Professional Development Short Course On:

ELINT Interception and Analysis

Instructor:

Richard G. Wiley, Ph. D.

ATI Course Schedule: http://www.ATIcourses.com/schedule.htm
ATI's Space Based Radar: http://www.aticourses.com/ELINT_analysis_3.htm
ELINT Interception and Analysis

Summary
The course covers methods to intercept radar and other non-communication signals and then how to analyze the signals to determine their functions and capabilities. Practical exercises illustrate the principles involved. Participants receive the hardcover textbook, *ELINT: The Interception and Analysis of Radar Signals* by the instructor.

Instructor
Richard G. Wiley, Ph. D. is vice president and chief scientist of Research Associates of Syracuse, Inc. He has worked in ELINT since the 1960s. He has published 5 books, including the textbook for this course, as well as many technical papers. His accomplishments include the first fielded computer based TOA system and the first receiver specifically designed to intercept LPI radar signals. He was co-founder of Research Associates of Syracuse which provides technical solutions for today’s ELINT environment.

Course Outline

Day 1
- Character and uses of ELINT
- Radar fundamentals
- RF generation and propagation
- Noise figure and bandwidth
- Sensitivity and dynamic range
- Pulse density vs altitude
- ELINT range advantage

Day 2
- Crystal video receivers
- Noise limited vs gain limited
- Superhet receivers
- Analog and digital IFM receivers
- Channelized and Bragg Cell receivers
- Microscan and other receivers
- Modern phase processing receivers
- Direction finding techniques

Day 3
- Emitter location via triangulation
- Time difference of arrival (TDOA)
- Probability of Interception
- ERP analysis
- Polarization analysis
- Beam shape analysis
- Antenna scan analysis
- Pulse shape analysis

Day 4
- Intrapulse Modulation
- Wideband signals
- PRI Types
- MTI and pulse Doppler analysis
- PRI measurement problems
- Deinterleaving
- Delta-T and other histograms
- RF analysis and coherence Measures
- ELINT parameter limits
- LPI Radar and the future of ELINT

What You Will Learn
- Special Characteristics of Receivers designed for ELINT
  - Uses for Wideband receivers not generally used in radar and communications systems
  - Application of Probability of Interception theory using several examples
- The ELINT advantage of one way vs radar’s two way propagation
- Direction Finding and Emitter Location problems and solutions
  - How TDOA and FDOA location techniques work
  - Error ellipses and their applications to real world systems
- Antenna basics from both the interception and radar signal analysis viewpoints
- RF Coherence, why it is important and how to measure it
- Intrapulse Modulation, both intentional (pulse compression) and unintentional
- PRI Measurement and Analysis
  - Stagger and Jitter and other types of PRI modulation definitions and analysis techniques
  - Effects of noise, scanning and platform motion
  - Optimum methods of analysis under different conditions
  - Time based deinterleaving methods
- Introduction to ELINT data files and applications to EW systems
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Low Probability of Interception

• The radar designer tries to make the signal weak
• Then the ESM system cannot detect it.
• For radar this can be difficult.
• 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

- Pulse-High Peak Power
- CW--Low Peak Power
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:

\[ \delta = \frac{S_{E(\text{min})}}{S_{R(\text{min})}} \sim \frac{\text{NoiseBWOfInt.Rx.}}{\text{NoiseBWOfRadarRx}} \]
Intercept Range/Radar Range

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

(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.
Example for Pulsed Radar Designs

- Radar range = 100 km
- RCS = 1 sq meter
- Rx Ant Gain = 1, Sidelobe Tx Ant. Gain = 1
- ESM Rx 20 dB poorer sensitivity than Radar Rx
- The Sidelobes of the Radar can be detected by ESM at a range of over 30 times the range at which the radar can detect its target
- Main beam detection over 1000 times Radar Range
Frequency/Time for Modern Radar Signals

- **Frequency Agility Band**: (depends on Component Design, ECM Factors, Designer Ingenuity)

- **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.
ESM Receiver Strategies

• Detection of a radar using only the energy has the advantage that the ESM 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 systems designed for specific signal properties
# Range Comparisons for Pilot Radar

<table>
<thead>
<tr>
<th>Target Cross-section (m²)</th>
<th>Radar Range</th>
<th>ESM Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10KW Pulsed</td>
<td>1W FMCW</td>
</tr>
<tr>
<td></td>
<td>Radar</td>
<td>Radar</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>100</td>
<td>26</td>
<td>28</td>
</tr>
</tbody>
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Intercept Range/Radar Range = \(\frac{2.5}{16} = .156\)

= \(\frac{25}{28} = .893\)
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

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
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
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

Peaks of Hough Transform show the positive and negative slopes of the triangular FM waveform.
WVD and CWD comparison for LFM signal (SNR -15dB)

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)

WVD of 2 LFM signals in noise

HT of WVD of 2 LFM signals in noise

CWD of 2 LFM signals in noise

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)

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

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).
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
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.
You have enjoyed an ATI's preview of

ELINT Interception and Analysis

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