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Detection and Parameter Extraction of Low Probability of Intercept Frequency Hopping Signals using the Spectrogram and the Reassigned Spectrogram

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Abstract

Digital intercept receivers are currently moving away from Fourier-based analysis and towards classical time-frequency analysis techniques, such as the Wigner-Ville distribution, Choi-Williams distribution, spectrogram, and scalogram, for the purpose of analyzing low probability of intercept radar signals (e.g. triangular modulated frequency modulated continuous wave and frequency shift keying). Although these classical time-frequency techniques are an improvement over the Fourier-based analysis, they still suffer from a lack of readability, due to cross-term interference, and a mediocre performance in low SNR environments. This lack of readability may lead to inaccurate detection and parameter extraction of these radar signals. In this paper, the use of the Hough transform, because of its ability to suppress cross-term interference, separate signals from cross-terms, and perform well in the presence of noise, is proposed as an improved signal analysis technique. With these qualities, the Hough transform has the potential to produce better readability and consequently, more accurate signal detection and parameter extraction metrics.

Index terms— radar detection, hough transform, low probability of intercept.

1 Introduction a) Frequency hopping techniques

low probability of intercept (LPI) radar that uses frequency hopping techniques changes the transmitting frequency in time over a wide bandwidth in order to prevent an intercept receiver from intercepting the waveform. The frequency slots used are chosen from a frequency hopping sequence, and it is this unknown sequence that gives the radar the advantage over the intercept receiver in terms of processing gain. The frequency sequence appears random to the intercept receiver, and so the possibility of it following the changes in frequency is remote **??**PAC09]. This prevents a jammer from reactively jamming the transmitted frequency [ADA04]. Frequency hopping radar performance depends only slightly on the code used, given that certain properties are met. This allows for a larger variety of codes, making it more difficult to intercept 1 Though classical time-frequency analysis techniques are a great improvement over Fourier analysis techniques, they may suffer from poor timefrequency localization, as described above. This may result in degraded readability of time-frequency representations, potentially leading to inaccurate LPI radar signal detection and parameter extraction metrics, and as such, can lead to decisions based on inaccurate information.

2 c) Reassignment method

A promising avenue for overcoming this deficiency is the utilization of the reassignment method. The reassignment method, which can be applied to most energy distributions [HIP00], has, in theory, a perfectly localized distribution for chirps, tones and impulses [BOA03], making it a good candidate for the analysis of certain

LPI radar signals, such as the triangular modulated frequency modulated continuous wave (FMCW) (which can be viewed as back-to-back chirps) and the frequency shift keying (FSK) (which can be viewed as tones).

3 d) Spectrogram and reassigned spectrogram

The spectrogram is defined as the magnitude squared of the STFT[BOA03], [HIP00], [HLA92], [MIT01], [PAC09]. For non-stationary signals, the STFT is usually in the form of the spectrogram [GRI08].

The STFT of a signal ??(??)is given in equation 2.5 as:?? ?? (??, ð ??"ð ??"; ?) = ? ??(??)? +? ?? (????)?? ??? 2??ð ??"ð ??"?? ???? (2.5)

Where ?(??) is a short time analysis window localized around ?? = 0 and ð ??"ð ??" = 0. Because multiplication by the relatively short window ?(?? ? ??) effectively suppresses the signal outside a neighborhood around the analysis point ?? = ??, the STFT is a 'local' spectrum of the signal ??(??) around ??. Think of the window ?(??) as sliding along the signal ??(??) and for each shift ?(?? ? ??) we compute the usual Fourier transform of the product function ??(??)?(?? ? ??) . The observation window allows localization of the spectrum in time, but also smears the spectrum in frequency in accordance with the uncertainty principle, leading to a trade-off between time resolution and frequency resolution. In general, if the window is short, the time resolution is good, but the frequency resolution is poor, and if the window is long, the frequency resolution is good, but the time resolution is poor.

The STFT was the first tool devised for analyzing a signal in both time and frequency simultaneously. For analysis of human speech, the main method was, and still is, the STFT. In general, the STFT is still the most widely used method for studying non-stationary signals **??**COH95].

The spectrogram (the squared modulus of the STFT) is given by equation 2.6 as:?? ?? (??, ð ??"ð ??") = ?? ??(??) +? ?? ?(?? ? ??)?? ??? 2??ð ??"ð ??"?? ????? 2 (2.6)

The spectrogram is a real-valued and nonnegative distribution. Since the window h of the STFT is assumed of unit energy, the spectrogram satisfies the global energy distribution property. Thus we can interpret the spectrogram as a measure of the energy of the signal contained in the time-frequency domain centered on the point (t, f) and whose shape is independent of this localization.

Here are some properties of the spectrogram: 1) time and frequency covariance -the spectrogram preserves time and frequency shifts, thus the spectrogram is an element of the class of quadratic time-frequency distributions that are covariant by translation in time and in frequency (i.e. Cohen's class); 2) time-frequency resolution -the time-frequency resolution of the spectrogram is limited exactly as it is for the STFT; there is a trade-off between time resolution and frequency resolution. This poor resolution is the main drawback of this representation; 3) interference structure -as it is a quadratic (or bilinear) representation, the spectrogram of the sum of two signals is not the sum of the two spectrograms (quadratic superposition principle); there is a crossspectrogram part and a real part. Thus, as for every quadratic distribution, the spectrogram presents interference terms; however, those interference terms are restricted to those regions of the time-frequency plane where the signals overlap. Thus if the signal components are sufficiently distant so that their spectrograms do not overlap significantly, then the interference term will nearly be identically zero[COH95], [HLA92], [ISI96].

The original idea of reassignment was introduced in an attempt to improve the spectrogram [OZD03]. As with any other bilinear energy distribution, the spectrogram is faced with an unavoidable trade-off between the reduction of misleading interference terms and a sharp localization of the signal components.

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We can define the spectrogram as a twodimensional convolution of the WVD of the signal by the WVD of the analysis window, as in equation 2.9:?? ?? (??, ð ??"ð ??"; ?) = ? ?? ?? +? ?? (??, ??)?? ? (?? ? ??, ð ??"ð ??" ? ??)???? ???? (2.9)

Therefore, the distribution reduces the interference terms of the signal's WVD, but at the expense of time and frequency localization. However, a closer look at equation 2.9 shows that ?? ? (?? ? ??, ð ??"ð ??" ? ??) delimits a time-frequency domain at the vicinity of the (??, ð ??"ð ??") point, inside which a weighted average of the signal's WVD values is performed. The key point of the reassignment principle is that these values have no reason to be symmetrically distributed around (??, ð ??"ð ??") , which is the geometrical center of this domain. Therefore, their average should not be assigned at this point, but rather at the center of gravity of this domain, which is much more representative of the local energy distribution of the signal [BOA03]. Reasoning with a mechanical analogy, the local energy distribution ?? ? (?? ? ??, ð ??"ð ??" ? ??)?? ?? (??, ??) (as a function of ?? and ??) can be considered as a mass distribution, and it is much more accurate to assign the total mass (i.e. the spectrogram value) to the center of gravity of the domain rather than to its geometrical center. Another way to look at it is this: the total mass of an object is assigned to its geometrical center, an arbitrary point which except in the very specific case of a homogeneous distribution, has no reason to suit the actual distribution. A much more meaningful choice is to assign the total mass of an object, as well as the spectrogram value, to the center of gravity of their respective distribution [BOA03]. This is exactly how the reassignment method proceeds: it moves each value of the spectrogram computed at any point (??, ð ??"ð ??") to another point (?? ,ð ??"ð ??"

?) which is the center of gravity of the signal energy distribution around (??, ð ??”ð ??”) (see equations 2.10 and 2.11) [LIX08]:?? (??; ??, ð ??”ð ??”) = ? ?? ?? ? (?????,ð ??”ð ??”???)?? ?? (??,??)???? ???? +? ?? ? ?? ? (?????,ð ??”ð ??”???)?? ?? (??,??)???? ???? +? ?? (2.10) ð ??”ð ??” ?(??; ??, ð ??”ð ??”) = ? ?? ?? ? (?? ? ??, ð ??”ð ??” ? ??)?? ?? (??, ??)???? ???? +? ?? ? ?? ? (?? ? ??, ð ??”ð ??” ? ??)?? ?? (??, ??)???? ???? +? ?? (2.11)

and thus leads to a reassigned spectrogram (equation (2.12)), whose value at any point (?? ? , ð ??”ð ??” ?) is the sum of all the spectrogram values reassigned to this point:?? ?? (??) (?? ? , ð ??”ð ??” ? ; ?) = ? ?? ?? +? ?? (??, ð ??”ð ??”; ?)????? ? ? ?? (??; ??, ð ??”ð ??”)??? ?ð ??”ð ??” ? ? ð ??”ð ??” ?(??; ??, ð ??”ð ??”)? ???? ??ð ??”ð ??” (2.12)

One of the most interesting properties of this new distribution is that it also uses the phase information of the STFT, and not only its squared modulus as in the spectrogram. It uses this information from the phase spectrum to sharpen the amplitude estimates in time and frequency. This can be seen from the following expressions of the reassignment operators: (??). This leads to an efficient implementation for the reassigned spectrogram without explicitly computing the partial derivatives of phase. The reassigned spectrogram may thus be computed by using 3 STFTs, each having a different window (the window function h; the same window with a weighted time ramp t*h; the derivative of the window function h with respect to time (dh/dt)). Reassigned spectrograms are therefore very easy to implement, and do not require a drastic increase in computational complexity.?? (??; ??, ð ??”ð ??”) = ? ??? ?? (

One of the most important properties of the reassignment method is that the application of the reassignment process to any distribution of Cohen's class theoretically yields perfectly localized distributions for chirp signals, frequency tones, and impulses, since the WVD does so also. As mentioned earlier, this is one of the reasons that the reassignment method can be chosen as a signal process analysis tool for analyzing LPI radar waveforms such as triangular modulated FMCW waveforms (which can be viewed as back-toback chirps) and FSK waveforms (which can be viewed as frequency tones).

The reassignment method provides readability improvement. The components are much better localized and very concentrated. In order to rectify the classical time-frequency analysis deficiency of poor time-frequency localization, there needs to be a method that produces more concentrated distributions, which the reassignment method does. This squeezing quality of the reassignment method lead to improved readability -which leads to more accurate metrics extractedwhich in turn, creates a more informed and safer intercept receiver environment.

5 II.

6 Methodology

The methodologies detailed in this section describe the processes involved in obtaining and comparing metrics between the classical time-frequency analysis technique of the spectrogram vs. the reassigned spectrogram, for the detection and characterization of low probability of intercept frequency hopping radar signals.

The tools used for this testing were: MATLAB (version 8.3), Signal Processing Toolbox (version 6.21), Wavelet Toolbox (version 4.13), Image Processing Toolbox (version 9.0), Time-Frequency Toolbox (version 1.0) (http://tftb.nongnu.org/).

All testing was accomplished on a desktop computer (Dell Precision T1700; Processor -Intel Xeon CPU E3-1226 v3 3.30GHz; Installed RAM -32.0GB; System type -64-bit operating system, x64-based processor).

Testing was performed for the 4 component frequency hopping waveform, whose parameters were chosen for academic validation of signal processing techniques. Due to computer processing resources they were not meant to represent real-world values. The number of samples for each test was chosen to be 512, which seemed to be the optimum size for the desktop computer. Testing was performed at three different SNR levels: 10dB, 0dB, and the lowest SNR at which the signal could be detected. The noise added was white Gaussian noise, which best reflects the thermal noise present in the IF section of an intercept receiver [PAC09]. Kaiser windowing was used, when windowing was applicable. 100 runs were performed for each test, for statistical purposes. The plots included in this paper were done at a threshold of 5% of the maximum intensity and were linear scale (not dB) of analytic (complex) signals; the color bar represented intensity. The signal processing tools used for each task were the spectrogram and the reassigned spectrogram.

The 4 component frequency hopping signal (prevalent in the LPI arena [AMS09]) had the following parameters: sampling frequency=5KHz; carrier frequencies=1KHz, 1.75KHz, 0.75KHz, 1.25KHz; modulation bandwidth=1KHz; modulation period=.025sec.

After each particular run of each test, metrics were extracted from the time-frequency representation. The different metrics extracted were as follows:

Plot (processing) time: Time required for plot to be displayed.

Percent detection: Percent of time signal was detectedsignal was declared a detection if any portion of each of the signal components (4 signal components for frequency hopping) exceeded a set threshold (a certain percentage of the maximum intensity of the timefrequency representation).

Threshold percentages were determined based on visual detections of low SNR signals (lowest SNR at which the signal could be visually detected in the timefrequency representation) (see Figure 1). For visually detected low SNR plots (like this one), the percent of max intensity for the peak z-value of each of the signal components

was noted (here 98%, 78%, 75%, 63%), and the lowest of these 4 values was recorded (63%). Ten test runs were performed for both timefrequency analysis tools (spectrogram and reassigned spectrogram) for this waveform. The average of these recorded low values was determined and then assigned as the threshold for that particular time-frequency analysis tool. Note -the threshold value assigned for the spectrogram was 60%. For percent detection determination, these threshold values were included in the time-frequency plot algorithms so that the thresholds could be applied automatically during the plotting process. From the threshold plot, the signal was declared a detection if any portion of each of the signal components was visible (see Figure 2). Modulation bandwidth: Distance from highest frequency value of signal (at a threshold of 20% maximum intensity) to lowest frequency value of signal (at same threshold) in Y-direction (frequency).

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The threshold percentage was determined based on manual measurement of the modulation bandwidth of the signal in the time-frequency representation. This was accomplished for ten test runs of each time-frequency analysis tool (spectrogram and reassigned spectrogram), for the 4 component frequency hopping waveform. During each manual measurement, the max intensity of the high and low measuring points was recorded. The average of the max intensity values for these test runs was 20%. This was adopted as the threshold value, and is representative of what is obtained when performing manual measurements. This 20% threshold was also implemented for determining the modulation period and the time-frequency localization (both are described below).

For modulation bandwidth determination, the 20% threshold value was included in the time-frequency plot algorithms so that the threshold could be applied automatically during the plotting process. From the threshold plot, the modulation bandwidth was manually measured (see Figure **??**). From this threshold plot, the modulation period was measured manually from the left side of the signal (left red arrow) to the right side of the signal (right red arrow) in the x-direction (time). This was done for all 4 signal components, and the average value was determined.

Time-frequency localization: From Figure 6, the time-frequency localization is a manual measurement (at a threshold of 20% maximum intensity) of the 'thickness' (in the y-direction) of the center of each of the 4 frequency hopping signal components, and then the average of the 4 values are determined. The average frequency 'thickness' is then converted to: percent of the entire y-axis. Lowest detectable SNR: The lowest SNR level at which at least a portion of each of the signal components exceeded the set threshold listed in the percent detection section above.

For lowest detectable SNR determination, these threshold values were included in the time-frequency plot algorithms so that the thresholds could be applied automatically during the plotting process. From the threshold plot, the signal was declared a detection if any portion of each of the signal components was visible.

The lowest SNR level for which the signal was declared a detection is the lowest detectable SNR (see Figure **??**).

The data from all 100 runs for each test was used to produce the actual, error, and percent error for each of these metrics listed above.

The metrics from the spectrogram were then compared to the metrics from the reassigned spectrogram. By and large, the reassigned spectrogram outperformed the spectrogram, as will be shown in the results section. 1, the reassigned spectrogram outperformed the spectrogram in average percent error: carrier frequency (0.74% vs. 0.93%), modulation bandwidth (10.82% vs. 25.70%), modulation period (9.30% vs. 11.84%), and time-frequency localization (ydirection) (4.05% vs. 9.09%);and in average: percent detection (86.84% vs. 67.24%), and lowest detectable SNR (-3.5db vs. -2.7db), while the spectrogram outperformed the reassigned spectrogram in average plot time (4.72s vs. 7.62s).

Figure **??** shows comparative plots of the spectrogram vs. the reassigned spectrogram (4 component frequency hopping) at SNRs of 10dB (top), 0dB (middle), and -3dB (bottom). IV.

8 Discussion

This section will elaborate on the results from the previous section.

From Table 1, the performance of the spectrogram and the reassigned spectrogram will be summarized, including strengths, weaknesses, and generic scenarios in which each particular signal analysis tool might be used.

The spectrogram outperformed the reassigned spectrogram in average plot time (4.72s vs 7.62s). However, the spectrogram was outperformed by the reassigned spectrogram in every other category. The spectrogram's extreme reduction of cross-term interference is grounds for its good plot time, but at the expense of signal localization (i.e. it produces a 'thicker' signal (as is seen in Figure **??**) -due to the trade-off between cross-term interference and signal localization). This poor signal localization ('thicker' signal), coupled with the reassigned spectrogram's 'squeezing' quality, can account for the spectrogram being outperformed by the reassigned spectrogram in the areas of: average percent error of modulation bandwidth, modulation period, time-frequency localization (y-direction), lowest detectable SNR, and percent detection. Note that average percent detection and lowest detectable SNR are both based on visual detection in the time-frequency representation. Figure **??** clearly

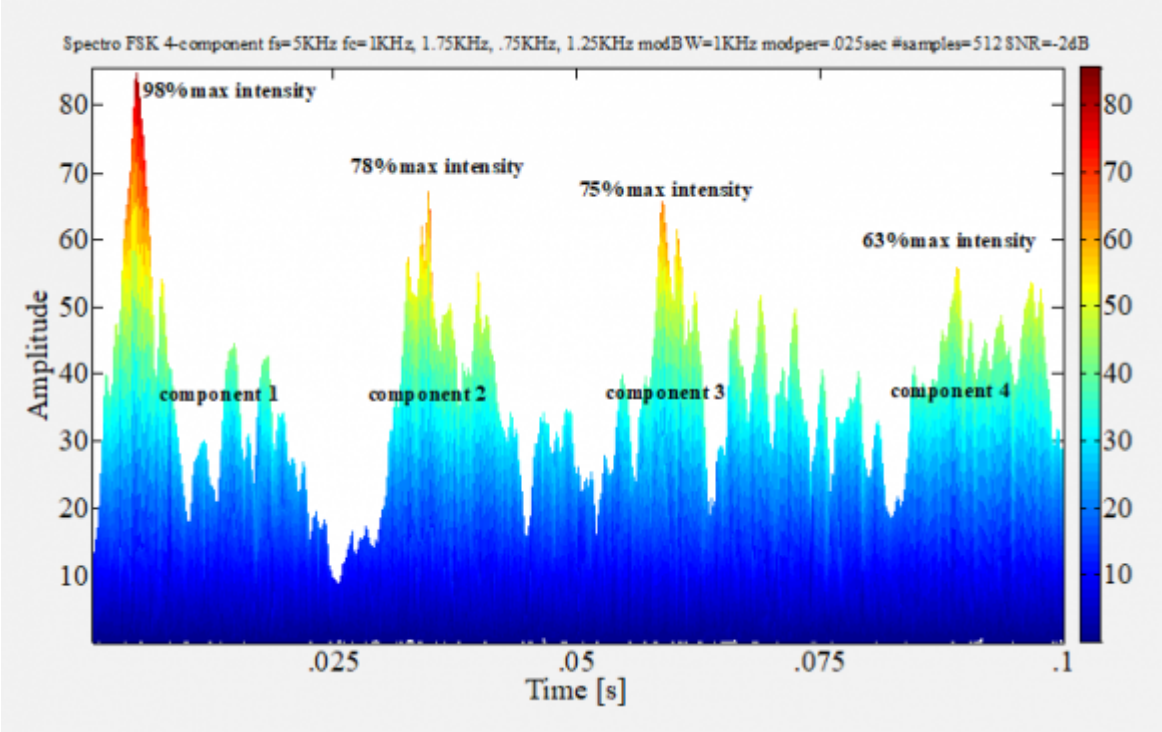
shows that the signals in the reassigned spectrogram plots are more readable than those in the spectrogram plots, which accounts for the reassigned spectrogram's better average percent detection and lowest detectable SNR. The spectrogram might be used in a scenario where a short plot time is necessary, but where accurate parameters are not as vital. Such a scenario might be a 'quick and dirty' check to see if a signal is present, without accurate extraction of its parameters. The reassigned spectrogram might be used in a scenario where you need accurate parameters, in a low SNR environment, in a quick time frame.

V.

9 Conclusions

Digital intercept receivers, whose main job is to detect and extract parameters from low probability of intercept radar signals, are currently moving away from Fourier-based analysis and towards classical timefrequency analysis techniques, such as the spectrogram, for the purpose of analyzing low probability of intercept radar signals. Based on the research performed for this paper (the novel direct comparison of the spectrogram versus the reassigned spectrogram for the signal analysis of low probability of intercept frequency hopping radar signals) it was shown that the reassigned spectrogram by-and-large outperformed the spectrogram in analyzing these low probability of intercept radar signals -for reasons brought out in the discussion section above. More accurate characterization metrics could well translate into saved equipment and lives.

Future plans include analysis of additional low probability of intercept radar waveforms, using additional time-frequency analysis and reassignment method techniques. [1]



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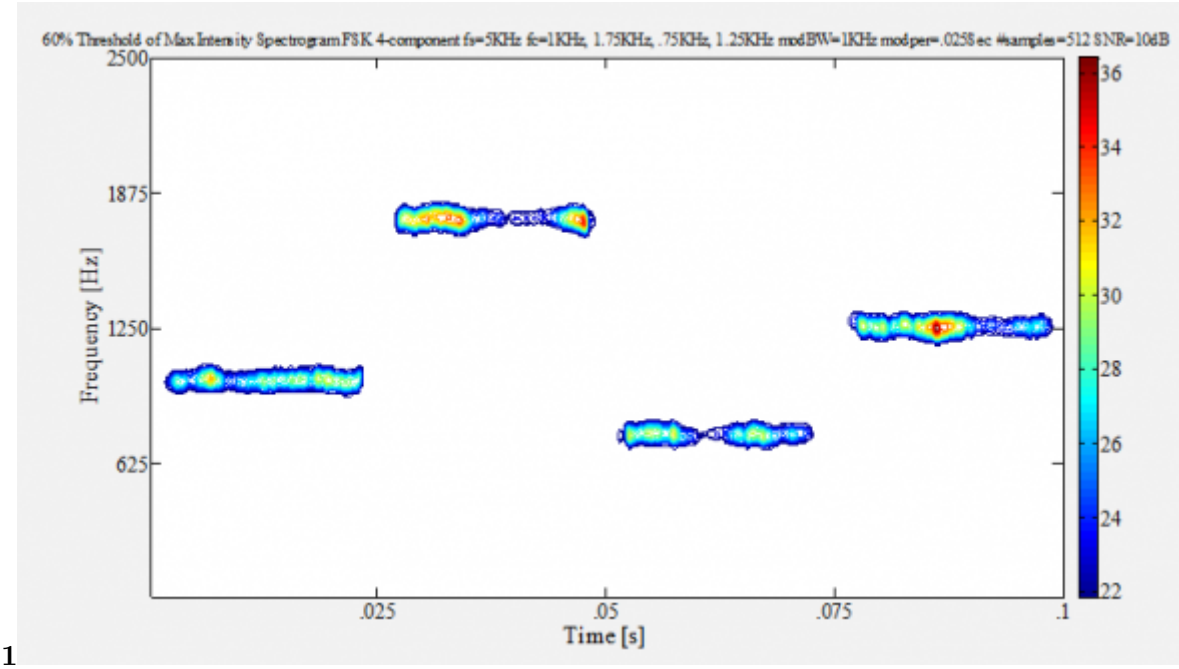

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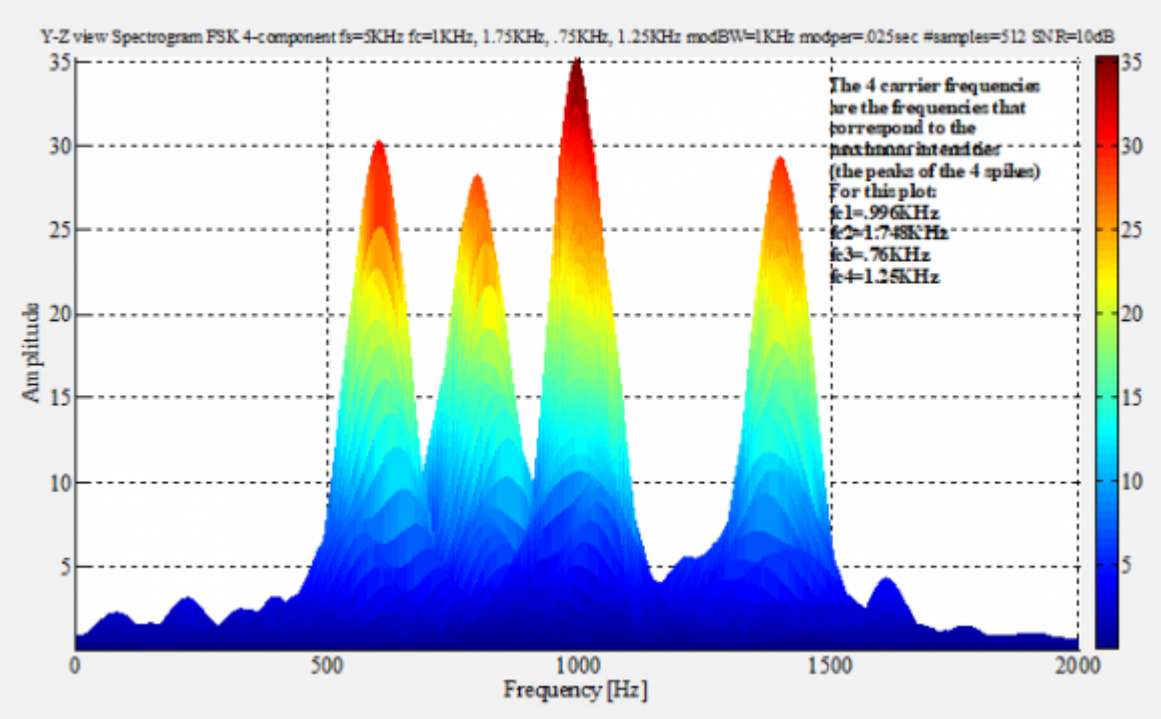
Figure 2: Figure 1 :



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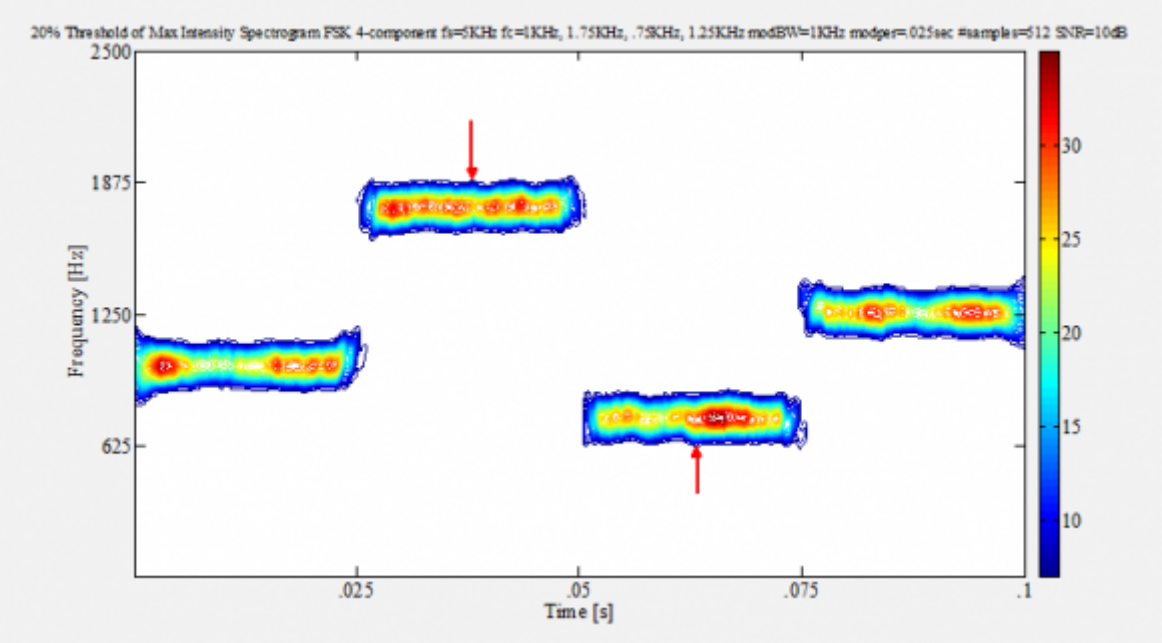

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Figure 4: Figure 2 :

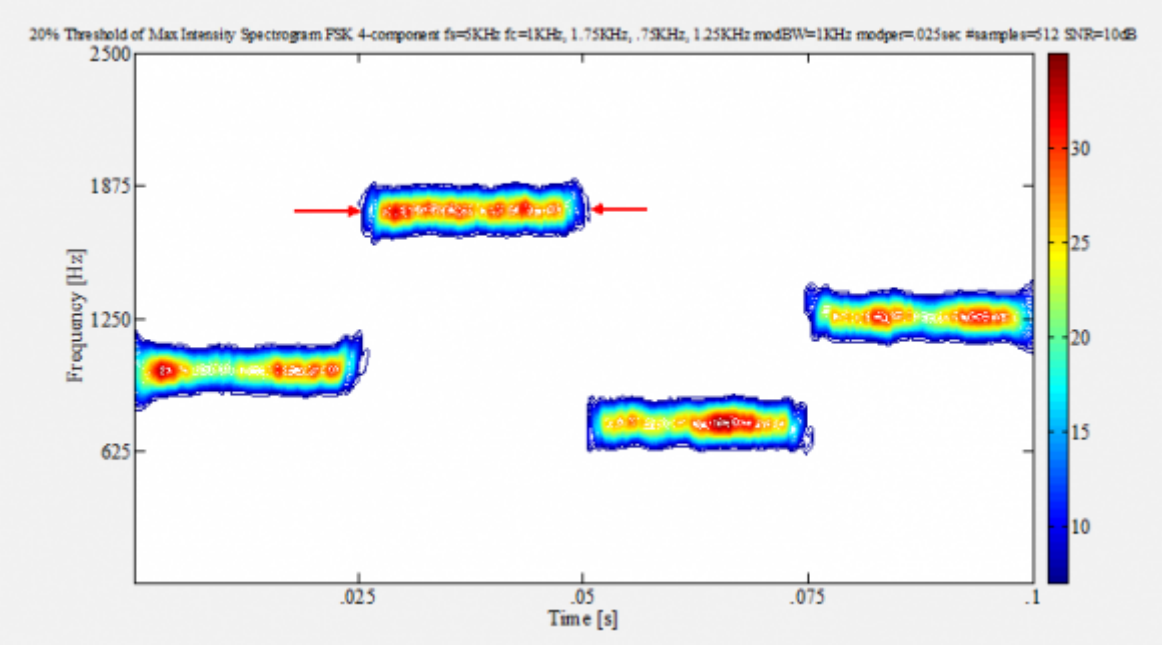

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Figure 5: Figure 3 :

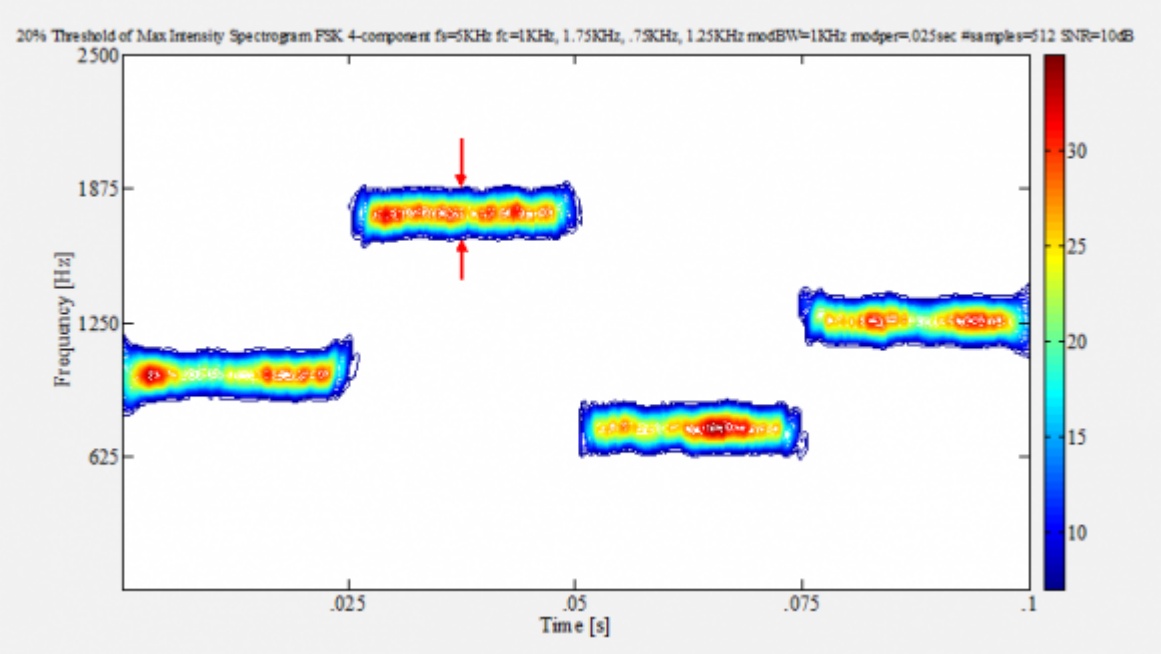

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Figure 6: Figure 4 :Figure 5 :

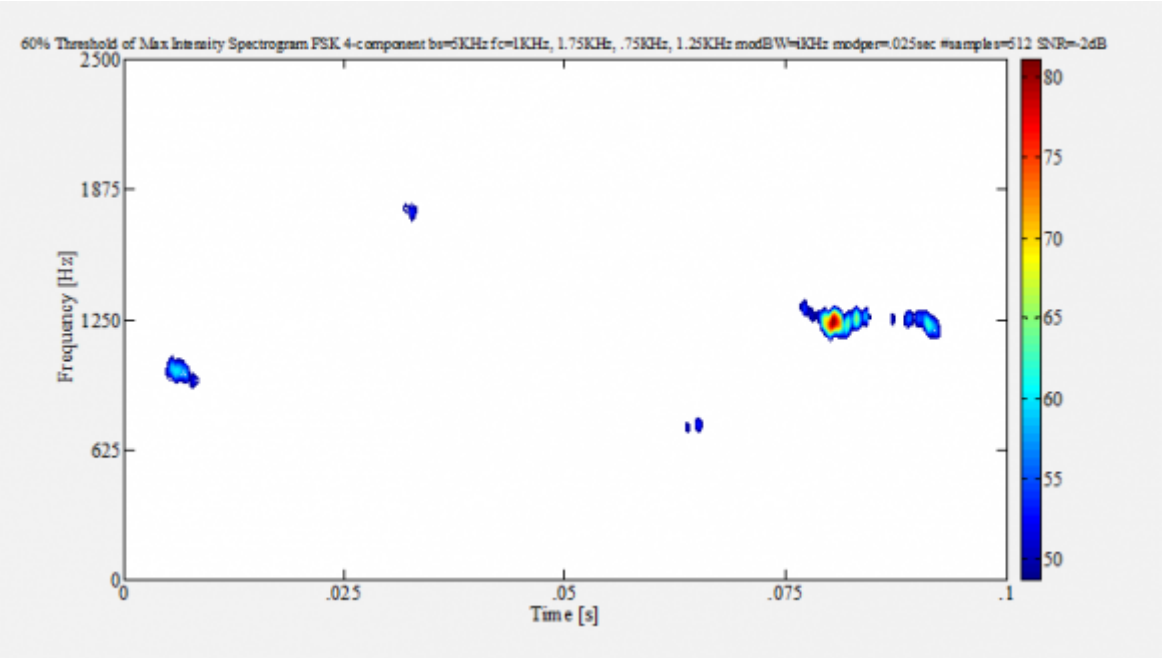

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Figure 7: Figure 6 :

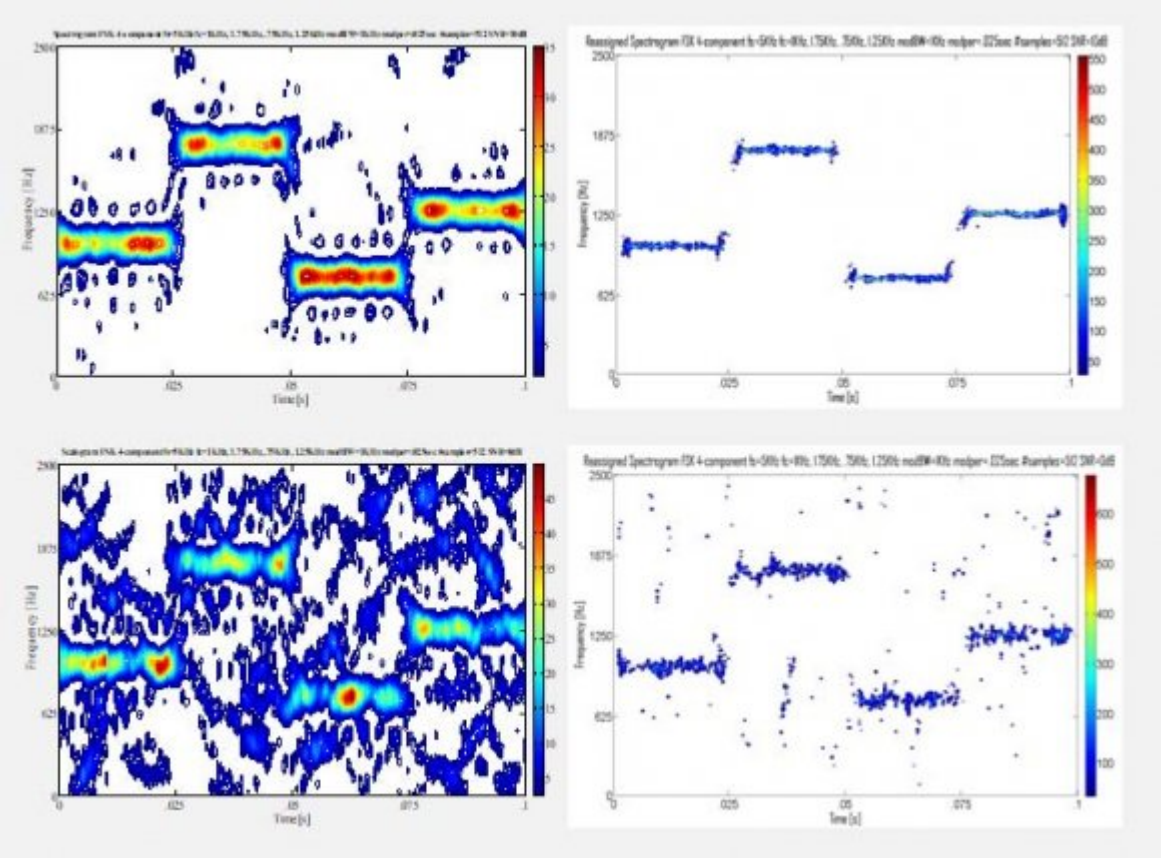

Figure 8:

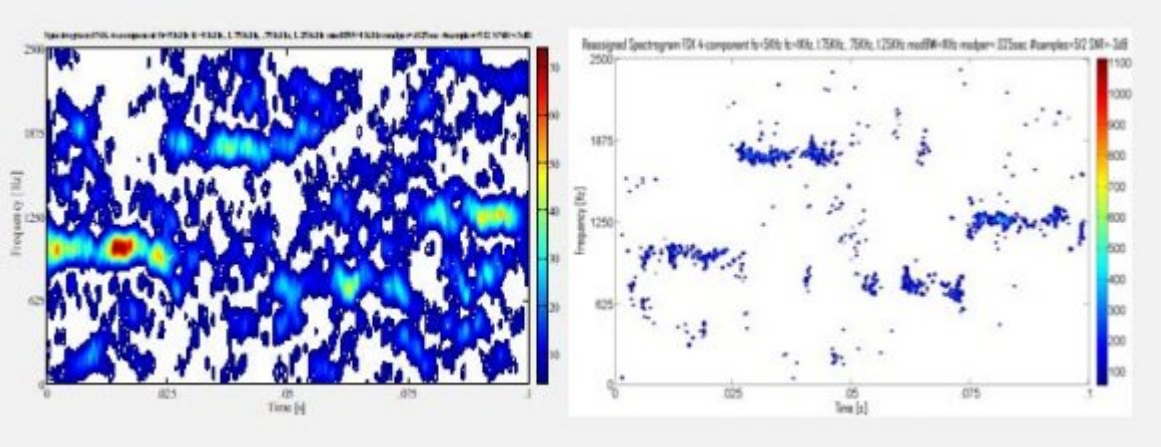

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Figure 9: Figure 7 :Figure 8 :

1

presents the overall test metrics for the
signal processing analysis techniques used in this
testing (spectrogram versusre assigned spectrogram).

Figure 10: Table 1

1

carrier frequency	0.93%	0.74%
modulation bandwidth	25.70%	10.82%
modulation period	11.84%	9.30%
time-frequency localization-y	9.09%	4.05%
percent detection	67.24%	86.84%
lowest detectable snr	-2.7db	-3.5db
plottime	4.72s	7.62s

From Table

Figure 11: Table 1 :

[Xia and Chen (1999)] 'A Quantitative SNR Analysis for the Pseudo Wigner-Ville Distribution'. X Xia , V Chen . *IEEE Transactions on Signal Processing* October, 1999. 47 (10) p. .

[Wei et al. (2003)] 'Analysis of Multicomponent LFM Signals Using Time-Frequency and The Gray-Scale Inverse Hough Transform'. G Wei , S Wu , E Mao . *IEEE Workshop on Statistical Signal Processing* September 28 -October 1, 2003. p. .

[Conference Record of the Twenty-Eighth Asilomar Conference on Signals, Systems and Computers ()] *Conference Record of the Twenty-Eighth Asilomar Conference on Signals, Systems and Computers*, 1994. p. .

[Pac09] ace ()]b6 *Detecting and Classifying Low Probability of Intercept Radar*, [Pac09] Pace , P . 2009. Norwood, MA: Artech House.

[Papandreou et al.] *Detection and Estimation of Generalized Chirps Using Time-Frequency Representations*, A Papandreou , G F Boudreaux-Bartels , S Kay .

[Mitra ()] *Digital Signal Processing, A Computer-Based Approach, Second Edition*, S Mitra . 2001. Boston, MA: McGraw-Hill.

[Rangayyan and Krishnan ()] 'Feature Identification in the Time-Frequency Plane by Using the Hough-Radon Transform'. R Rangayyan , S Krishnan . *Pattern Recognition* 2001. 34 p. .

[Li and Bi ()] X Li , G Bi . *A New Reassigned Time-Frequency Representation. 16 th European Signal Processing Conference*, (Lausanne, Switzerland) August 25-29, 2008. p. .

[Hlawatsch and Boudreaux-Bartels (1992)] 'Linear and Quadratic Time-Frequency Signal Representations'. F Hlawatsch , G F Boudreaux-Bartels . *IEEE Signal Processing Mag* April 1992. 9 (2) p. .

[Li and Xiao (2003)] 'Recursive Filtering Radon-Ambiguity Transform Algorithm for Detecting Multi-LFM Signals'. Y Li , X Xiao . *Journal of Electronics (China)* May 2003. 20 (3) p. .

[Ozd03] zdemir (2003)]b5 *Time-Frequency Component Analyzer. Dissertation*, [Ozd03] Ozdemir , A . Sept. 2003. Ankara, Turkey. Bilkent University

[Auger et al. ()] *Time-Frequency Toolbox Users Manual*, F Auger , P Flandrin , P Goncalves , O Lemoine . 1996. Centre National de la Recherche Scientifique and Rice University