DREP Technical
Memorandum 87-7

(3)

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## VISUAL DETECTION OF LOW CONTRAST BANDS IN SPECKLED IMAGERY

by

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## ABSTRACT

The human visual system performance in detecting low contrast bands in speckled imagery was examined. For exactly known signals it was found that approximately a 4.9-fold increase in signal amplitude was needed to achieve results comparable to the optimum matched filter detector. For signals of random orientation this factor is approximately 4.6. Due to the complex and largely unknown nature of the human visual system and the choices that must be made in preparing the images, caution must be exercised when applying these results.

## 1. INTRODUCTION

When rough surfaces are illuminated by coherent radiation whose wavelength is of the order of that typical of the surface roughness, interference of the reflected waves produces a noise called speckle [1,2]. Its effect is to give the image a "grainy" appearance which often masks features of interest[3]. In this paper the performance of the human visual system was examined for the detection of low contrast bands in speckle noise.

Much research has been done evaluating the effect of speckle on image recognition, detection and resolution, and techniques have been proposed to reduce the effect of speckle [1,2,4-6]. This study is concerned with the human visual system's ability to detect objects in speckle. Section 2 describes the experiments performed and visual results obtained. In Section 3 these results are compared with those of the optimum detector, the matched filter. It is shown how this work makes more precise the findings reported by Lyzenga[7] for the detection of wake patterns in synthetic aperture radar images. It was this problem that motivated the study[7-10]. Section 4 contains a summary of the present work.

## 2. EXPERIMENT

### a) Design

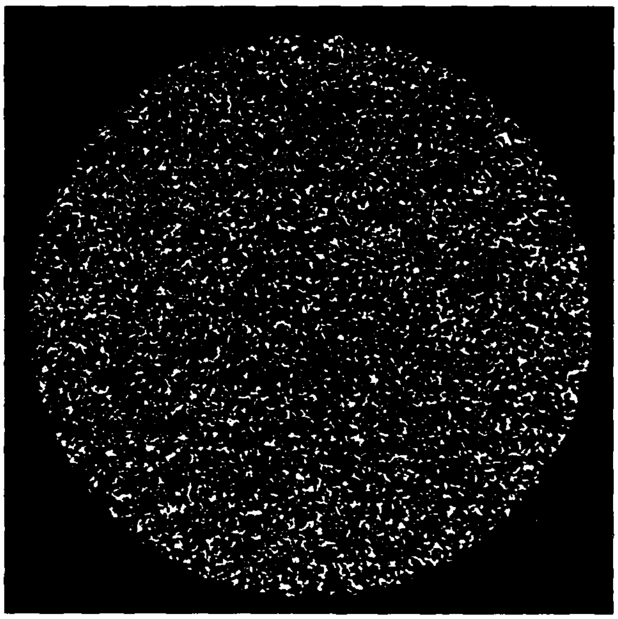
In order to study the human visual system's performance a number of circular digital images were prepared. An 8-bit intensity scale was used with 0 being the blackest black and 255 the whitest white. The radius of the circle was 256 pixels. The individual noise intensities are independent and were randomly generated on a computer, which allowed control of signal-to-noise ratio. A signal, if present, was 128 pixels wide, running vertically through the middle of the image.

Let $i(x,y)$ denote the pixel intensity at location $(x,y)$, then

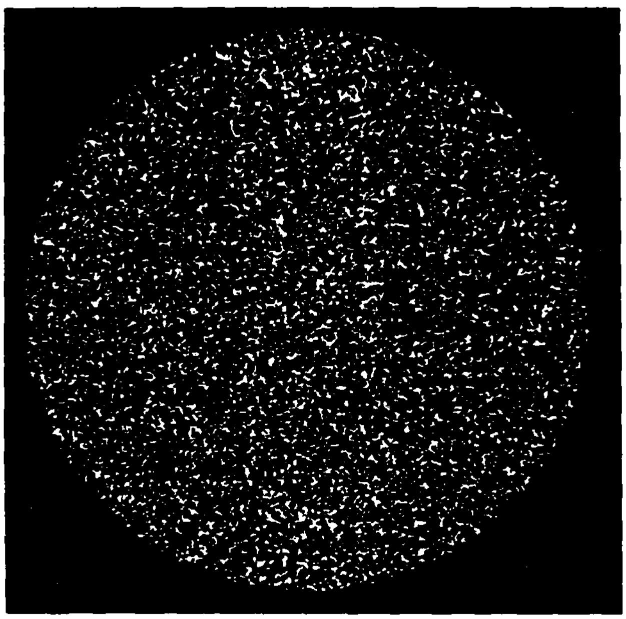
$$i(x,y) = n(x,y)\,(1 + s(x,y)) \qquad (1)$$

where $n(x,y)$ is speckle noise and $s(x,y)$ is the signal. Speckle noise obeys an exponential distribution. The mean of an exponential random variable equals its standard deviation, and so, when a signal is present with amplitude $s(x,y)$, the mean and standard deviation both become $1 + s(x,y)$. Hence in regions where $s(x,y)$ is positive,the image has more large values compared to regions where the signal amplitude is negative.

Figure 1(a) is an example of a noise only image and Figure 1(b) an image containing a signal where $s(x,y)$ is +0.070. (The original images used in the experiment were produced on glossy photographic paper.)



(a) Noise only image



(b) Image containing signal of amplitude +0.070.

Figure 1. Typical images used during the experiments.

The problem of determining an accurate measure of a human's visual detection ability is very difficult. A large number of factors influence the result[11]. These include:

i) the photographic process used (black and white or pseudo color, glossy or matte prints, size of the photograph);
ii) the observer and the viewing environment (skill and training of the operator, viewing distance and lighting conditions);
iii) type of pre-processing (linear, log, square root, histogram equalized, filtered).

In the preparation of this report some time was spent viewing images produced using different photographic processes and types of pre-processing. They were also viewed under many conditions. It is felt that near "optimum" conditions occurred when no pre-processing was done except to set the largest 2.5 percent of the pixel intensities to 255 (in theory the range of intensities is 0 to infinity). The size of the circular images is as given in Figure 1, about a 7.5-centimeter diameter.

The instructions presented to the observers included two example photographs as in Figures 1(a) and (b). The observers were asked to decide their best viewing angle and distance in order to determine whether a signal was present in the image.

b) <u>Known Orientation</u>

After the instructions and training, all observers were given four sets of photographs. Each set had about 10 photographs in it, about half of which were noise only and half with images containing a signal. The observers were told that all signals in the set had the same amplitude, and whether this amplitude was positive or negative. They were asked to decide whether an image was noise-only or noise-times-signal. This is a simple hypothesis testing problem with the null hypothesis being noise only[12].

Two of the amplitudes provided corresponded to signals which were judged in the preliminary analysis to be "just discernible". The other two amplitudes gave "discernible" signals. These choices were, of course, subjective.

The cumulative results of 20 observers are presented in Table 1. One observer's set of results is not included because the total number of errors was much larger than the average number of errors. The denominator of the fractional form of the probability of detection is the number of trials at the corresponding signal amplitude. The overall false alarm probability was 0.037 (17/460).

Table 1. Probability of detection versus signal amplitude for signals of known orientation. False alarm probability is 0.037.

| Signal Amplitude | Probability of Detection |
|---|---|
| -0.060 | 1.0 (80/80) |
| -0.045 | 0.80 (80/100) |
| +0.045 | 0.64 (64/100) |
| +0.060 | 0.99 (79/80) |

c) Random Orientation

For the second experiment the circular portion of the photographs was cut out and a random cut placed at the edge. The observers again had to decide whether the image was noise-only or noise-times-signal. If it was decided that the large was noise-times-signal. the orientation of the center of the signal with respect to the random cut had to be reported. The orientation was considered correct if it was within $30^{\circ}$ of the true value. The reason for this particular value is discussed in Section 3 and Appendix B. The results of this experiment are in Table 2. As in the previous experiment, 20 observers took part. The detection probabilities are almost the same as those in Table 1 while the false alarm probability has increased by a factor of 2.2.

Table 2. Probability of detection versus signal amplitude for signals of random orientation. False alarm probablity equals 0.08 (37/460).

| Signal Amplitude | Probability of Detection |
|---|---|
| -0.060 | 1.0 (80/80) |
| -0.045 | 0.83 (83/100) |
| +0.045 | 0.63 (63/100) |
| +0.060 | 0.96 (77/80) |

## 3. COMPARISON WITH THE OPTIMUM DETECTOR

### a) Matched Filter

For the problem posed in Section 2(b), the optimum processing method, according to the Neyman-Pearson criterion, is the matched filter[8]. The appropriate test statistic U is defined as:

$$U = \frac{1}{N} \sum_{R} i(x,y) \tag{2}$$

where i(x,y) represents the pixel values, the summation is over the region R that might contain a signal and N is the number of pixels in R. It is accepted that a signal is present only if U is greater than some predetermined threshold value. The probability of detection, PDET, is (see Appendix A):

$$PDET = Q\left(\frac{Z(\alpha)}{1+a} - \frac{254.6\ |a|}{1+a}\right) \tag{3}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-x^2/2)dx$,

$\alpha$ is the false alarm probability and $Q(Z(\alpha) = \alpha$. Here a is a constant signal amplitude. If a is close to zero, Equation 3 reduces to

$$PDET = Q(Z(\alpha) - 254.6\ |a|) \tag{4}$$

The quantity $254.6|a|$ is the square root of the detection index[13]. For a = 0.045 this square root is 11.5, and for a = 0.06 it is 15.3.

b) <u>Known Orientation</u>

Equation 3 yields the probability of detection for any false alarm probability and value of signal amplitude. Only empirical results as in Section 2 are possible for the visual system. Here a value of signal amplitude is set and false alarm probabilities are experimentally determined. Note that these probabilities are only estimates of the true probability. Also they are only meaningful for values of 'a' which yield signals that are discernible (at least in some cases). Thus a complete comparison is not possible.

It can be asked, however: when visual detection is possible, what is the approximate ratio of signal amplitude for visual detection, $a_{vis}$, to that required in matched filtering, $a_{mf}$, to obtain identical probabilities of false alarm and detection? The data from Table 1 and Equation 3 answer this question. Substituting 0.80 for PDET and 0.037 for $\alpha$ (the results for $a_{vis} = -0.045$) in Equation 3 yields $a_{mf} = -0.01024$. Then $a_{vis}/a_{mf} = 4.39$. For $a_{vis}$ equal to +0.045 the ratio is 5.35. The values of $a = \pm 0.045$ were chosen rather than $\pm 0.060$ because the visual probabilities are only estimates and the function Q(x) varies most slowly when Q(x) is around 0.5. It can also be noted that human observers do comparatively better detecting darker signals (about 4.39 times the signal amplitude required by matched filtering) than brighter signals (for which a factor of 5.35 is needed). Many observers made the same comment after viewing the images.

The above ratios are independent estimates of the same random variable. Their average has a smaller variance than either of the individual estimates and gives a more accurate estimate of the desired ratio. Hence it is concluded that a signal amplitude approximately 4.9 times larger is required for visual detection as compared to the matched filter. Lyzenga[7] determined this factor to be about 3 using a less precise analysis on a more complicated signal. Lyzenga also concluded that the square root of the detection index must be about 12 to obtain a signal "judged visually detectable". The results for detection index equal to 11.5 (visual detection probabilities of 0.64 and 0.80 when the absolute signal amplitude was 0.045) supports this conclusion.

c) <u>Random Orientation</u>

This problem is an example of composite hypothesis testing[12]. The hypothesis is noise-only and the alternative is signal-times-noise with the signal's orientation being uniform over $0^{\circ}$ to $360^{\circ}$. The detection method is to calculate the matched filter test statistic for all orientations of the image and then to decide that a signal is present if any of these statistics are above a pre-assigned threshold. Thus, if a signal is present, the appropriate test statistic would be the same as that for the case of known orientation. Hence the probability of detection for this composite test would be the same as that for the simple hypothesis test. However, because many more test statistics are calculated, the overall false alarm probability increases. (A study of Tables 1 and 2 shows that the visual system also seems to operate in this way. The detection probabilities for a given amplitude are the same but the false alarm probability increases). The method of Hughes[8] is followed to approximate the relationship between the per decision false alarm probability, $\alpha$, and the overall or image false alarm probability, $\alpha_o$.

For region R the test statistic U(R) is $\frac{1}{N} \Sigma\, i(x,y)$

where the sum is over the pixels in the region R. If test statistics are calculated for two regions which overlap, then the test statistics will be correlated. The question is to determine how many independent test statistics there are when the many correlated statistics above are used. If this number is j, then it is easy to see

$$(1 - \alpha_o) = (1 - \alpha)^j \qquad (5)$$

In Appendix B it is shown that j is approximately 3.

A comparison between the human visual system and the above detector can now be made. For an overall false alarm probability of 0.08 (as achieved by observers) the individual matched filter decision false alarm probability, using Equation 5, must be 0.0274. To find $a_{mf}$ for $a_{vis}$ = +0.045, detection and false alarm probabilities of 0.63 and 0.0274, respectively, are substituted into Equation 3. This results in a matched filter dsignal amplitude of 0.00885 and hence a visual-to-matched-filter ratio of 5.1. A similar calculation when the visual signal amplitude is -0.045 gives the factor as 4.0. Finally, on averaging these estimates it is concluded that the signal amplitude for visual detection must be about 4.6 times as large as that of the composite matched filter detector to achieve the same performance.

## 4. SUMMARY

Two experiments were performed to measure the detection performance of the human visual system and compare it with that of the optimum detector. For a signal known exactly the signal's amplitude must be about 4.9 times larger for visual detection as compared to the optimum detector. For a signal of random orientation this factor is approximately 4.6. The square root of the detection index must be about 12 for a signal to be visually discernible.

Caution must be exercised in applying these results. The expertise of the observer, the signal, the type of image pre-processing and photographic process employed are some of the factors that influence the result.

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## APPENDIX A

### PROBABILITY OF DETECTION OF A KNOWN SIGNAL

In order to determine the probability of detection of the optimum matched filter of Equation 2, Section 3 (a), the distribution of the test statistic U is required for i(x,y) equal to noise-only and also for i(x,y) equal to noise-times-signal with a signal amplitude of a. In both cases U is the sum of a large number of independent random variables. For the former situation each i(x,y) has a mean and standard deviation of 1, and for the latter the mean and standard deviation are (1+a).

According to the Central Limit Theorem[12], the distribution of U is Gaussian with mean 1 and standard deviation $\frac{1}{\sqrt{N}}$ for for noise-only and U has mean 1+a and standard deviation $1+a/\sqrt{N}$ for noise-times-signal. These density functions are illustrated in Figure A1.

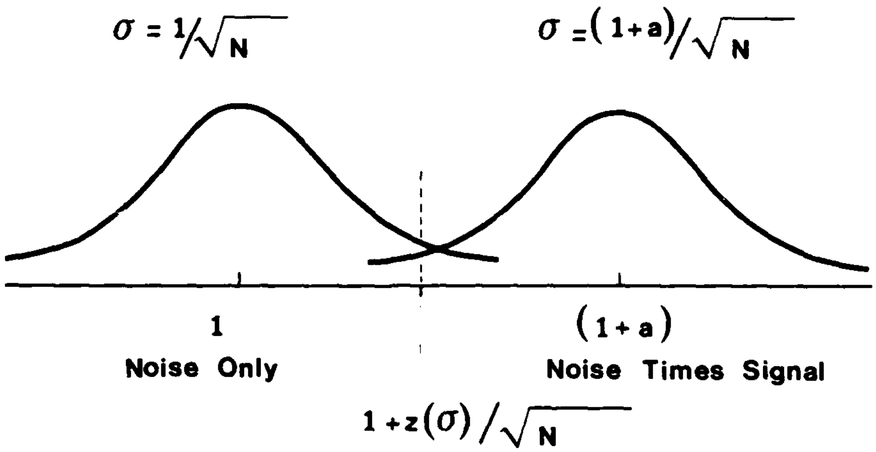


Figure A1 The probability density function of U for an image equal to noise-only and to noise-times-signal when the signal amplitude is positive.

For a false alarm probability of α, the detection threshold is set at $1 + Z(\alpha)/\sqrt{N}$. Then the probability of detection, PDET, is:

$$\text{PDET} = \frac{1}{\sqrt{2\pi}(1+a)} \int_{\beta}^{\infty} \exp(-(x-(1+a))^2/(2(1+a)^2/N)dx$$

Where $\beta = 1+Z(\alpha)/\sqrt{N}$

Let $t = \dfrac{x - (1 + a)}{(1+a)\sqrt{N}}$ and the above has the form

$$PDET = Q\left(\frac{Z(\alpha)}{1+a} - \frac{a}{1+a}\sqrt{N}\right) \qquad \text{(A1)}$$

Where $Q(x) = \dfrac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-t^2/2)dt$

A similar result is obtained if a is negative except that the sign is positive for the second term. For a circle of radius 256 and line width 128, $\sqrt{N}$ is 254.6 and Equation A1 reduces to Equation 3.

## APPENDIX B

## NUMBER OF INDEPENDENT DECISIONS USING THE COMPOSITE MATCHED FILTER

The correlation coefficient between the test stastics for regions $R_1$and $R_2$, denoted $r(R_1, R_2)$, is

$$r(R_1, R_2) = \frac{E\,(U(R_1)U(R_2)) - E(U(R_1))\,E(U(R_2))}{\sigma_U(R_1)\ \sigma_U(R_2)} \qquad (B1)$$

$$= \frac{k}{N}$$

where E is expectation and $\sigma$ is standard deviation. The quantity k is the number of pixels common to regions 1 and 2, and N is the number of pixels in the regions. Following Hughes[8] it was decided that only one independent test is being made for all regions where the correlation coefficient is greater than or equal to 0.5. That is, for some arbitrary orientation an angle of rotation is determined so that all the test statistics based on regions whose orientation is less than or equal to this angle have a correlation coefficient greater than or equal to 0.5. For all these test statistics it is assumed that only one independent decision is being made.

With the aid of Figure B1 it can be seen that this angle is about $30^o$. Consider regions 1 and 2 as defined in the Figure. Recall that the width of the vertical line is one-half (128) of the radius (256). For the angular rotation $\Theta$ shown in the Figure the common area ABCD (shaded on the Figure) is $2/\sqrt{15}$, or 0.516 (it is four times the area of AOD, i.e., $4/2\sqrt{15}$). As the area of the sector AECF is 0.989 the correlation coefficient is very closely approximated by 0.5. The angle between regions 1 and 2 is $2 \sin^{-1}(1/4) = 28.90^o \simeq 30^o$. Thus, for a rotation of $60^o$ ($\pm 30^o$ about the center) one independent decision is made. Test statistics for rotations to $180^o$ are equivalent to 3 independent decisions. Test statistics for rotations of $180^o$ to $360^o$ are redundant due to symmetry.

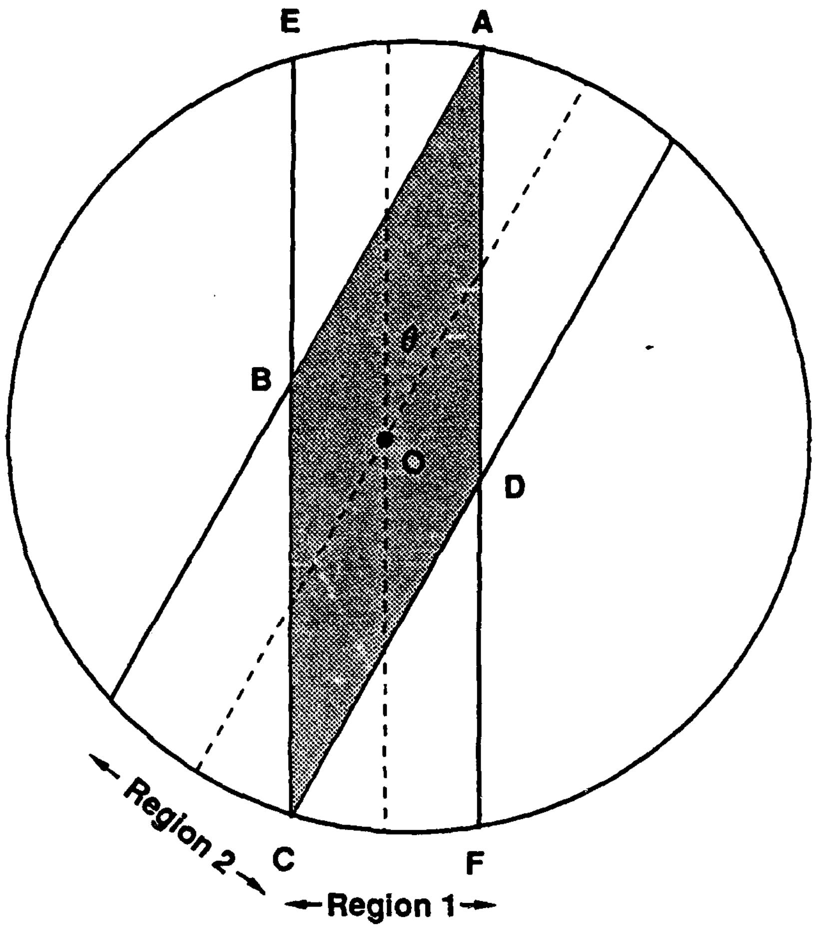


Figure B2 Two regions whose test statistics have a correlation of about 0.5. The shaded area corresponds to the intersection of these regions.

REPORT NO.: DREP Technical Memorandum 87-7

TITLE: VISUAL DETECTION OF LOW CONTRAST BANDS IN SPECKLED IMAGERY

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DATED: August 1987

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VISUAL DETECTION OF LOW CONTRAST BANDS IN SPECKLED IMAGERY (U)

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)
WILMUT, Michael J.

5. DATE OF PUBLICATION (month and year of publication of document) October 1987

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 16

6b. NO. OF REFS (total cited in document) 13

6. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)
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