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TECHNICAL MEMORANDUM 89-03

ANALYSIS OF A TWO-PASS MODIFIED HOUGH TRANSFORM TECHNIQUE FOR THE DETECTION OF WAKE LIKE SIGNALS.

by

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ABSTRACT

Various authors have employed versions of the Hough Transform for the detection of lines in images containing multiplicative speckle noise. In this paper a procedure is developed using the Modified Hough Transform (MHT) for the detection of signals of low signal-to-noise ratio. The signal can be considered as being composed of a sum of narrow lines. The expected number of signal and false lines to be found in an image can be determined as a function of the false alarm probability per decision. The MHT performance is compared to that of the matched filter.

The method is applied to noisy images containing a wake-like signal. The MHT is able to detect the signal pattern at signal-to-noise ratios for which the signal is just visible on a good image display system. A two pass system, employing prior knowledge about the signal, gives improved detection performance.

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1.0 INTRODUCTION

The Hough Transform has been used by various authors for the detection of lines – both narrow and wide – in noisy images[1–4]. Images of interest result from Synthetic Aperture Radar (SAR) sensing of land or sea surfaces.[1–4] The noise in the images – due to its multiplicative nature – gives the images a "grainy" appearance and is called speckle noise[5].

This report investigates the problem of detecting a wake-like signal, which may be considered as being composed of a sum of narrow lines, in speckle noise. The signal has low signal-to-noise ratio.

The signal and noise model is given in Section 2. The Modified Hough Transform (MHT) technique is described in Section 3 and applied to simulated data. Section 4 provides a performance analysis of the method and comparisons are made with matched filter (MF) detection. Section 5 contains conclusions for the study.

2.0 MODEL OF A WAKE IMAGE

2.1 Speckle Noise

Speckle or exponential noise occurs in many physical phenomena including SAR observations of land or ocean surfaces. Its density function, when the mean is 1, is given by:

$$P(n) = \begin{cases} 0 & \text{if } n < 0 \\ e^{-n} & \text{if } n \geq 0 \end{cases} \tag{1}$$

Speckle noise is multiplicative, that is, the observed pixel intensity, $m(x,y)$ at location (x,y), is given by:

$$m(x,y) = n(x,y)(1 + s(x,y)) \tag{2}$$

where $n(x,y)$ is the speckle and $s(x,y)$ is the signal.

2.2 Signal Model

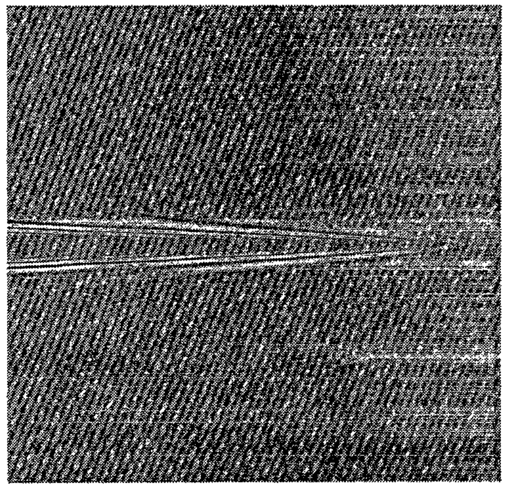
The wake-like signal to be detected is shown in Figure 1(a). This signal may be thought of as being composed of a sum of narrow non-overlapping straight lines. Figure 1(b) is an approximation of Figure 1(a) in terms of nine narrow lines. Further details concerning this description are found in the next Section.

3.0 MODIFIED HOUGH TRANSFORM

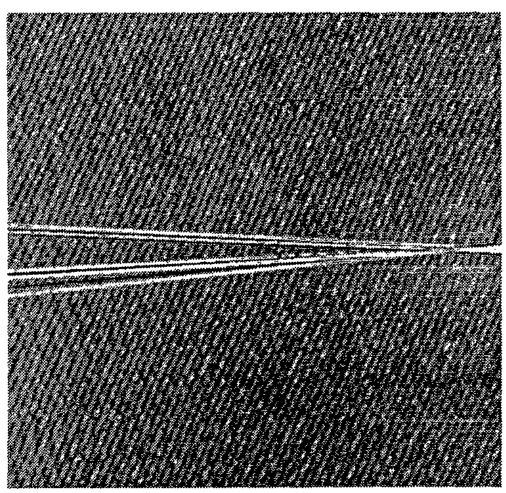
The Hough Transform [6,7] maps a line in Cartesian co- ordinate space into (ρ, θ) co-ordinate space, as described by the following expression:

$$\rho = x cos\theta + y sin\theta, \tag{3}$$

where ρ is the distance of the line from the origin and θ is the angle of its normal with respect to the positive x axis. The procedure is illustated in Figure 2.



(a)



(b)

Figure 1. Wake-Like Signal Model

(a) Wake-Like Signal

(b) Nine narrow lines used to approximate Figure 1(a).

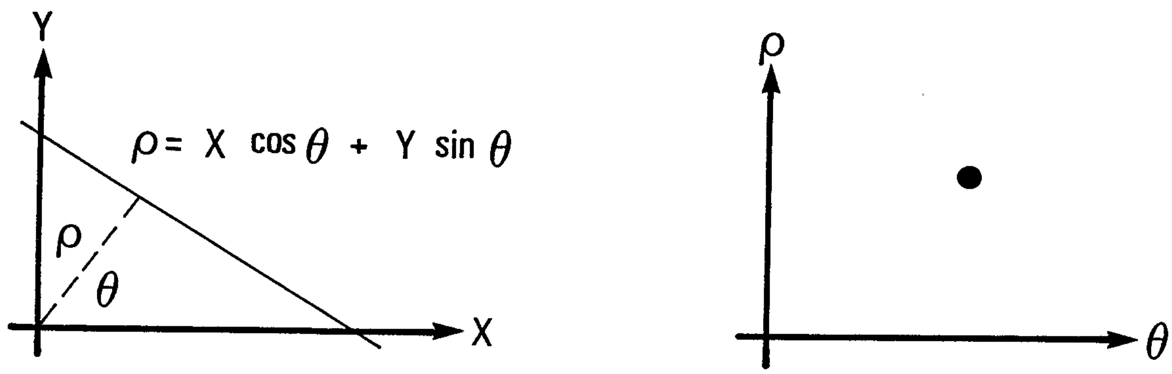
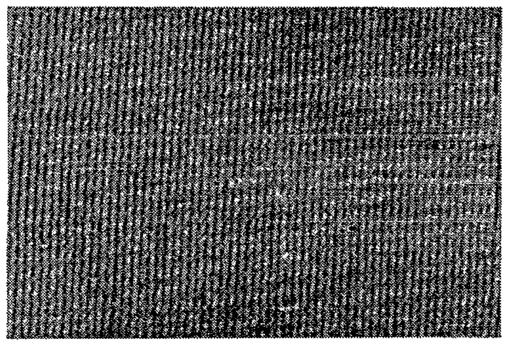


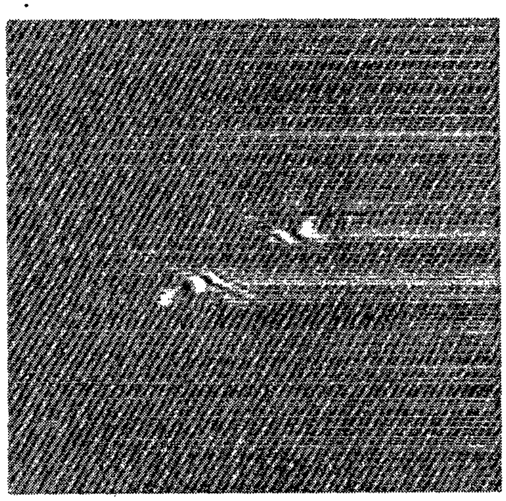
Figure 2. A Line and its Hough Transform
(a) Line with normal parameters(ρ, θ)
(b) Modified Hough Transform of the line of (a)

The application of the transform to discrete images is discussed in References 3 and 4. The result is the Modified Hough Transform (MHT). In the following, the output of the transform process will be either the mean pixel intensity values for line (ρ_i, θ_j) or the number of standard deviations this mean line intensity differs from the spatial image mean. The standard deviation used in the latter output is the spatial image standard deviation and the output is called the standard deviation map.

Figure 3 is the MHT of the signal in Figure 1(a). The angle increments are half degrees and the rho increments are unity. Figure 3(a) is the transform of the whole image and Figure 3(b) the "zoomed" version of the signal region. The largest intensities are 3.4% above the mean level and the smallest 3.8% below the level. The MHT of a set of infinite parallel lines of width W in the spatial domain is a line of length W at a constant angle. For lines of finite length the transform is ridge-like containing a line segment at an angle θ and length of about W. Inspection of Figure 3(b) shows the signal has produced two areas which differ significantly in intensity from the background. The lower left area contains three bright and two dark line segments and the upper right area two bright and two dark line segments. All segments are of length 2 or 3. The spatial domain lines corresponding to these MHT domain line segments are shown in Figure 1(b).

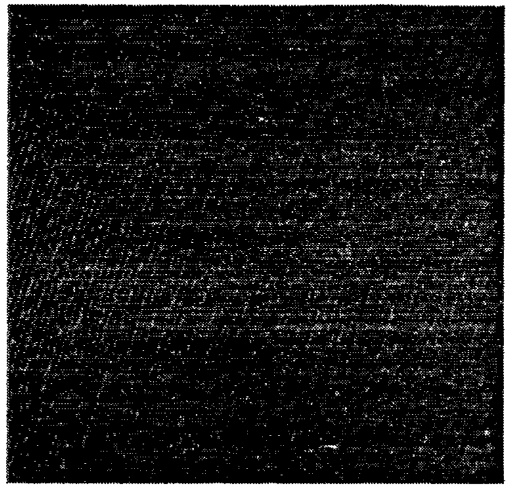


(a)



(b)

Figure 3. Modified Hough Transform of Figure 1(a)
(a) Transform of the Whole Image
(b) "Zoomed" Version of the Signal Region of (a)



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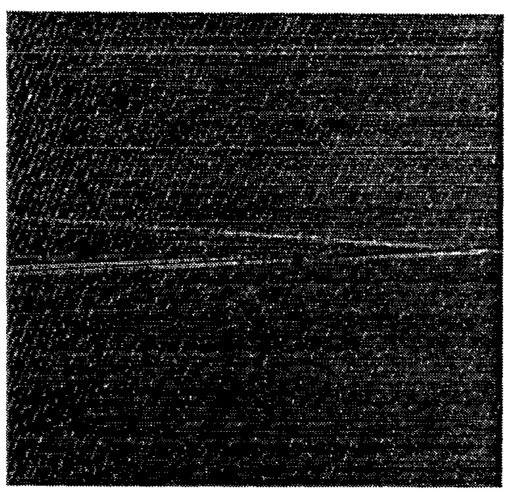

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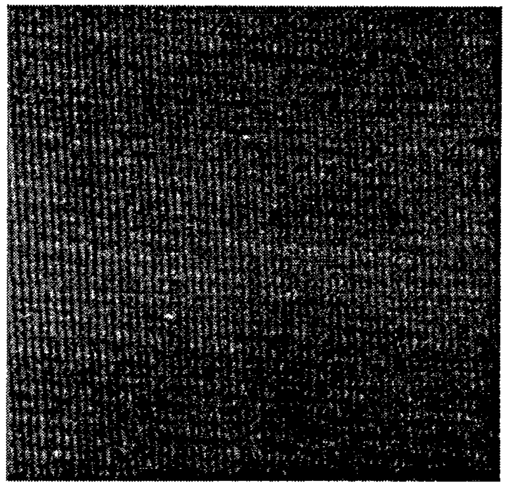
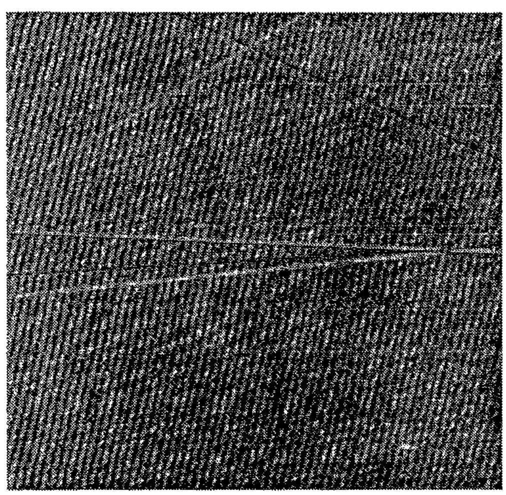
Figure 4. (a) Signal of Figure 1(a) Multiplied by Speckle Noise. Detection Index is 20.
(b) Statistically Significant Linear Features in 4(a) Recovered by MHT Method.



(a)



(b)

Figure 5. (a) Signal of Figure 1(a) Multiplied by Speckle Noise.
(b) Statistically Significant Linear Features in 5(a) Recovered by MHT Method.

The MHT is now applied to noisy images containing the signal of Figure 1(a). The method consists of three steps. First, the MHT standard deviation map is obtained. Second, all rho-theta combinations $(\rho_i,\ \theta_j) + (\rho_{i+1},\ \theta_j)$ which are more than K standard deviations from the mean are located. Finally, the lines corresponding to these regions are displayed in the spatial domain.

Figures 4 and 5 illustrate the method for two different signal-to-noise ratios. The (a) part of each Figure is the noisy image containing a signal. The signal is barely visible in the photographic reproduction, but can be seen more clearly on an image display system. All lines of width 2 which are more than 4.125 standard deviations from the mean are displayed in the (b) part of each Figure. Comparison of these recovered features with the original signal of Figure 1(a) shows that the location of these linear features is quite accurate. Seven of the nine lines are recovered from Figure 4(a) with one false line present and four of the nine from Figure 5(a) with two false lines.

The (b) parts of Figures 4 and 5 can be used as an aid in the recognition of the wake signal in the (a) parts or as a detection scheme in themselves. In both of the recovered images the signal can be recognized (from the pattern of the reconstructed signal lines) and false lines disregarded.

4.0 ANALYSIS

Next, the performance of the MHT method is obtained. The performance depends on the a priori knowledge available when implementing the method. A comparison is made with the performance of the matched filter (MF) which is optimum when the signal is known exactly.

4.1 Matched Filter Processing

Here it is assumed that the form and location of the signal as well as the mean and standard deviation of the noise are known a priori. It can be shown[8] that the optimum processor, according to the Neyman-Pearson criterion, is the matched filter. The test statistic, U, is:

$$U = \frac{1}{N} \sum_{R} m(x, y) s(x, y) \tag{4}$$

where the summation is taken over the N pixels in the region R that might contain a signal. Recall that $s(x, y)$ is the signal and $m(x, y)$ the observed pixel intensity. It is accepted that a signal is present if U is greater than some preassigned threshold value. The probability of detection, $PDET$, is:

$$PDET = Q(Q^{-1}(PFA) - DI)) \tag{5}$$

where PFA is the false alarm probability, DI the detection index equal to $(\Sigma s^2(x,y))^{1/2}/\sigma_N$ and $Q(x) = \int_x^\infty \exp(-x^2/2)dx$. The quantity σ_N is the noise standard deviation which for the noise given by Equation 1 is unity. Equation 5 directly relates the detection index and false alarm and detection probabilities, when the signal is known exactly. The effect of not knowing the signal location has also been studied by Hughes[8].

4.2 Modified Hough Transform Method

In many cases of practical interest the form of the signal is not known. The following shows that, for cases where the signal can be decomposed into non-overlapping lines which extend across the whole image, the MHT method may be employed advantageously. Let w_i be the width of one of the non- overlapping lines making up the signal, $1 + a_i$ its mean and line length n_i. According to the Central Limit Theorem the MHT outputs of noisy images are Gaussian Statistics. Call these random variables t_i. From the above if a signal is present the statistic t_i will have mean $1 + a_i$ and standard deviation $(1 + a_i)/(n_i w_i)^{1/2}$. If no signal is present a_i would be zero in the above.

4.2.1 Signal Location and Sign Known in MHT Domain

Various degrees of knowledge could be available at the detection stage. At one extreme assume the location and sign of the a_i are known. The i-th line is said to be present if t_i is greater than a given threshold. Then the probability of detecting line i, $PDET(i)$ is:

$$PDET(i) = Q\left[\frac{Q^{-1}(PFA) - |a_i|\sqrt{n_i w_i}}{1 + a_i}\right] \tag{6a}$$

$$\cong Q(Q^{-1}(PFA) - d(i)) \tag{6b}$$

Here PFA is the false alarm probability per decision and $d(i)$ is $|a_i|\sqrt{n_i w_i}$. The approximation holds when the a_i are small. Let X_i be 0 if it is decided the line is noise only and 1 otherwise. Then the probability that X_i equals 1 is PFA for noise only and PDET(i) when a signal is present; the signal will be detected only if at least m of the k X_i are 1. Since under both hypotheses the X_i are independent random variables, the overall detection and false alarm probabilities are easily found. Table I is a set of results for the wake-like signal. The final column is the ratio of signal amplitudes required by the MHT method and MF methods to achieve the same performance. It is noted for these detection and false alarm probabilities that a doubling of signal amplitudes (approximately) is required for the MHT to achieve results comparable to the MF (i.e., the optimum).

Table I Ratio of signal amplitudes using MHT and MF methods to achieve noted PDET and PFA. The location and sign of the signal is assumed known in the MHT domain.

	MHT		
DI	PDET	PFA	a_{MHT}/a_{MF}
6	.03	10^{-6}	2.09
	.36	10^{-4}	1.8
8.48	.25	10^{-6}	2.07
	.6	10^{-4}	2.12
13.4	.9	10^{-6}	2.24
	.995	10^{-4}	2.12

4.2.2 Signal Unknown Except Line Widths Approximately the Same

It is assumed here that the line widths are approximately the same and are known a priori. However, the location and sign of the a_i are unknown. This is a more realistic scenario than that of Section 4.2.1. The detection scheme is to decide that a line is present when the t_i statistic's absolute value is greater than a preassigned threshold. The probability of detecting line i is:

$$PDET(i) = Q\left[\frac{Q^{-1}(PFA/2) - |a_i|\sqrt{n_i w_i}}{1 + a_i}\right] \qquad (7a)$$

$$\cong Q(Q^{-1}(PFA/2) - d(i)) \qquad (7b)$$

The false alarm probability per decision is PFA. Calculations similar to those in Section 4.2.1 can be carried out to determine the probability of detecting individual lines and hence m of k lines for any m. Equations 6(b) and 7(b) are the same except that PFA must be divided by 2 in the latter because the signal's sign is no longer assumed known.

Equation 7(a) and 7(b) were used to calculate the expected number of signal lines detected for the wake-like signal of Figure 1(a). Typical values for a set of detection indexs of interest are given in Table II under the one- step column. The two-step column is discussed in the next section. The observed numbers of signal lines from a set of noisy images with the same detection indices are given in the column headed observed. In both cases the false alarm rate per decision is 3.7×10^{-5}. Good agreement is noted between the theory and illustrative examples.

Table II Theoretically expected and observed number of signal lines detected for the wake like signal of Figure 1. These quantities are functions of the detection index.

Detection Index	Observed	Expected Number of Signal Lines One Step*	Expected Number of Signal Lines Two Step**	Two Step Percent Increase
24	7	7.37	7.8	6
20	7	5.99	6.86	14
17	4	3.81	5.07	33
15	-	2.57	3.59	39
12	-	.97	1.25	28

*False alarm probability is 3.7×10^{-5} per decision.

**False alarm probability is 10^{-3} per decision at Step 2.

The other quantity of importance to determine is the expected number of image false lines as a function of PFA, the false alarm probability per decision. If NI is the number of independent decisions made when testing the image for lines, this expected number would be NI PFA. In this method the test statistics are not independent. Assume the discrete spatial image has pixel values one unit apart. Then for parellel lines of width one the statistics for line parameters (ρ_i, θ_j) and $(\rho + \Delta\rho,\ \theta)$ are independent if $\Delta\rho$ is greater than one, but the statistics for $(\rho,\ \theta)$ and $(\rho,\ \theta + \Delta\theta)$ are not (because these lines cross and thus contain common pixel values). Also, the statistics of overlapping lines of width W greater than one are correlated when either θ or ρ are incremented.

As it is very difficult, if not impossible, to find analytically the number of independent decisions, an empirical study was performed. The spatial images of concern were 512 pixels by 512 pixels. The intensity values at each point were independent. The rho increment was one and angle increment was one-half degree in the MHT. The number of ρ and θ values was 512 and 360 respectively. For lines of width one it was found that the ratio of observed false lines to expected false lines for independent decisions was 0.75 while for lines of width two this ratio was 0.35. Thus when the false alarm probability per decision is 3.7×10^{-5} the expected number of false lines is $(3.7 \times 10^{-5})(512)(360)(0.35) = 2.33$ per image.

4.3.3 Prior Signal Knowledge

An examination of Figure 1(b) reveals a characteristic feature of the lines which approximates the wake-like signal. Within each arm of the signal the lines are nearly parallel and are alternately darker and brighter than the background. The result in the Hough domain (Figure 3(b) is two signal regions (corresponding to the two signal arms). Within each region are alternating bright and dark areas. These areas have almost constant angle values and are close together in rho (Figure 3).

This prior knowledge is exploited in a two pass detection algorithm. Step One is as before, statistically significant lines of width two are found when the false alarm probability per decision is PFA1. At Step Two the area about the regions located in Step One is checked for lines opposite in amplitude using a higher false alarm probability per decision, PFA2. All lines from Steps One and Two are then displayed. The following finds the probability of detecting a line at Step One or Two. Let the probability of detecting line i at step j be $P(i,j)$ where $i = 1, 2, ..., 9$ and $j = 1, 2$. Then the probability of detecting line i, $PDET(i)$ is:

$$PDET(i) = P(i,1) + (1 - P(i,1))P_n(i)P(i,2) \tag{8}$$

Where

$P(i,1)$ = probability of detecting line i atStep 1

$P_n(i)$ = probability of detecting neighbouring lines to line i at Step 1

$P(i,2)$ = probability of detecting line i at Step 2.

From the previous definitions (Equations 6(b) and 7(b)),

$$P(i,1) = Q(Q^{-1}(PFA1/2) - d(i)) \tag{9}$$

$$P(i,2) = Q(Q^{-1}(PFA2) - d(i)) - Q(Q^{-1}(PFA1/2) - d(i)) \tag{10}$$

Also $P_n(i)$ can be shown to be a function of the Step 1 detection probabilities.

An area 5 wide in theta increments and 7 in rho increments centered at a signal line always encloses the neighbouring lines in the present empirical tests and was used for the Step 2 parameters. The results of this method are given in Table II under the two step column. The parameter PFA2 was 10^{-3}. Naturally the expected number of detected signal lines increases. The percent increase in expected signal lines for the two step as compared to the one step method is given in the last column.

The tradeoff is an increase in the number of false lines. Recall from Section 4.3.2 the expected number of false lines is 2.33 when the false alarm probability per decision is 3.7×10^{-5}. For each false line obtained at Step 1 a further 5×7 or 35 decisions are made with a false alarm probability per decision of PFA2. Again from Section 4.3.2 only $(35)(.35) = 12.25$ independent statistics are obtained. Hence the expected number of false lines for each false line found at Step 1 is $(12.25)(PFA2 - 1.8 \times 10^{-5})$. When PFA2 is 10^{-3} this equals .012 or only a 1.2% increase in expected false lines. In other words, relatively high values of PFA2 can be used in the method with little increase in the number of false lines.

5.0 DISCUSSION AND CONCLUSIONS

The MHT has been studied for the detection of signals which can be approximated by a set of non-overlapping straight lines. The standard deviation map is a technique which displays the statistical significance of each line. This means that constant detection and false alarm probabilities are obtained over the whole image.

Theory has been developed to allow the calculation of the probability of detecting each individual line as well as the probability of detecting m of k lines and the expected number of lines for an arbitrary signal whose MHT has been calculated. These are functions of the false alarm probability per decision and the signal parameters. The performance of this method was compared to that obtained with a matched filter.

The expected number of false lines per image is a function of the false alarm probability per decision, the MHT parameters, image dimensions and line width. It must be found empirically for each case.

The MHT method was applied to detect the wake-like signal of Figure 1(a). A simple reconstruction was employed which displayed all significant regions in the Hough domain as their corresponding lines in the spatial domain. The signal was recognizable for detection indices as low as 17. Such signals were just visible in the noisy spatial domain images with a good display system. A two-pass detection system was described which incorporates prior knowledge about the wake-like signal. This leads to improved performance.

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