monochrome visible, 13.6 in the MWIR night and 10.6 cycles on target in the MWIR day case. These results are shown graphically in Figures 12 and 13A and 13B respectively. The results are also shown in tabular summary format in Table 4.

Table 4. Results Summary

Discrimination Metric	MWIR (night)	MWIR (day)	Visible (day) greyscale
Observers	22	10	13
DeltaT	1.6 C	7.3 C	N/A
Char Dim	3.9 m	3.9 m	3.9 m
N50	**4.0**	**2.8**	**4.0**
V50	**13.6**	**10.6**	**14.0**

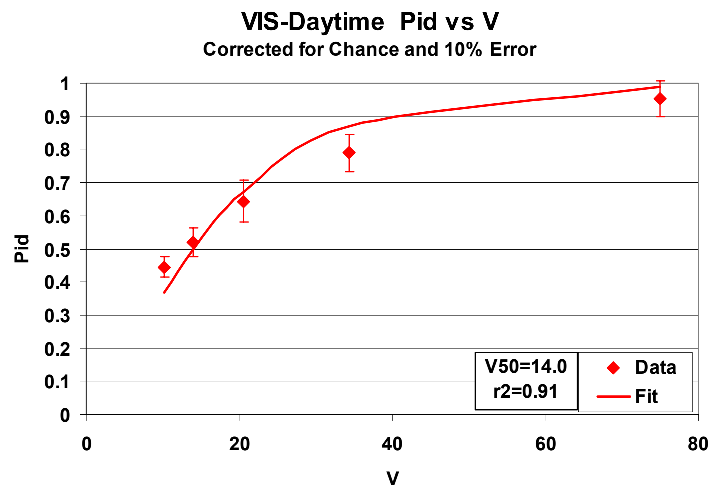


Figure 12. TTP Metric Visible Results.

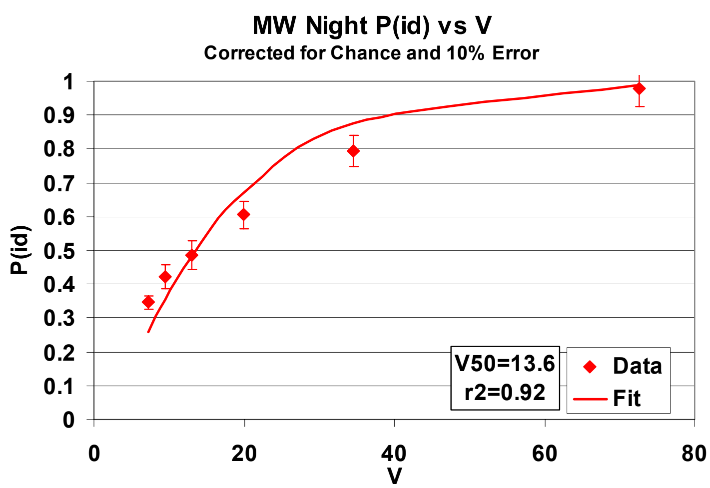


Figure 13A. TTP Metric MWIR Night Results.

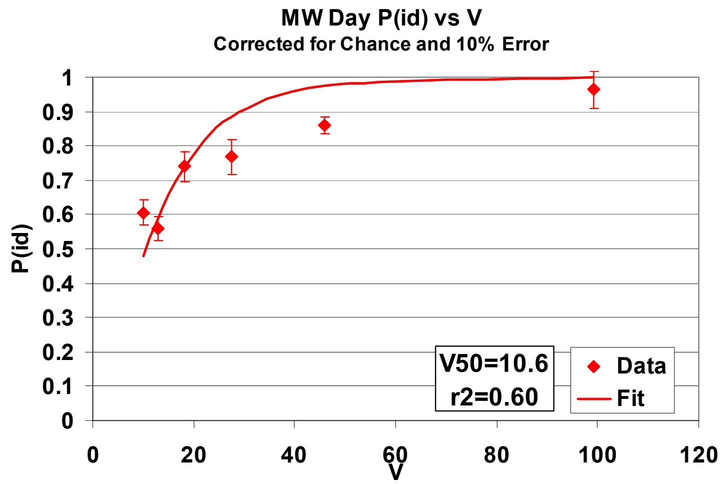


Figure 13B. TTP Metric MWIR Day Results

9.0 DISCUSSION

The results presented in the previous section can be used for sensor design by using the N_{50}s or V_{50}s provided in the process described in the target acquisition section. Coupling the criteria with the acquisition process will allow the sensor designer/analyzer a means for determining sensor performance against an average array of boats in the identification process. That is, sensors can be designed or analyzed against an *ensemble* array of boats that include easy to discriminate boats and difficult to discriminate boats. Using a 90 percent probability of identification requirement will provide sound sensor design rules. However, if it is required that a particular boat be identified, further experimentation is required.

One significant result is that the difficulty in boat identification was strongly dependent on boat aspect. For the MWIR night case, the N_{50} for the bow and stern aspects was 4.7 cycles on target and the port and starboard aspects was 2.4 cycles on target. Identifying boats from bow and stern was twice as difficult as identifying boats from broadside. Some discussion between the authors brought up the issue of whether a direct bow or stern aspect should be a consideration since any small angle deviation from bow or stern provided a significant increase in target area and views of significant features. However, a good point is that if the boat were approaching (worst case for anchored high value asset) or fleeing would result in a direct bow or stern view. The MWIR night V_{50} for bow/stern was 17.9 cycles on target and the MWIR night V_{50} for broadside was 8.5 cycles on target. The visible N_{50} for bow/stern was 5.3 cycles on target and broadside was 2.5 cycles on target. Finally, the visible V_{50} for bow/stern was 21.3 cycles on target and broadside was 8.5 cycles on target.

Another significant result was the lower N_{50}, 2.8, for the MWIR during the day than during the night, 4.0. This is somewhat counter to conventional reasoning that the solar contribution should be treated as clutter enhancing. In this result, the authors believe the task is actually made easier since in the MWIR signatures are actually a combination of reflective and emissive. At night, without the solar reflection, MWIR appears purely emissive. The day signatures actually include reflective and emissive components, and hence have more information. This results in a lower task difficulty to ID vessels in the day time MWIR.

10.0 CONCLUSIONS

We have determined the discrimination criteria, N_{50} or V_{50}, for identifying maritime small craft in both the midwave infrared and visible bands. These are numerical metrics describing the difficulty of identifying boats. These metrics may be used by sensor designers, evaluators or wargamers to predict the range performance or probability of identification for a given existing or future sensor by using the NVTherm or SSCAM models available from NVESD.

While we made significant progress in this experiment, the series of experiments will continue to further determine performance criteria for other tasks inherent in Maritime AT/FP. We also have the remainder of the signature data from this collection (LWIR day and night) to process and include in perception experiments. This will refine the picture of the applicability of these types of sensors.

Additionally, there are currently two other data collections/perception experiment efforts in the planning stage. The first is related to determining what a subject is doing from motion video, both infrared and visible. The second is related to determining the difficulty in detecting and classifying swimmers in the water. Both of these experiments will expand our ability to model and predict performance of AT/FP tasks in the maritime environment.

11.0 REFERENCES

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