# The Future of EW and Modern Radar Signals

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# The Signal Environment

- The period since WWII has seen the deployment of large number of pulsed radars, seekers and other threat systems in the microwave bands

- Recently newer, high duty factor or CW systems have been deployed.

- The reduction in peak power makes EW more difficult (but not impossible)

# Tomorrow's Threats plus Yesterday's and Today's

- There is a trend to long duration, low peak power signals to make them less vulnerable

- But older systems will still be used, too.

- Therefore EW systems must operate when both the high power, short duration signals as well as low power long duration signals are present

- Today's EW Receivers are optimized for Yesterday's Threat Environment

# Modern Signals are Different

- "LPI" Radars are being deployed which use long duration pulses and pulse compression
- The next generation of EW equipment must be able to cope with these threats

# Low probability of ID

- The threat recognition process can clearly be disrupted by transmitting unexpected parameters.

- Using parameters similar to another non-threatening radar is one example

- Introducing parameter agility is another

- These will probably deceive the opponent only for a short time

# Low Probability of Interception

- Another is to try to make the signal so weak that the ESM system cannot detect it.

- As we will see, for radar this can be difficult.  It is this aspect that we will spend most of our time examining

- Spread Spectrum is a term used in communications.  (I say it does not apply to radar!)

# Radar is not "Spread Spectrum"

- In communications, the transmitted spectrum is spread over an arbitrarily wide band. The spreading is removed in the receiver. The interceptor may not be able to detect the wideband signal in noise.

- In radar, the transmitted bandwidth determines range resolution. Wideband signals break up the echo and thus reduce target detectability
  - what you transmit is what you get back
  - synchronizing the receiver *is* the ranging process

# Modern Radar Waveforms

- Energy on target, not peak power determines radar performance

- A CW radar has peak power 30 dB lower than a pulsed radar with a duty factor of .001, e.g. 1 microsecond Pulse Duration and 1 millisecond PRI.

- Frequency or Phase Modulation is needed to obtain the desired Range Resolution

# Intercepting Modern Radar

- Lower Peak Power helps the radar

- Earlier Radar designs were concerned with target detection and with ECM

- Today's radar designs are also concerned with Countering ESM (Intercept Receivers)

- Tomorrow's Intercept Receivers must cope with new types of Radar Signals

# CW Radar Reduces Peak Power

Power

Pulse-High Peak Power

CW--Low Peak Power

Time
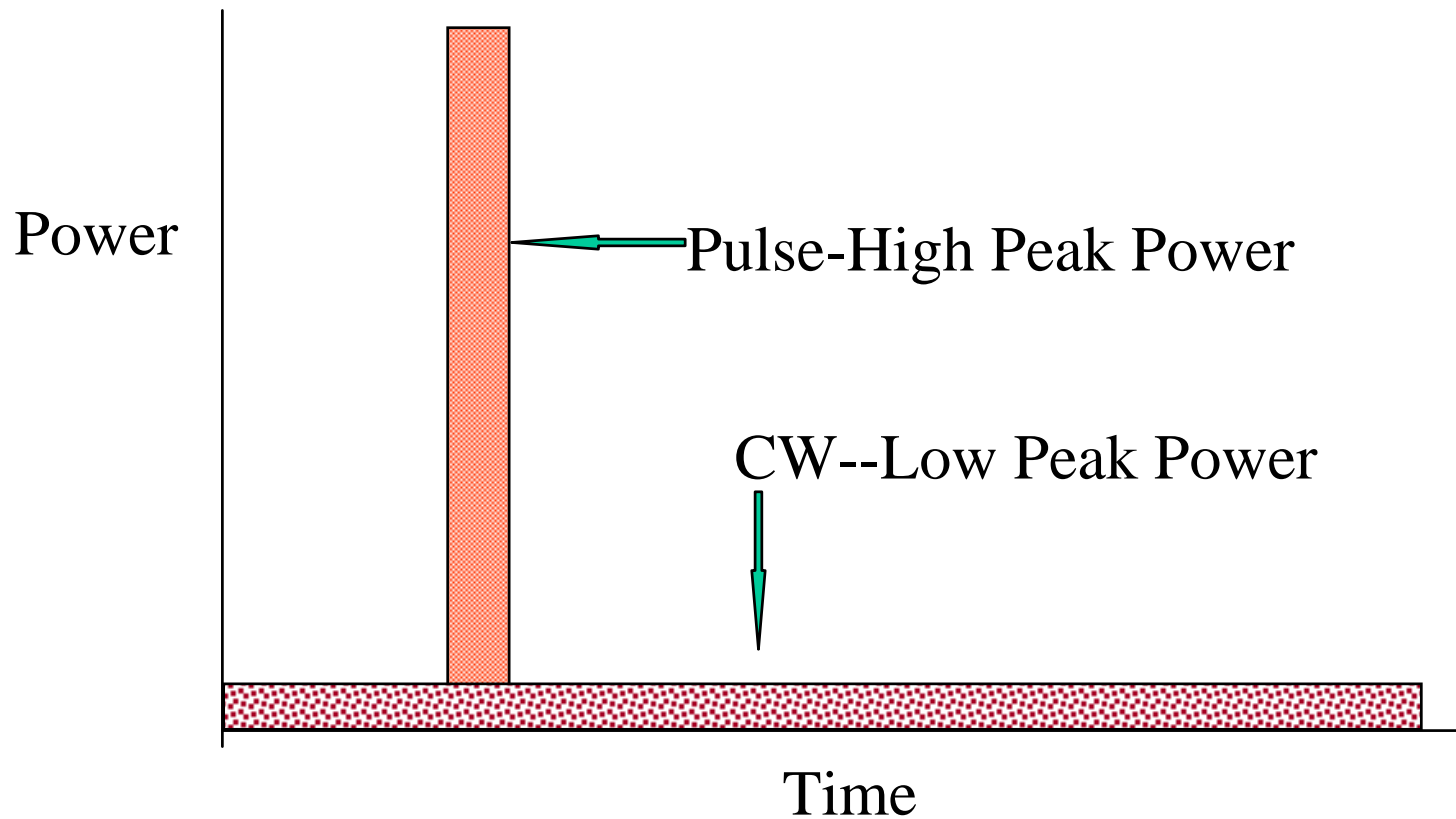
# History of LPI Radar

- Hughes/MICOM 1980s CW/Phase coded with separate antennas for Tx and Rx. Dev. model only (17Km for 3 sq m target) Later versions were built by other companies.

- Phillips Laboratory-UK devised FM/CW scheme for cancellation of leakage to allow simultaneous Tx/Rx (late 80s)

- Phillips broken up in early 90s. CelsiusTech in Sweden and Signaal in Holland market FM/CW systems

# Today's LPI Radars

- ## Netherlands

  - Signaal: Squire Portable Battlefield Surv. (Man @10km, jeep@16 km); Scout FMCW Naval/Coastal Border Surv. (Ship/Truck mount); Page FMCW Gap filler SHORAD (manpack and other platforms available) (fighter at 16 KM)

- ## Sweden

  - CelciusTech: Pilot FMCW, Shipboard, RF Switch to use existing T/R and Antenna or LPI (1MW-1W)

  - Ericsson: HARD (60W peak power in Whispering mode) used for SHORAD

- ## FGAN (Germany) OLPI-- Dev. Model

# Random Signal Radar

- Chinese authors publish IEEE-AES paper, July 1999. Reviews history since 1960

- Reviews types of random signal radar

- Author Guosui holds a Chinese patent on a Random FMCW fuse issued in 1987.

- Projects future growth due to availability of DSP and the need for counter-ESM

# LPI Radar Sensor

- April 2000 AES Systems Magazine

- Authors from Spain

- Propose Frequency Hop waveforms as better for LPI than LFM or PSK when the intercept receiver uses cyclo-stationary spectrum Analysis

# Deployed LPI Radars
## (Last updated in1998)

- Scout: over 130 deployed (per MSSC)

- Squire: Development being completed. Project over 1000 units in 5 years (MSSC)

- Page:  Production expected in 2002 (MSSC)

- Pilot:  less than 50 deployed (CelsiusTech)

- Hard: (Ericsson)

- MICOM: Laboratory only

- FGAN: OLPI, Laboratory only

# Range Equations

Signal received from the target by the radar receiver varies as range to the -4 power

$$S_R = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$$

Signal received at the ESM receiver varies as range to the -2 power

$$S_E = \frac{P_t G_t G_E \lambda^2}{(4\pi)^2 R_E^2}$$

# Receiver Sensitivities Compared

The radar receiver needs certain minimum
signal level to do its job.

Likewise the ESM receiver needs a certain minimum
signal level to do its job.

We can compare these:

$$\delta = \frac{S_{E(\min)}}{S_{R(\min)}} \sim \frac{NoiseBWofInt.Rx.}{NoiseBWofRadarRx}$$

# Intercept Range/Radar Range

$$\frac{R_E}{R_R} = R_R \left[ \frac{4\pi}{\delta} \bullet \frac{1}{\sigma} \bullet \frac{G_{TE}G_E}{G_T G_R} \bullet \frac{L_E}{L_R} \right]^{1/2} \quad (1)$$

Note that the ratio of the radar receiver sensitivity
to the ESM receiver sensitivity is in the denominator;
if the radar receiver is more sensitive the ratio of the
ESM range to the Radar range is reduced

# Plot of the Range Ratio
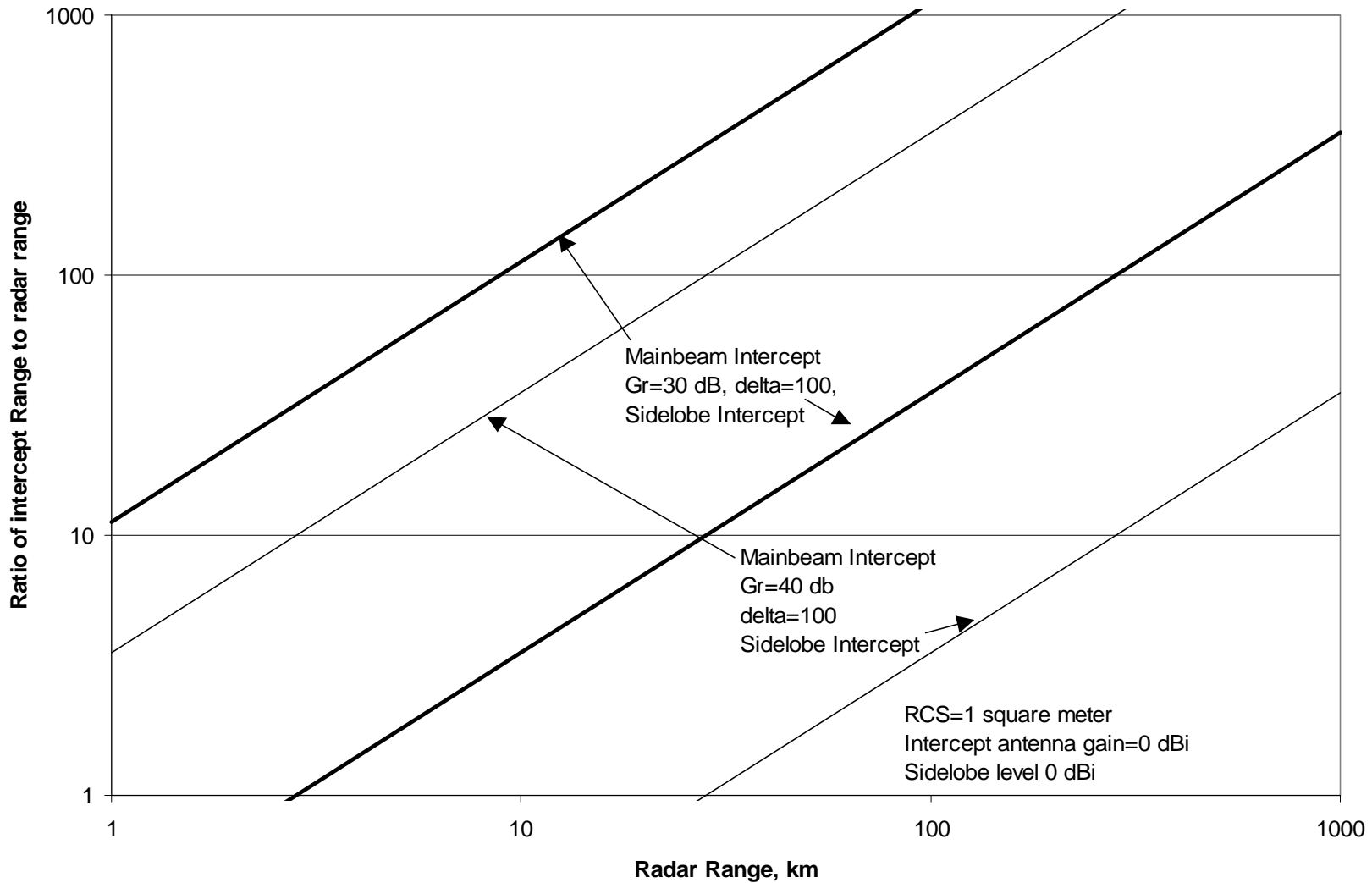
# Example for Existing Designs

- RCS =1 sq meter
- Rx Ant Gain =1, Sidelobe Tx Ant. Gain=1
- ESM Rx 20 dB less sensitive than Radar Rx
- Then the Sidelobes of the Radar can be detected at a range of over 30 times the range at which the radar can detect a target
- Main beam detection over1000 times Radar Range

# Future ESM Receivers

- 10-30 dB Sensitivity enhancement needed to cope with modern FMCW radar threats

- One way is to use narrow beam, high gain antennas

  - then a number of receive channels is needed to cover a given angular sector.  Number of receivers and antennas is equal to the antenna gain, i.e.10 to 1000

- Another way is through signal processing

# Klipper Equations

A way to relate Pre-D SNR and Video SNR

$$SNR_{out} := \frac{\left(SNR_{in}\right)^2}{2 \cdot \left(\dfrac{B_v}{B_r}\right) - \left(\dfrac{B_v}{B_r}\right)^2 + 4 \cdot \left(\dfrac{B_v}{B_r}\right) \cdot \left(SNR_{in}\right)}$$

$$SNR_{in} := \frac{2 \cdot SNR_{out}}{\dfrac{B_r}{B_v}} \cdot \left[1 + \left[1 + \frac{2 \cdot \left(\dfrac{B_r}{B_v}\right) - 1}{4 \cdot \left(SNR_{out}\right)}\right]^{\frac{1}{2}}\right]$$

# Klipper Equation Example

$$\text{SNR}_{\text{in}} = -1.8 \quad \text{dB}$$

$$\text{B}_{\text{v}} = 6.25 \cdot 10^{6} \quad \text{Hz}$$

$$\text{B}_{\text{r}} = 1 \cdot 10^{9} \quad \text{Hz}$$

$$\text{SNR}_{\text{out}} = 11.78 \quad \text{dB}$$

# Klipper Equation Comments

- Output SNR is the ratio of the signal envelope power to the noise power at the output of the detector

- Output SNR is not directly useable to obtain Pd and Pfa values from the usual curves

- The Tsui/Albersheim approximations provide the input SNR required to obtain specified Pd and Pfa values.

# Klipper Equation related to Effective Bandwidth

RAS

- Consider the case where (SNR in) is much less than one and RF Bandwidth is much larger than Video Bandwidth:

$$SNR_{out} := \left(SNR_{in}\right)^2 \cdot \frac{B_r}{B_v}$$

$$SNR_{out} := \left(\frac{S_{in}}{FkTB_r}\right)^2 \cdot \frac{B_r}{2\,B_v}$$

$$SNR_{out} := \frac{\left(S_{in}\right)^2}{\left(FkT \cdot \sqrt{2\,B_v\,B_r}\right)^2}$$

For a Square law detector SNR out is proportional to the square of SNR in

# Post-Detection Filtering Improves Output SNR

- Improvement is approximately the square root of the ratio of the predetection bandwidth to twice the post-detection bandwidth (Linear Detector)

- Improvement is relative to the SNR in the Input Band

# Frequency/Time for Modern Radar Signals



Frequency Agility Band

(Depends on Component Design, ECM Factors, Designer Ingenuity)

Frequency

Coherent Processing Interval
(depends on radar mission)

Time
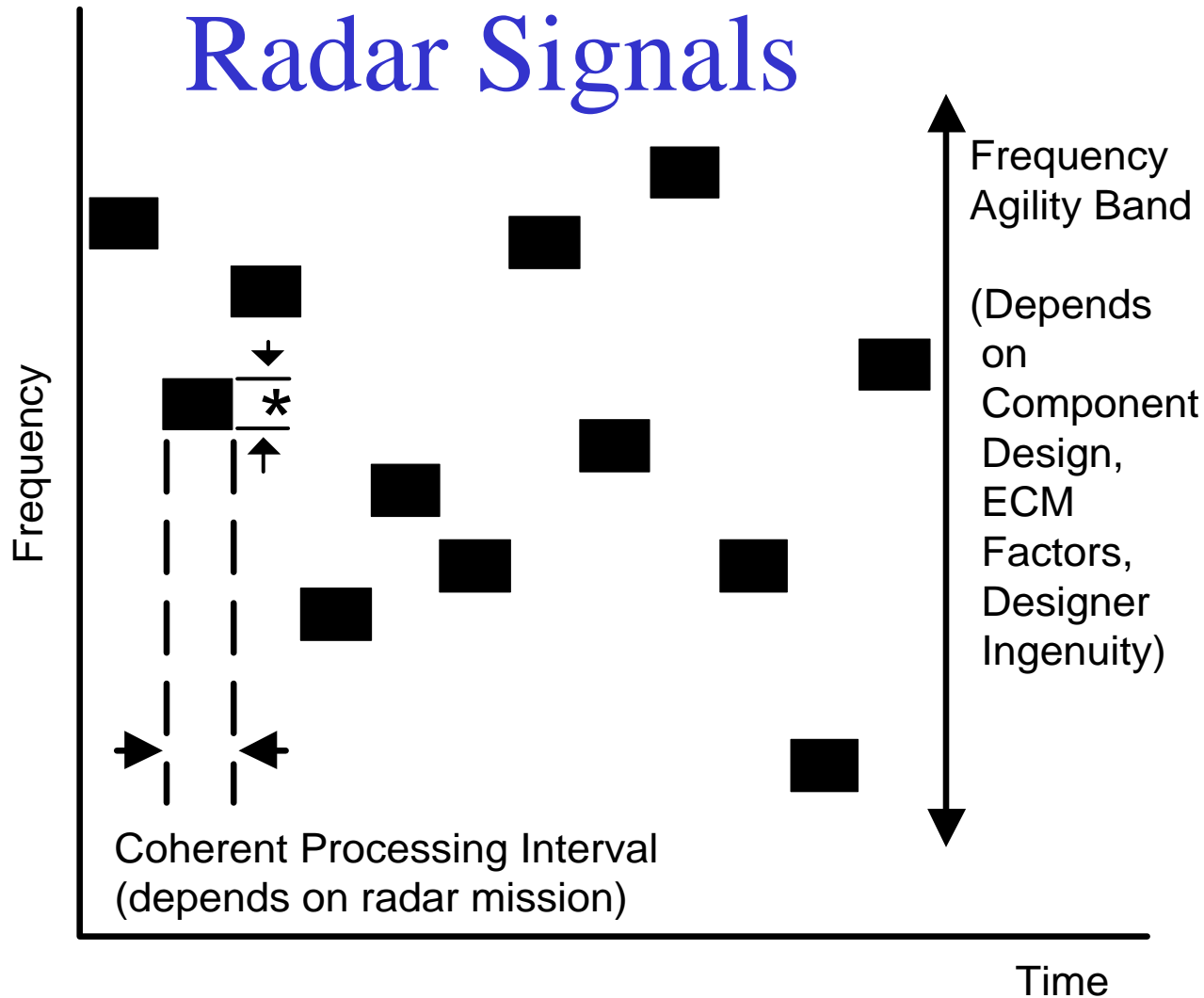
*Bandwidth Determines Range Resolution Which Depends on Radar Mission

# Types of "LPI" Radar Modulation

- FMCW ("Chirp")
- Phase Reversals (BPSK)
- Other Phase Modulations (QPSK, M-ary PSK)
- In short, any of the pulse compression modulations used by conventional radar.

# "LPI" Radar "Codes"

- True Noise (From a noise source, stored for later correlation in the radar receiver)

- Pseudonoise (nearly unpredictable unless the interceptor has the algorithm and key)

- The code must have good ambiguity properties in range and Doppler. Unpredictability is a plus.

# ESM Receiver Strategies

- Detection of a random signal radar using only the energy has the advantage that the detection performance is largely independent of the radar waveform

- Detection based on specific properties of the radar signal can be more efficient

- Radar usage of code/modulation diversity may defeat ESM designed for specific signal properties

# Range Comparisons for Pilot Radar

| Target Cross-section | Radar Range (km) | | ESM Sensitivity | ESM Range (km) | |
|---|---|---|---|---|---|
| (m$^2$) | 10KW Pulsed Radar | 1W FMCW Radar | -dBmi | 10KW Pulsed Radar | 1W FMCW Radar |
| 10 | 15 | 16 | -60 | 250 | 2.5 |
| 100 | 26 | 28 | -80 | 2,500 | 25 |
| 1,000 | 46 | 0 | | | |

Intercept Range/Radar Range=2.5/16=.156
=25/28=.893

# Signal Processing Techniques

- Non-coherent methods (radiometer) use average power over times comparable to radar's integration time, e.g., milliseconds (10-15 dB improvement)

- Coherent methods which use "nearly matched" filters, e.g., Wigner Hough Transform for linear FM signals (15-25 dB improvement)

- Cross Correlation method

# Non-coherent Approach

- Rapid Sweep Superhet Receiver (RSSR) proved usefulness of noncoherent or post-detection integration against LPI signals

- Technique should be routinely applied to processing wideband receiver outputs for discovering LPI signals

- Sensitivity improves with square root of n, number of sweeps per pulse

- Hough transform can be applied when chirp exceeds processor IF bandwidth

# Frequency Versus Time: Environment and RSSR Sweeps



Detection announced using 4 of 8 rule

Frequency (MHz)

2000 MHz

Time (µs)
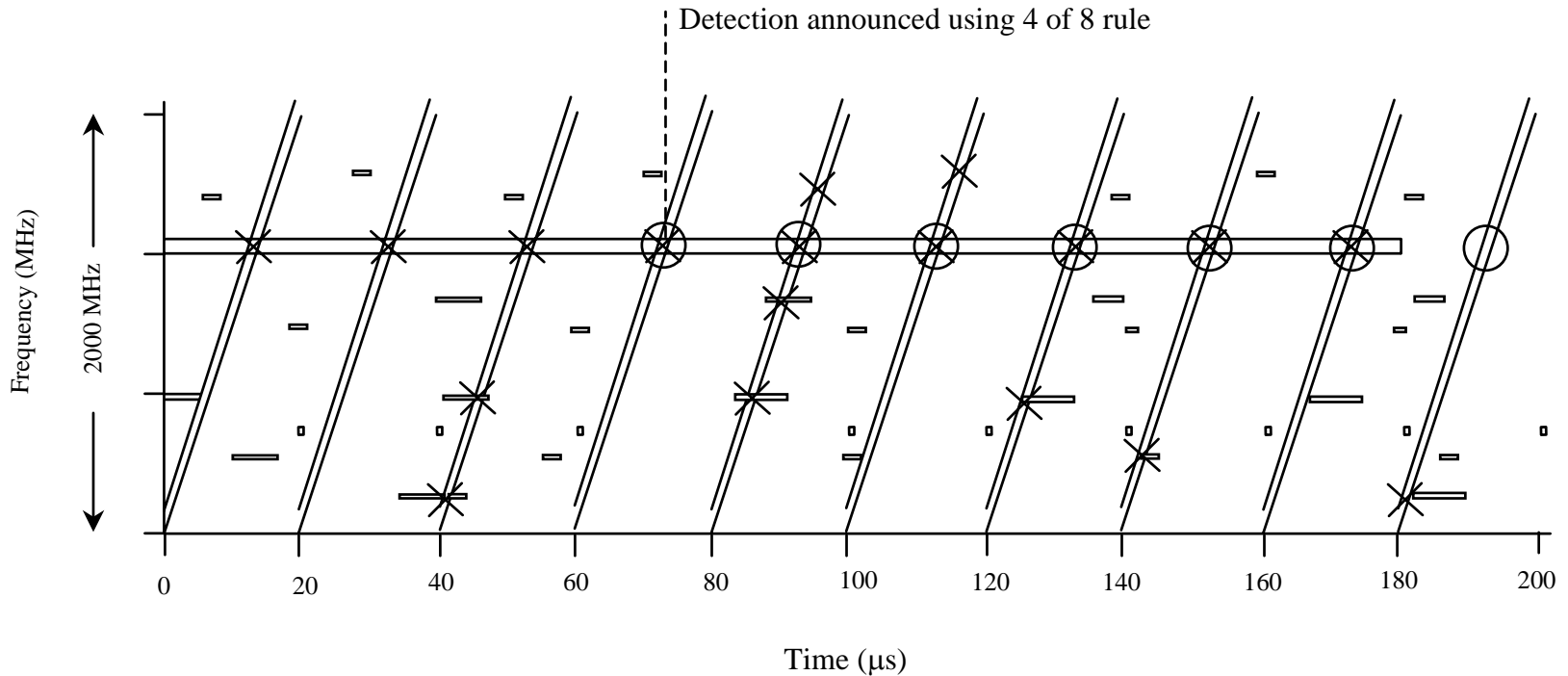
Note: 1. This shows one long pulse/CW (pulse compression) of low SNR with eight low duty cycle pulse trains of high SNR.

2. RSSR outputs for M=4, N=8 begin at the fourth sweep ⊗ or ◯ . X provides no output.

3. Microscan outputs occur for all of the strong short pulses but not the weak long pulses.

# Envelope Techniques

- RSSR uses many samples of the envelope prior to making a detection decision
- Various M/M, M/N and other statistical techniques for sensitivity enhancement can be used
- The past analog implementations could be done digitally in software and applied to a wideband digital data stream

RAS

# Required IF SNR

Pd=.9, Pfa=1E-6 (single Pulse SNR=13.2dB)

- M/N integration; N determined by signal duration during its Coherent Processing Interval or Pulse Width (M optimized).

- Note:  PW values shown are for 512 MHz Sweep Band. Reducing the Sweep to 256 MHz reduces the minimum PW by a factor of two.

- N=8           N=16           N=32           N=64
- PW>160us      PW>320us       PW>640us       PW>1320us
- M=4           M=6            M=8            M=12
- SNR=7.3dB     SNR=5.4dB      SNR=3.4dB      SNR=1.7dB
- Gain=5.9dB    Gain=7.8dB     Gain=9.8dB     Gain=11.5dB

# M/N Integration; N Large

**Detection and False Alarm Probabilities**
**IF SNR=-1.5 dB**

Pd,1=.118; Pfa,1= .0298
Pd, 256=.9; pfa, 256=.000001
Threshold =2.65
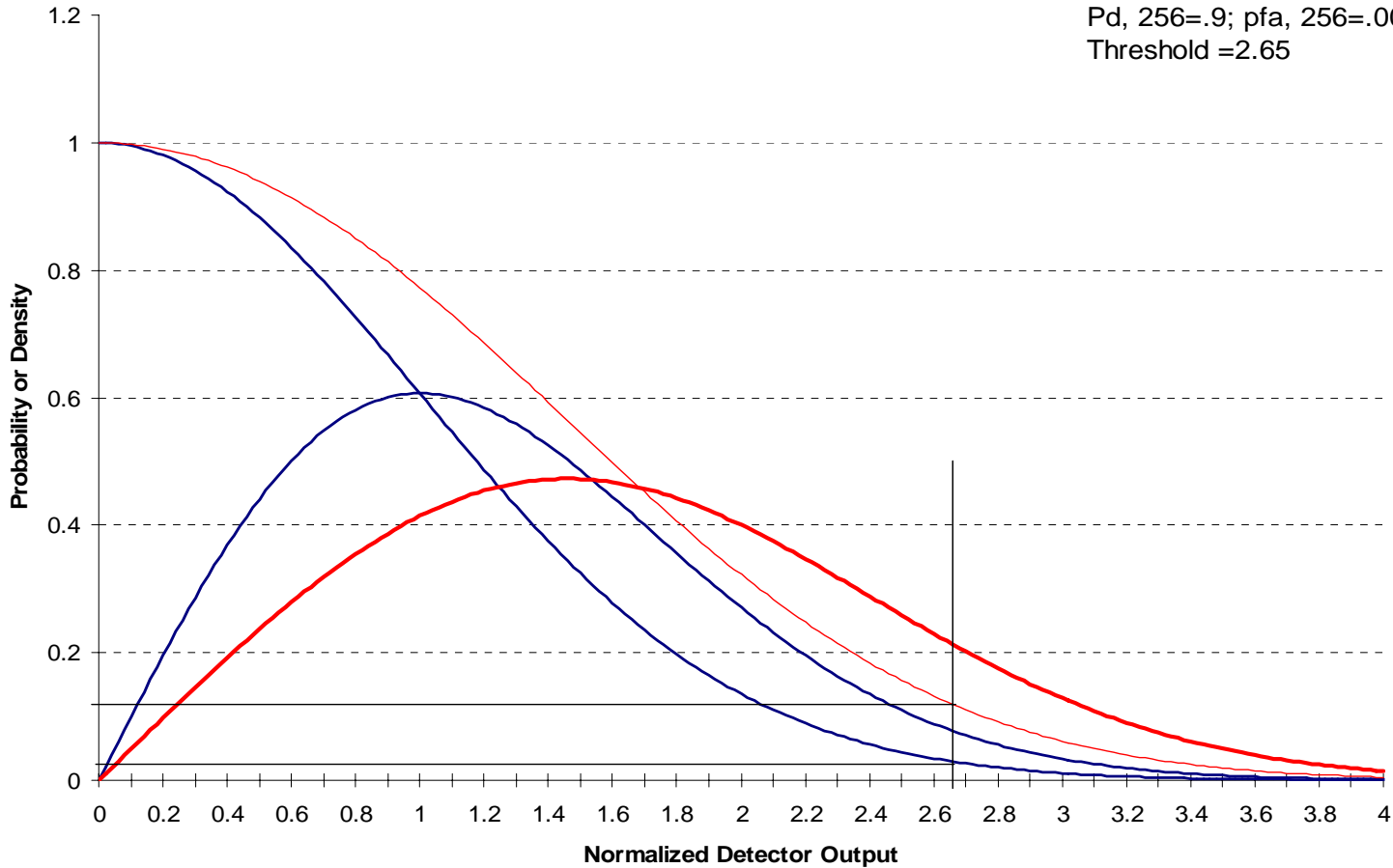
# RSSR Raster Display
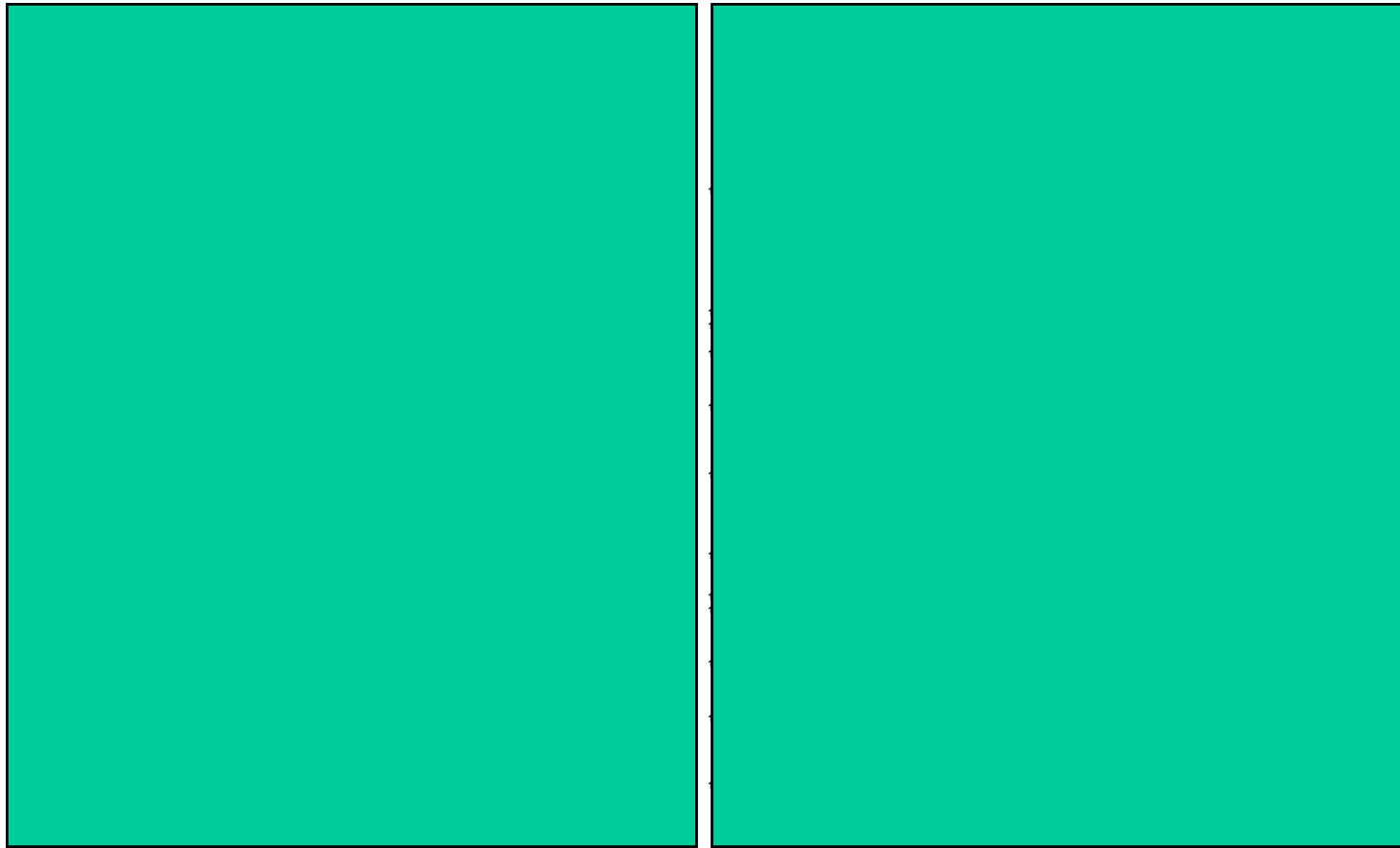
# RSSR Raster Display
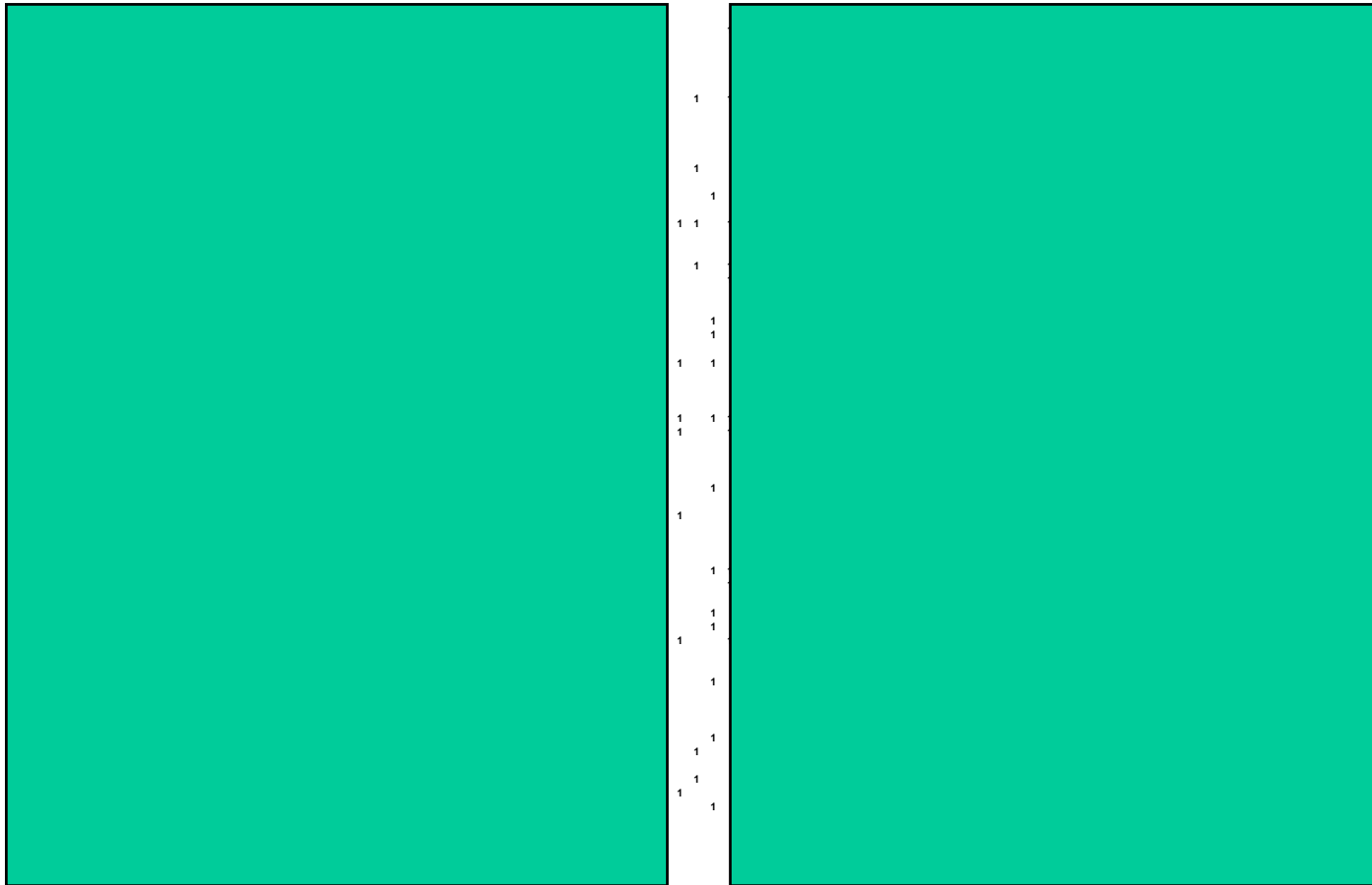
# RSSR Raster Display
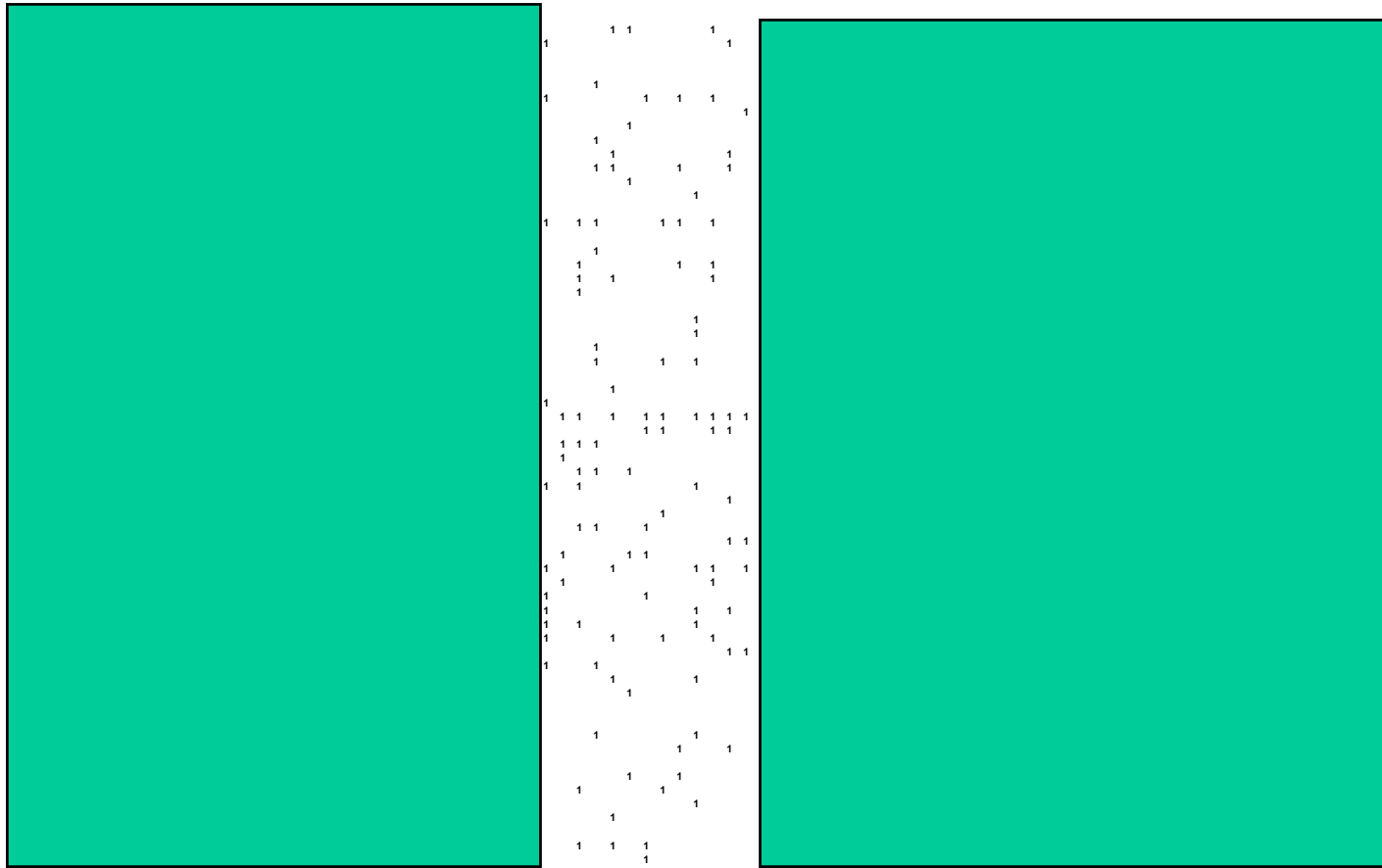
# RSSR Raster Display
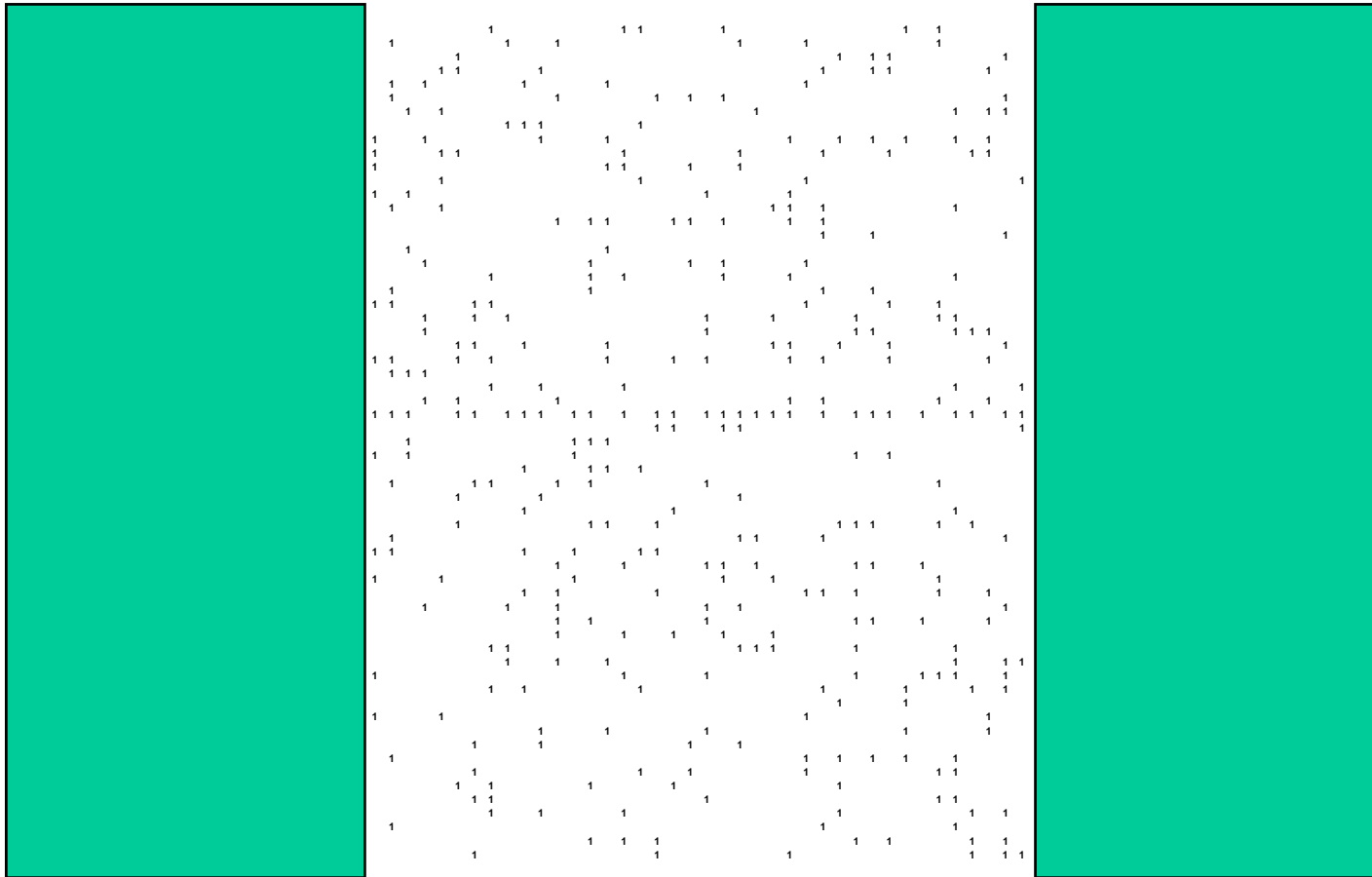
# RSSR Raster Display
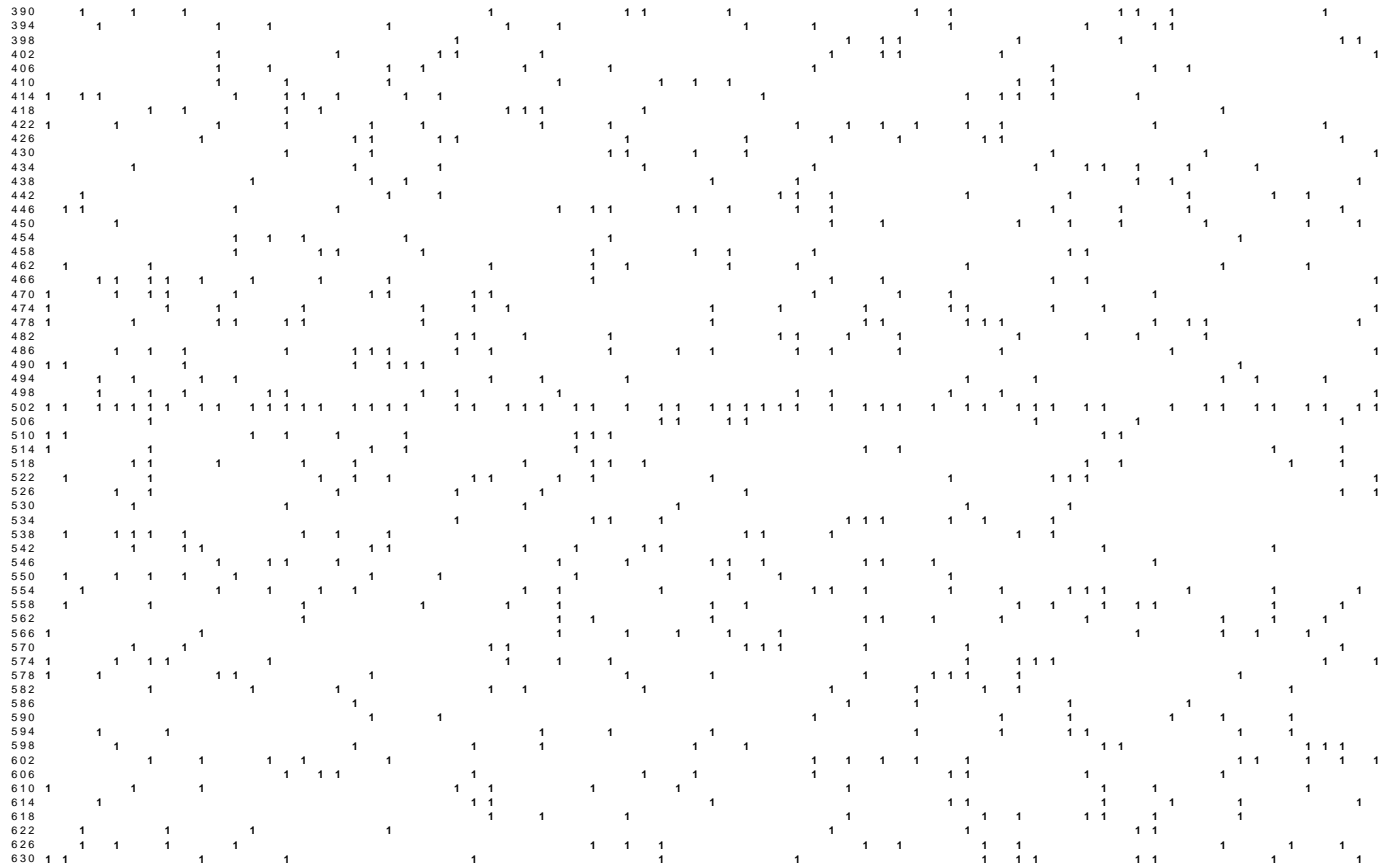
# "Coherent" Approaches

- "Coherent" means processing prior to the envelope detector

- Cross-Correlation using two or more channels-- performance independent of waveform

- Frequency-Time Processing detects CHIRP or CW signals in Noise ( *e.g.*,Wigner-Hough Transform)
    - Time coincident pulses detected separately

# Cross-Correlation Method

- Requires two channels with two antennas
- Sensitivity enhancement can be sufficient to deal with modern LPI FMCW radars on the battlefield ("almost coherent")
- Processes all modulation types equally well (Phase codes as well as FM)
- Provides AOA, Frequency and Bandwidth information

# Cross-Correlation Block Diagram

RAS



Antennas

Low-Noise RF Amplifiers

Mixers

LNA

$ct_d$

d

$\theta$

Weak Spread-Spectrum Signal

Stable Low-Noise Oscillator

~

LNA

Cross Correlator

X

Fourier Transform
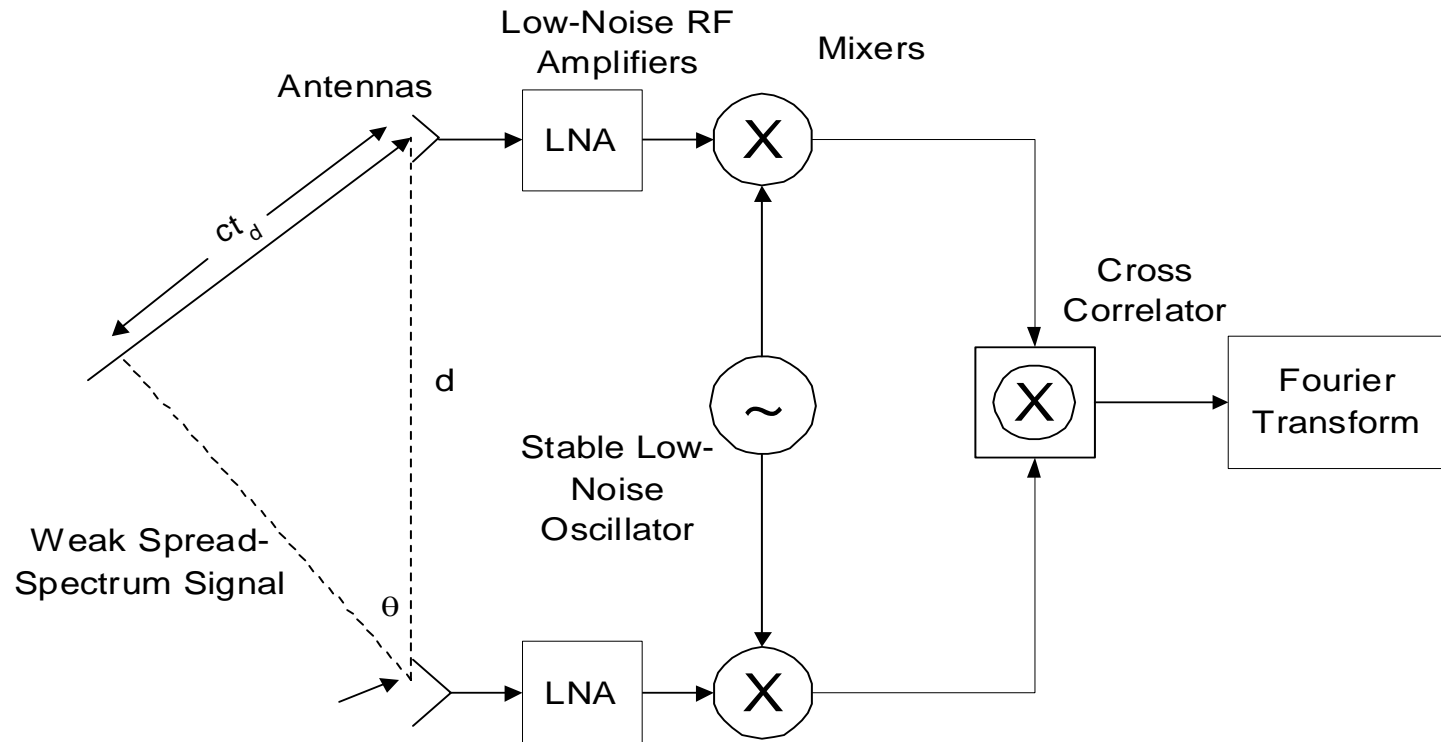
# Cross-Correlation (con't)

- Does not provide knowledge of the modulation type

- Modulation may be determined via high gain antenna directed toward the AOA of the LPI signal (dedicated ESM Rx)

- Significant signal processing load

- Wideband Cross-Correlation (large BT) beyond the current State-of-the-art(?)

# Choosing Corrrelation Parameters

RAS

- Correlation Time (T) is on the order of the radar's time on target or Integration time (Typically 1-10 ms)  Long enough to provide integration gain but not so long that the signal changes "very much"

- Receiver Bandwidth (B): wide to minimize search time; narrow to minimize noise and A/D speed.  (Several times wider than the likely modulation bandwidths.)

# Time-Frequency Transforms (Relationships and Descriptions)

- **Wigner-Ville Distribution (WVD)**
  - Good Time-Frequency resolution
  - Cross-term interference (for multiple signals), which is:
    - Strongly oscillatory
    - Twice the magnitude of autoterms
    - Midway between autoterms
    - Lower in energy for autoterms which are further apart
- **Ambiguity Function (AF)**
  - AF is the 2D Fourier Transform of the WVD
  - A correlative Time-Frequency distribution
- **Choi-Williams Distribution (CWD)**
  - Used to suppress WVD cross-term interference (for multiple signals), though preserves horizontal/vertical cross-terms in T-F plane
  - Basically a low-pass filter
- **Time-Frequency Distribution Series (Gabor Spectrogram) (TFDS)**
  - Used to suppress WVD cross-term interference (for multiple signals) by:
    - Decomposing WVD into Gabor expansion
    - Selecting only lower order harmonics (which filters cross-term interference)

# Time-Frequency Transforms (Relationships and Descriptions – cont'd)

- **Short-Time Fourier Transform (STFT)**
  - STFT is a sliding windowed Fourier Transform
  - Cannot accommodate both time and frequency resolution simultaneously
  - Square of STFT is Spectrogram (which is the convolution of the WVD of the signal and analysis function)
  - Not well suited for analyzing signals whose spectral content varies rapidly with time
- **Hough (Radon) Transform (HT)**
  - Discrete HT equals discrete Radon Transform
  - A mapping from image space to parameter space
  - Used in addition to T-F transform for detection of straight lines and other curves
  - Detection achieved by establishing a threshold value for amplitude of HT spike
- **Fractional Fourier Transform (FrFT)**
  - The FrFT is the operation which corresponds to the rotation of the WVD
  - The Radon Wigner Transform is the squared magnitude of the FrFT
  - Main application may be a fast computation of the AF and WVD
- **Cyclostationary Spectral Density (CSD)**
  - CSD is the FT of the Cyclic Autocorrelation Function (CAF)
  - CAF is basically the same as the AF
  - CSD emphasis is to find periodicities in the CAF (or AF)

# Ambiguity Function then Hough Transform of FMCW Signal-SNR -10dB
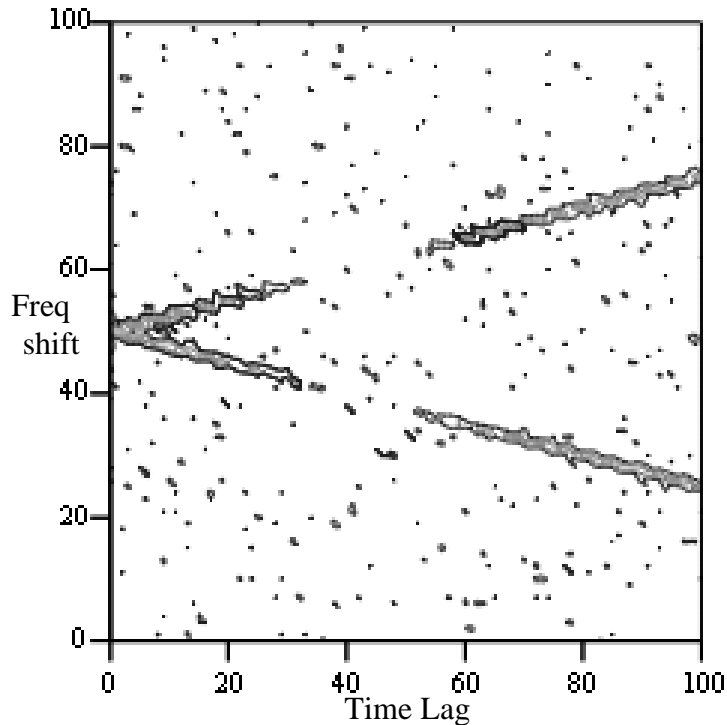


**Ambiguity Function**
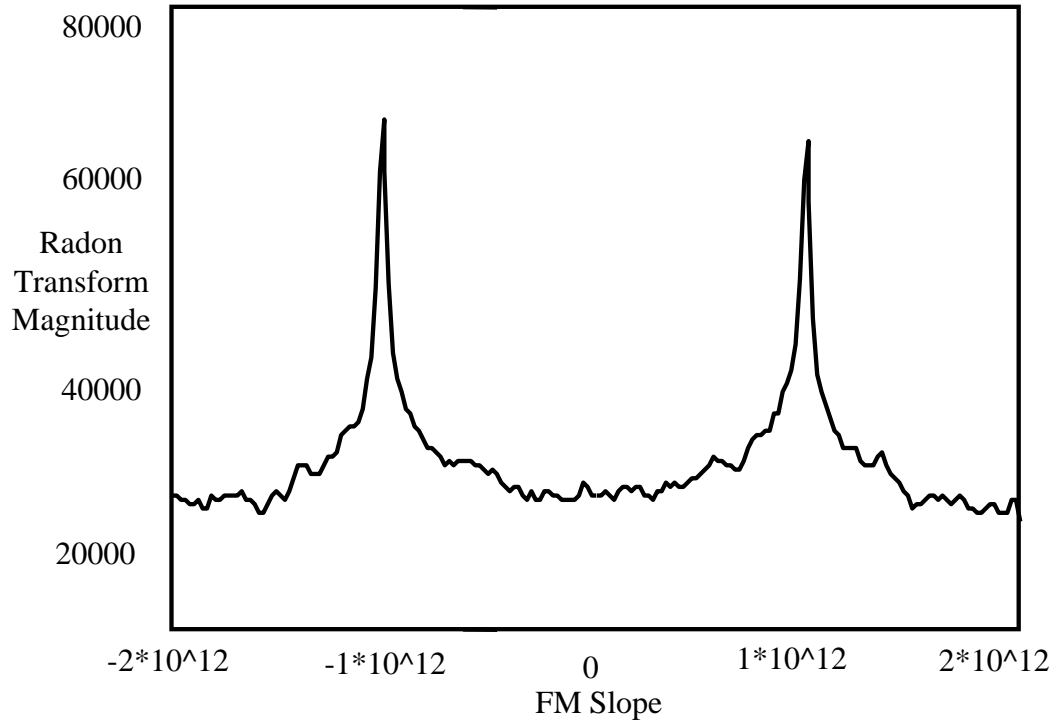


**Hough Transform**

Peaks of Hough Transform show the positive and negatives slopes of the triangular FM waveform

# WVD and CWD comparison for LFM signal (SNR -15dB)

RAS
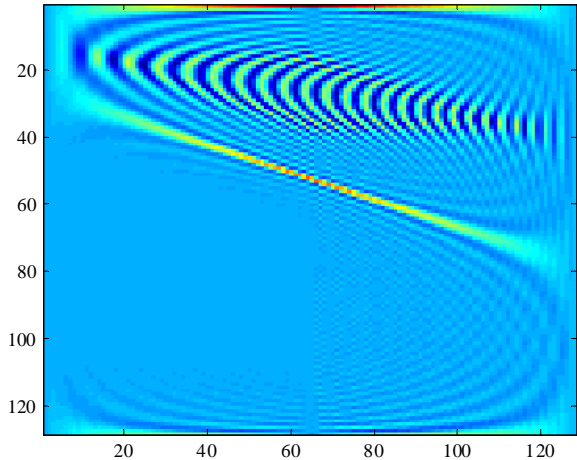


WVD of LFM signal in noise
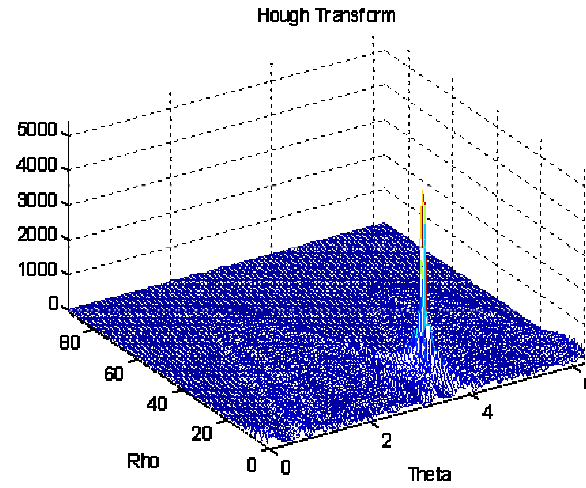


HT of WVD of LFM signal in noise
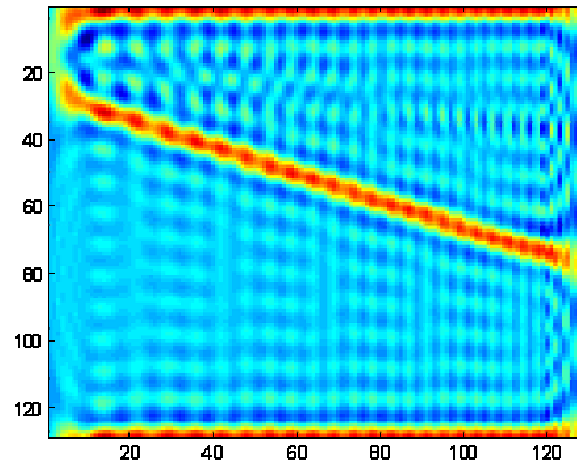


CWD of LFM signal in noise
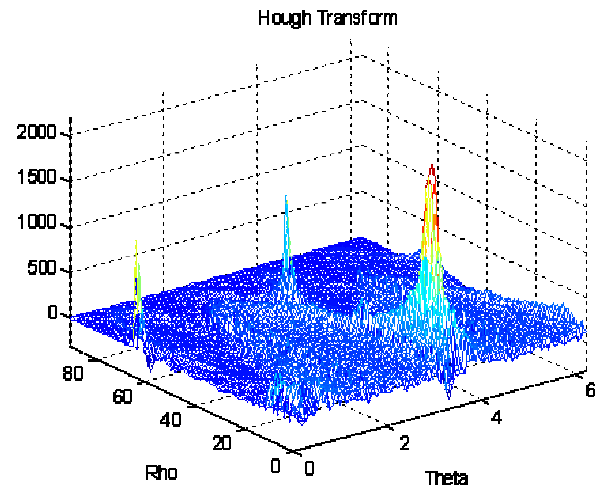


HT of CWD of LFM signal in noise

WVD has better T-F resolution and a 'tighter' HT spike.  1 WVD/CWD line maps to 1 HT spike.  Detection achieved via establishing a threshold value for the amplitude of the HT spike

# WVD and CWD comparison for 2 LFM signals (SNR -3dB)

RAS



WVD of 2 LFM signals in noise


Hough Transform
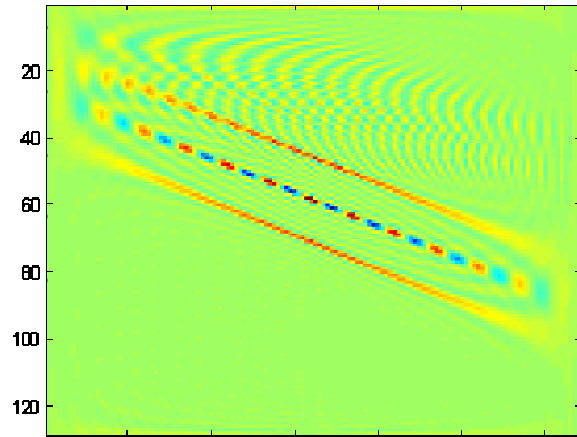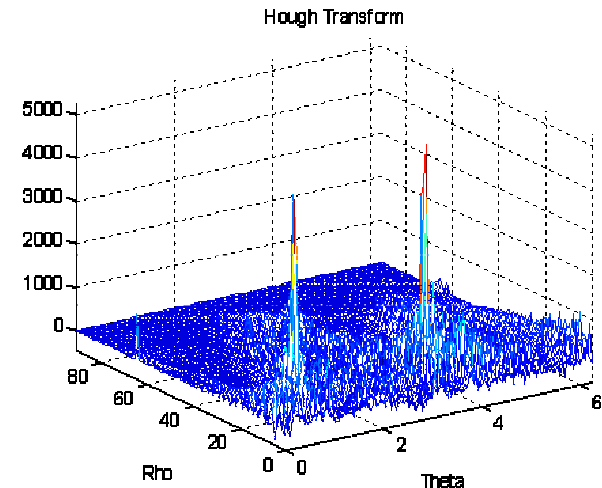
HT of WVD of 2 LFM signals in noise



CWD of 2 LFM signals in noise


Hough Transform
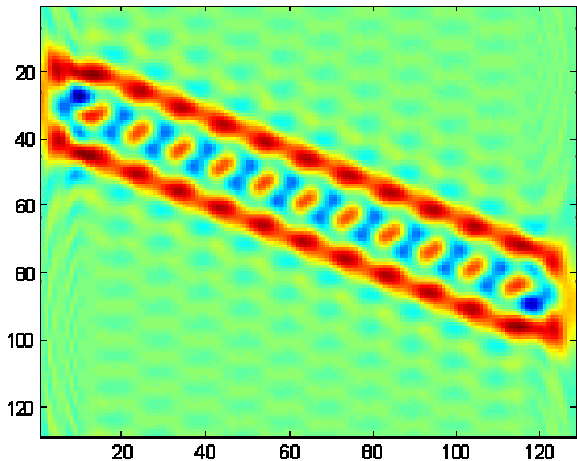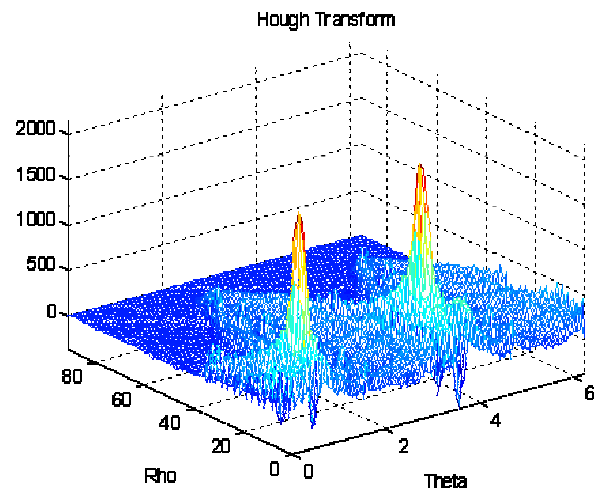
HT of CWD of 2 LFM signals in noise

WVD has better T-F resolution and 'tighter' HT spikes.  CWD suppresses some cross-term interference, but preserves horiz/vert cross-terms.  2 WVD/CWD lines map to 2 HT spikes.  Detection via HT ampl. threshold

# STFT of LFM signal and of 2 LFM signals (SNR -3dB)



STFT of LFM signal in noise



HT of STFT of LFM signal in noise



STFT of 2 LFM signals in noise



HT of STFT of 2 LFM signals in noise
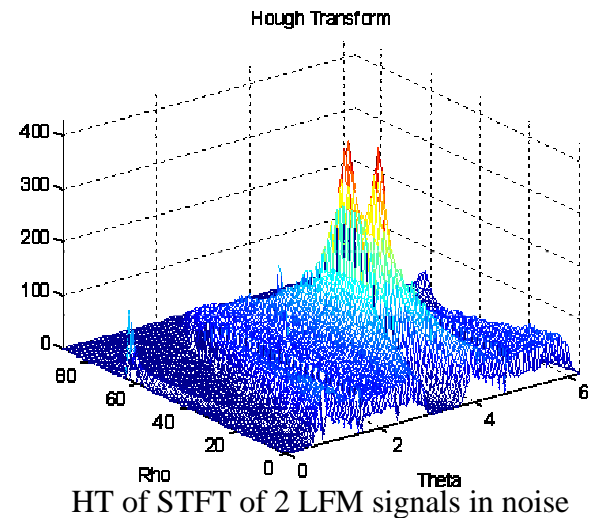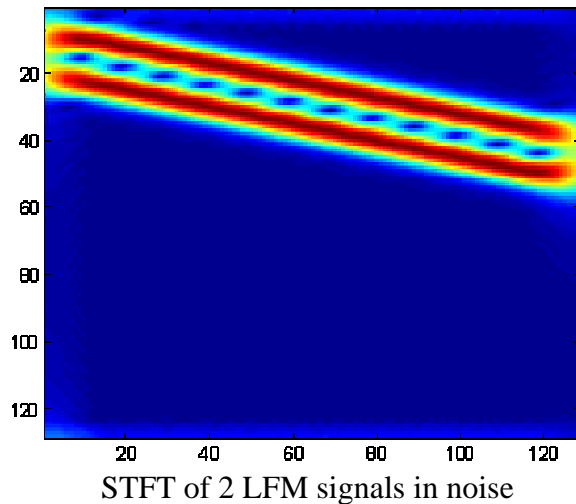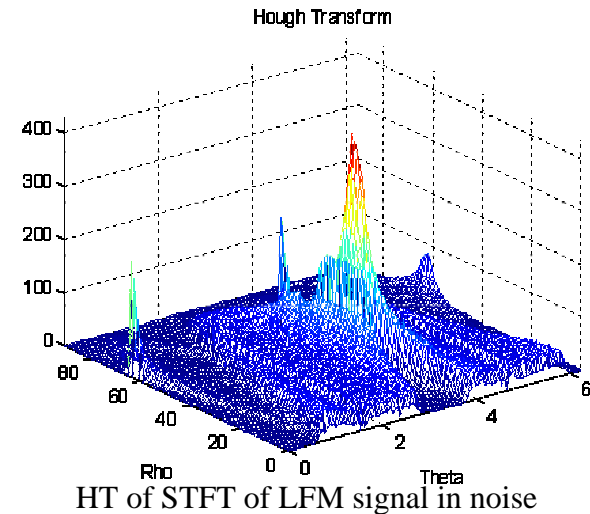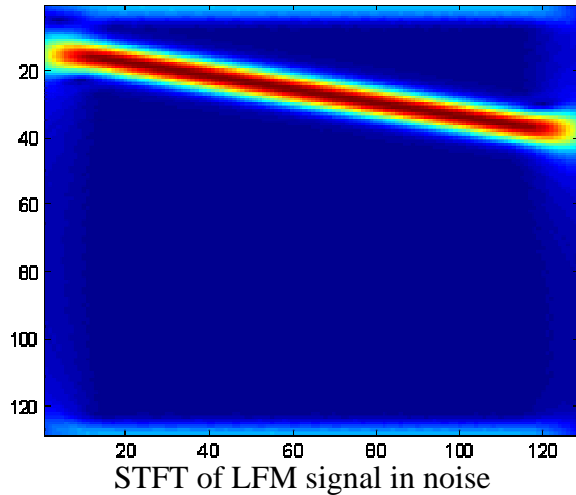
1 STFT line maps to 1 HT spike; 2 STFT lines map to 2 HT spikes. STFT T-F resolution inferior to that of WVD (STFT-window funct. imposes resolution limit). STFT superior to WVD for cross-term interf. Detection via HT ampl. threshold

# CWD for a BPSK signal plus 2 LFM signals (with and without noise)
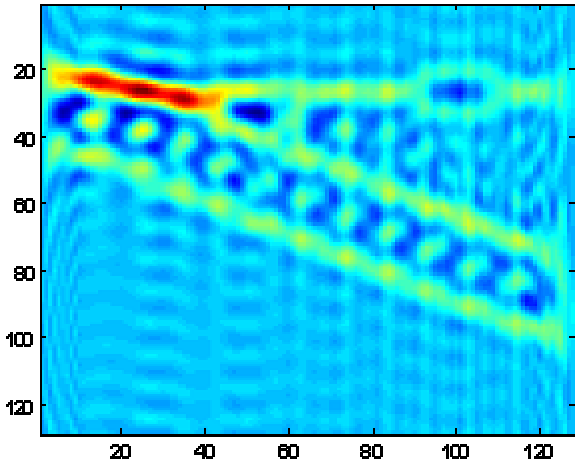


CWD of the 3 signals
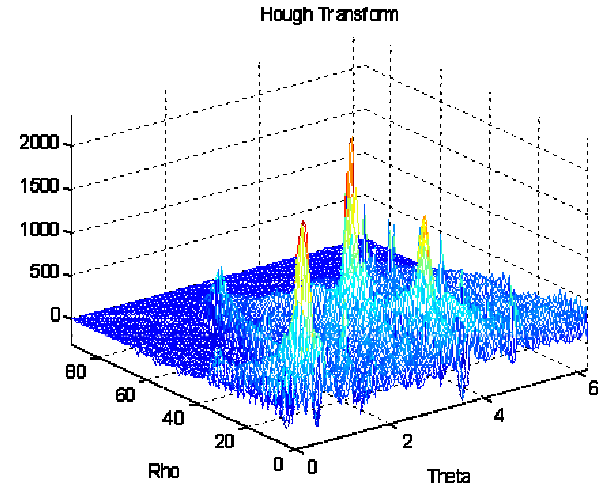


HT of CWD of the 3 signals
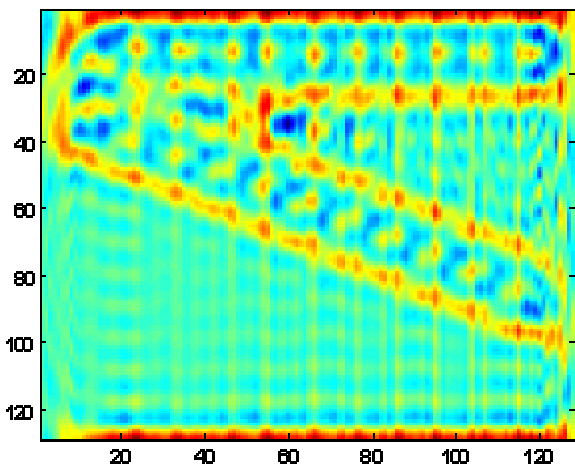


CWD of the 3 signals in noise (SNR -3dB)
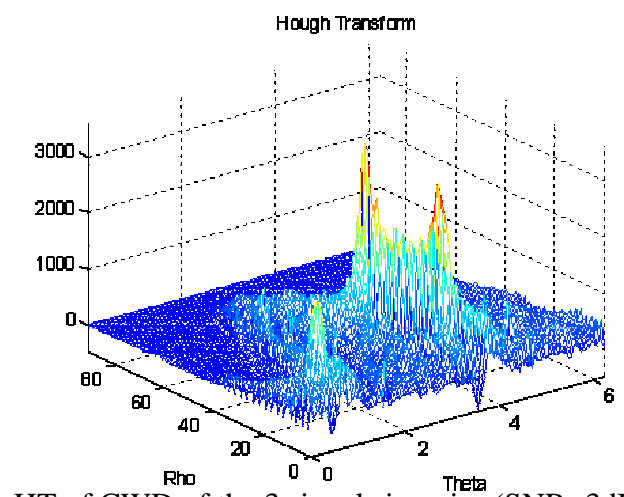


HT of CWD of the 3 signals in noise (SNR -3dB)

CWD suppresses some cross-terms and preserves horiz/vert cross-terms. Each of the 3 signals in the CWD plot maps to an HT spike.
Each of the HT spikes in the noise plot (bottom) is not as 'tight' as the HT spikes in the plot w/o noise (top).

# Heuristic Analysis
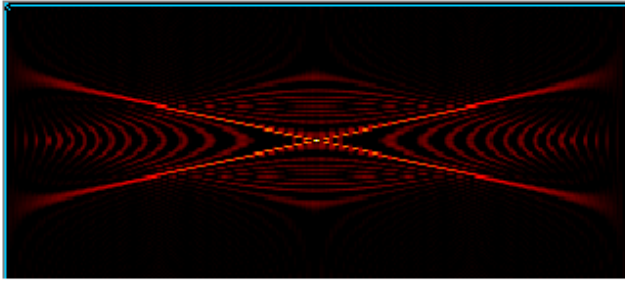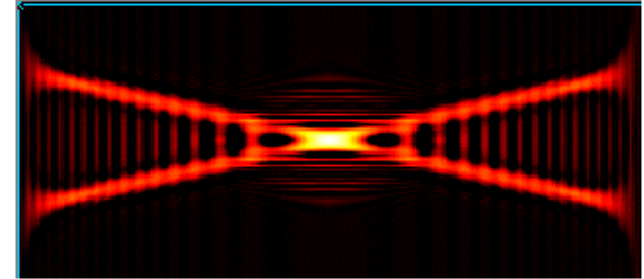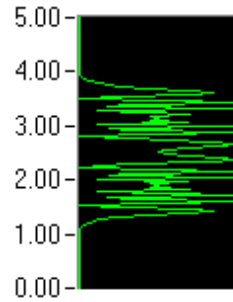# Frequency Hopper


WVD


CWD
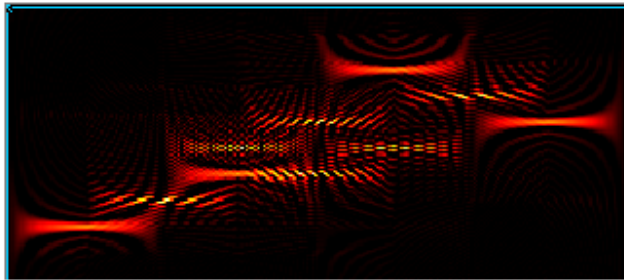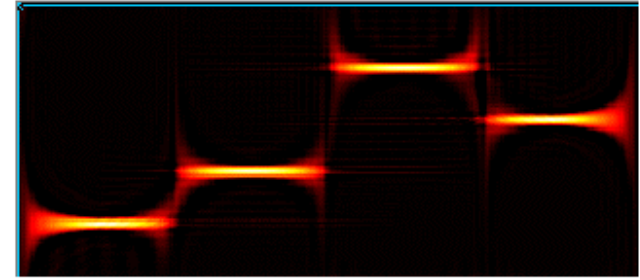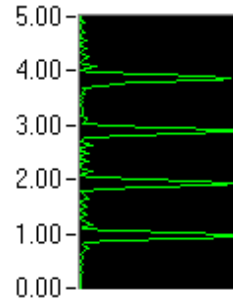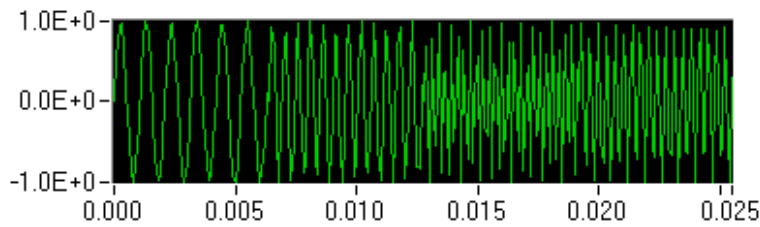

STFT
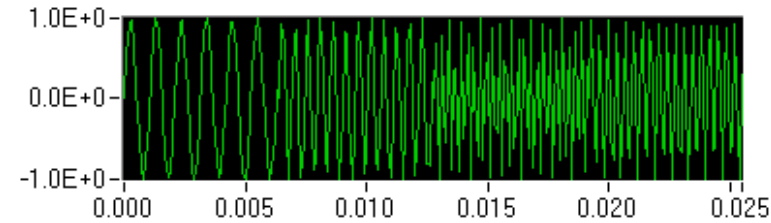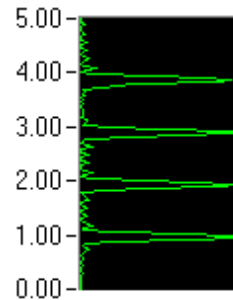

TFDS (3rd order)

WVD has best T-F resolution, but nasty cross-term interference. CWD suppresses some cross-terms, but preserves horiz/vert cross-terms. STFT has worst T-F resol., but no cross-terms. TFDS (3rd order) has best combo of T-F res. and limited cross-terms for this waveform.

# Heuristic Analysis
# Non-Linear Chirp
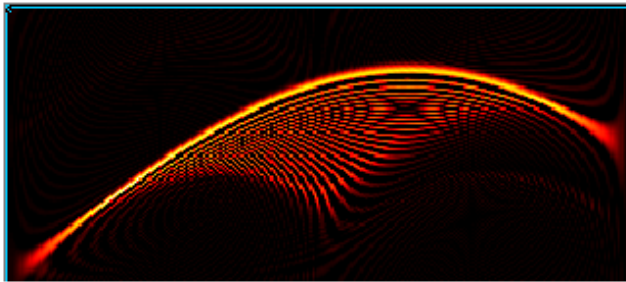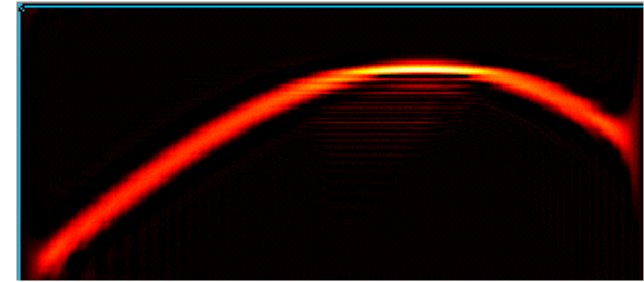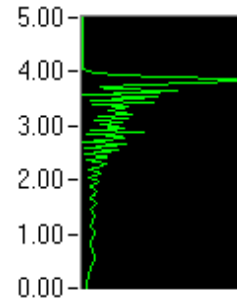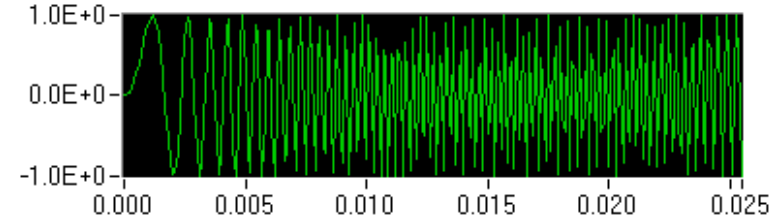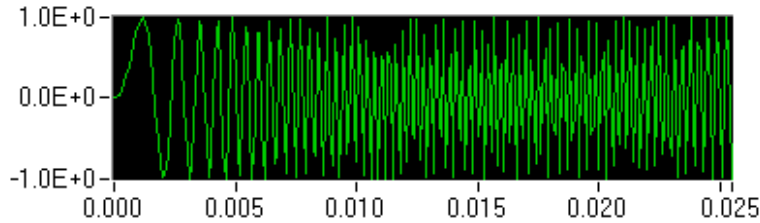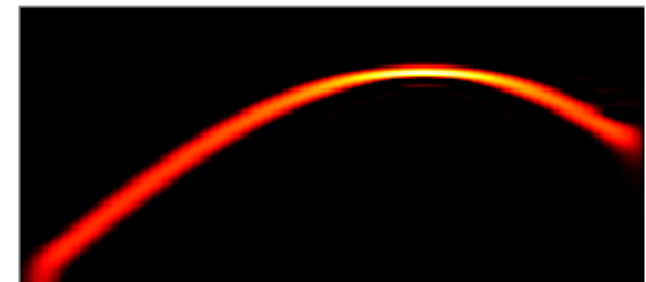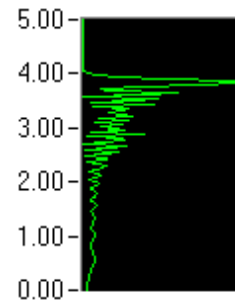
RAS



WVD



CWD



STFT



TFDS (3rd order)

WVD has best T-F resolution, but has cross-term interference. CWD suppresses some cross-terms, but preserves horiz/vert cross-terms. STFT has worse T-F resolution, but no cross-terms. TFDS (3rd order) and CWD a good choice for this waveform.
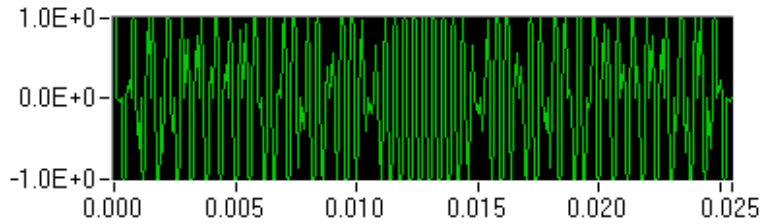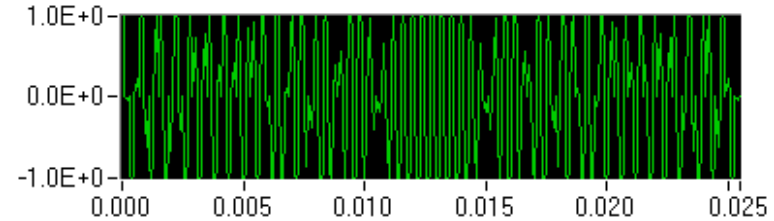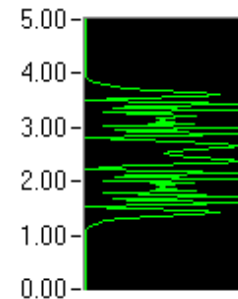
# Heuristic Analysis
# Two Chirps



WVD



CWD



STFT



TFDS (3$^{rd}$ order)

WVD has best T-F resolution, but has cross-term interference. CWD suppresses some cross-terms, but preserves horiz/vert cross-terms. STFT has the worst T-F resol., but no cross-terms.  TFDS (3$^{rd}$ order) and WVD (even w/cross-terms) are a good choice for this waveform.

# Predetection ESM Sensitivity Enhancement

- Wigner-Hough Transform
  – Approaches Coherent Integration
  – "Matched" to Chirp and Constant MOP
  – Separation of Simultaneous Pulses
- Provides Parametric information about Frequency and Chirp Rate
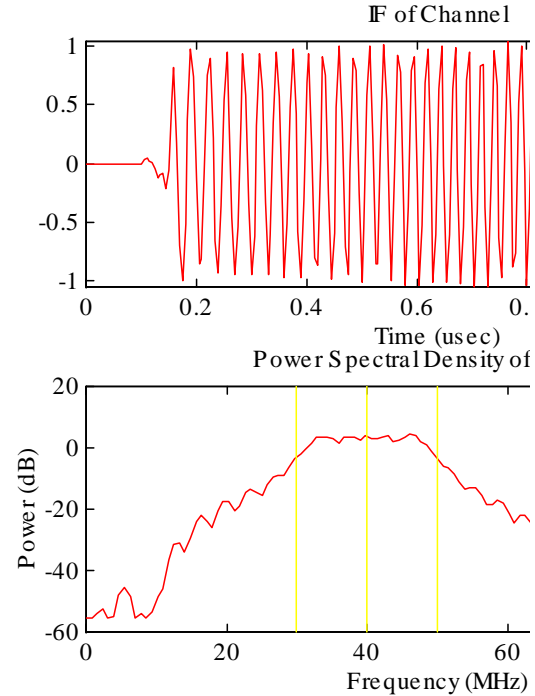
# Wigner-Hough Transform

*Wigner − Ville Transform*

$$W_{x,x}(t, f) = \int_{\tau = -\infty}^{\infty} x(t + \tau/2) \cdot x^*(t - \tau/2) \cdot e^{-j2\pi f\tau} d\tau$$
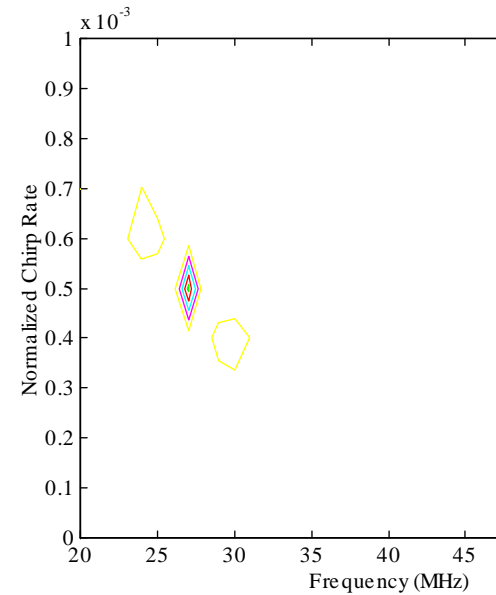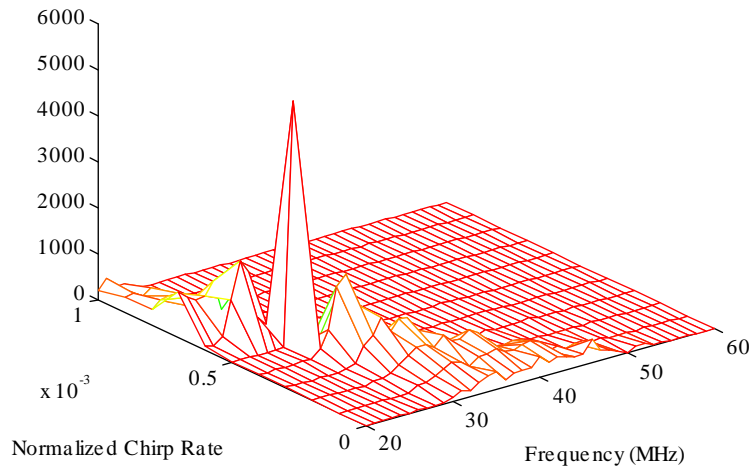
*Wigner − Hough Transform*

$$WH_{x,x}(f, g) = \iint W_{x,x}(t, \nu)\delta(\nu - g \cdot t)dt d\nu$$

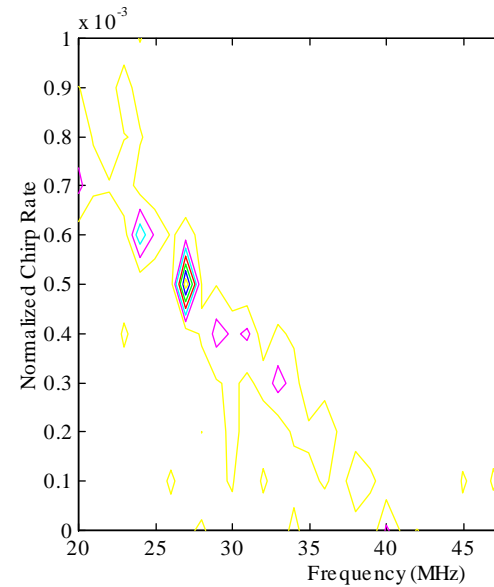$$= \int W_{x,x}(t, f + g \cdot t)dt$$
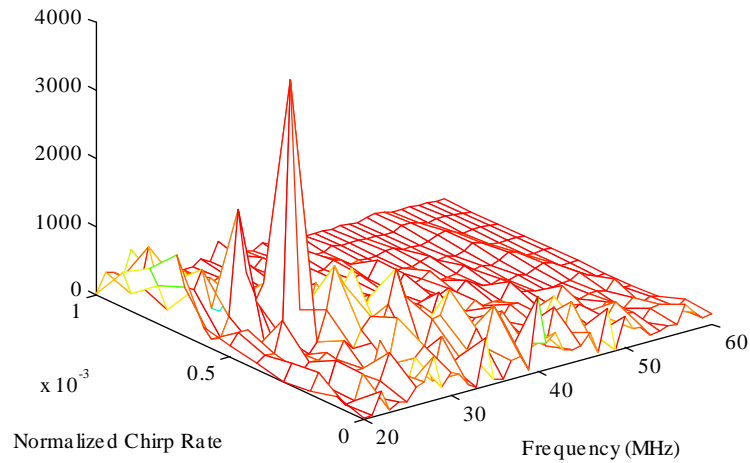
# W-H Transform Example

- 20 MHz Chirp

- 1 usec Pulse Duration

- 200 MHz Sample Rate
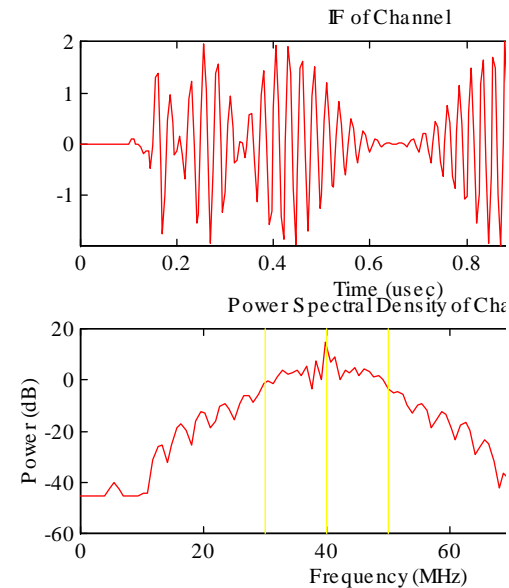
# W-H Transform
# (12 dB SNR)

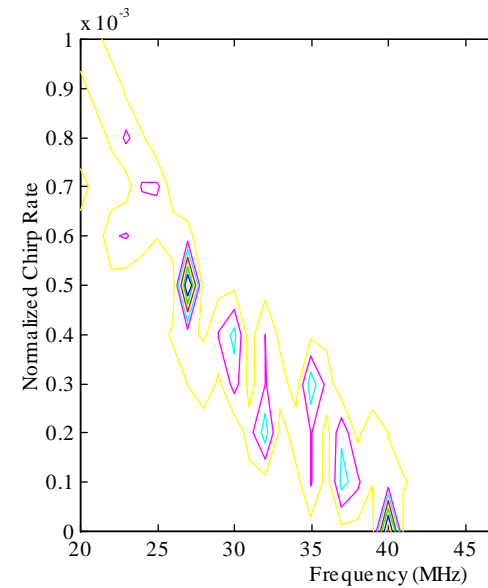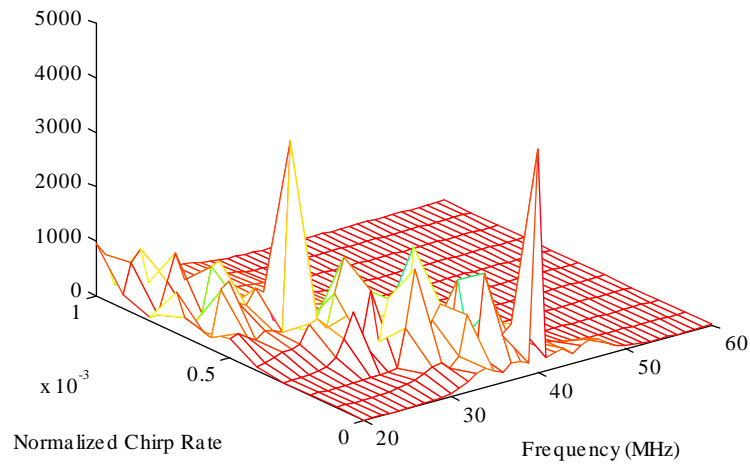# W-H Transform
# (0 dB SNR)

# Simultaneous Signals

- 2 Pulses
  - Same Center Frequency
  - Same TOA
- Pulse 1
  - 20 Mhz Chirp
- Pulse 2
  - Constant RF

# W-H Transform-simultaneous signals

# Summary

RAS

- Each T-F transform has its own strengths and weaknesses, and is very much application dependent, thusly a need to produce multiple algorithms for multiple applications

- T-F transforms are especially useful for recognizing wideband signals, non-stationary signals, and signals buried in noise

- Many of the T-F transforms and inter-related with one another

- WVD yields the best overall T-F resolution, but for multiple signals, is plagued with cross-term interference

- CWD, TFDS, and other T-F transforms can suppress cross-term interference, but at the cost of T-F resolution

- TFDS allows specific selection of order which makes for a good compromise between T-F resolution and cross-term interference

- STFT is not plagued with cross-term interference, but cannot accommodate both time and frequency resolution simultaneously (subject to the selection of the window function).  To 'catch' abrupt frequency jumps, the STFT must use a very short window, and is not recommended for very rapidly changing frequencies

- Hough Transform can be applied to a T-F transform and then used for the detection of straight lines and other curves.  An HT amplitude threshold can be set for detection

# Time-Frequency Approach



**Processing Model (Courtesy of NRL)**
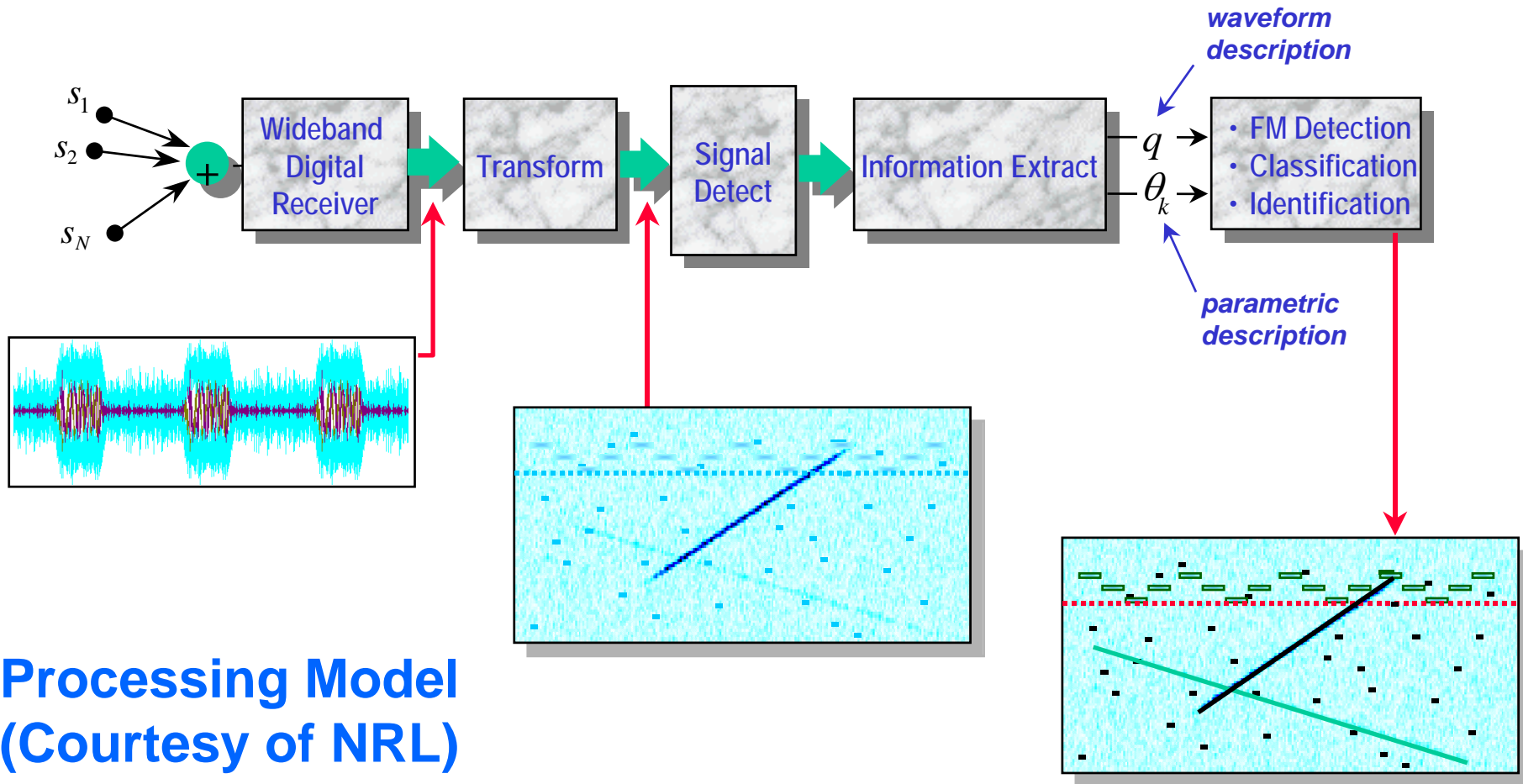
# Modern Receivers for Modern Threats

- Integration over times on the order of 1-10 ms over bandwidths on the order of 100 MHz. are required to cope with short range FMCW or Phase coded radars expected on the modern battlefield.  (BT~10, 000-100,000)

- Fast A/D conversion and DSP are the keys to implementation of these ESM strategies.