Classification of LPI Radar Signals Using Spectral Correlation and Support Vector Machines

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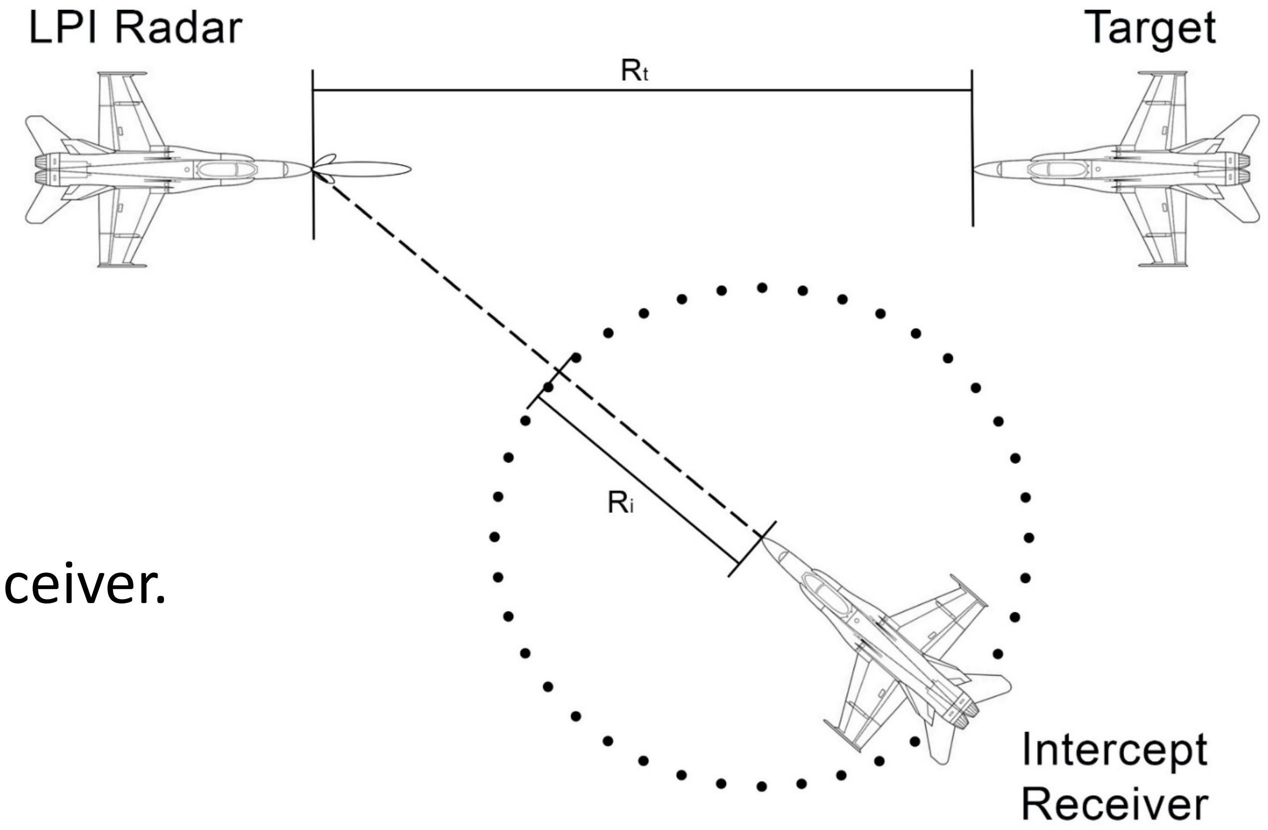
Outline

- Low-Probability of Intercept Radar
- Spectral Correlation of LPI Waveforms
- Classification of LPI Waveforms
- Results

LPI Radar

LPI Radar



Objective of LPI Radar

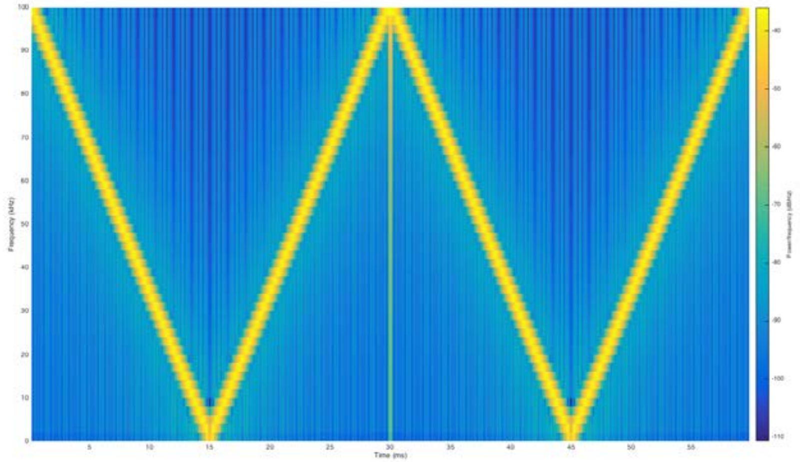
- Detect Target at range R_t
- Avoid interception $R_t >> R_i$
- R_i is the interception range of the receiver.

LPI Waveforms

- **Frequency Modulation Continuous Wave**
- **Frequency-Shift Keying**
  - Costas
  - M-ary FSK
- **Phase-Shift Keying**
  - Polyphase Codes
  - Frank Code
  - Polytime Codes

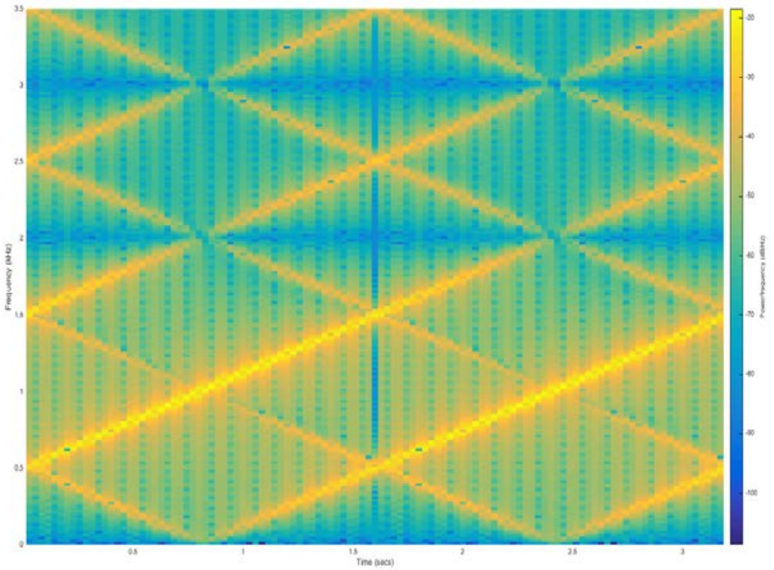
Frequency Modulation Continuous Wave

- $s_1(t) = \sin 2\pi \left[\left(f_c - \frac{B}{2} \right) t + \frac{B}{2T_p} t^2 \right]$
- Bandwidth B, Pulse period T_p, carrier frequency $\mathrm{f_c}$



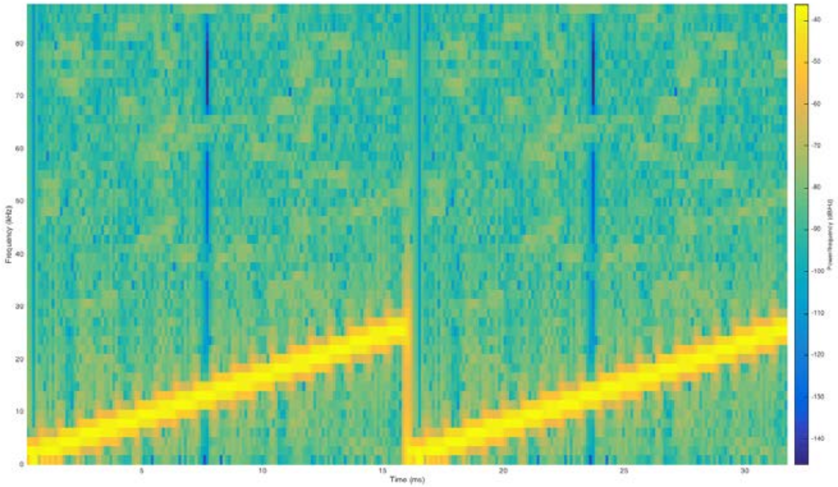
Polyphase Codes P1

- $\phi_k = \phi_{i,j} = -\frac{\pi}{M}[M - (2j-1)][(j-1)M + (i-1)]$
- With i samples for the j^{th} frequency for a total of M frequency steps



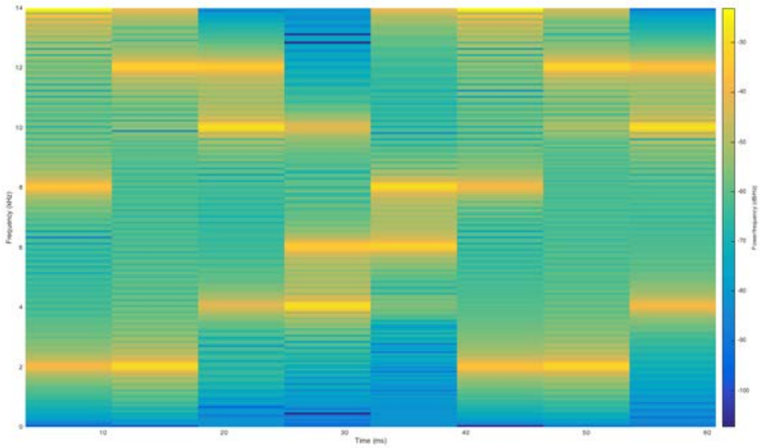
Polytime Codes (T1(n))

- $\phi_{T1}(t) = mod\left\{\frac{2\pi}{n} FLOOR\left((kt - jt)\frac{jn}{T}\right)\right\}$
- k segments in the code, n phase states, phase state j, code period T



Costas Code

- $s(t) = \cos\left(2\pi f_j t\right)$ With $j \in \{1, 2, \dots, N\}$
- Costas code: $f_{k+i} - f_k \neq f_{j+i} - f_j$
- Example: {2, 4, 8, 5, 10, 9, 7, 3, 6, 1} Hz



Spectral Correlation of LPI Waveforms

Cyclostationarity in LPI Waveforms

- A time series $x(t)$ is said to be cyclostationary if its autocorrelation function $R_x(t,\tau)$ is periodic in time t.

$$R_x(t+T,\tau) = R_x(t+T,\tau)$$

- Since such the autocorrelation is periodic, it has second-order periodicities of frequency α with:

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} R_x(t,\tau)e^{-2\pi i\alpha t}dt$$

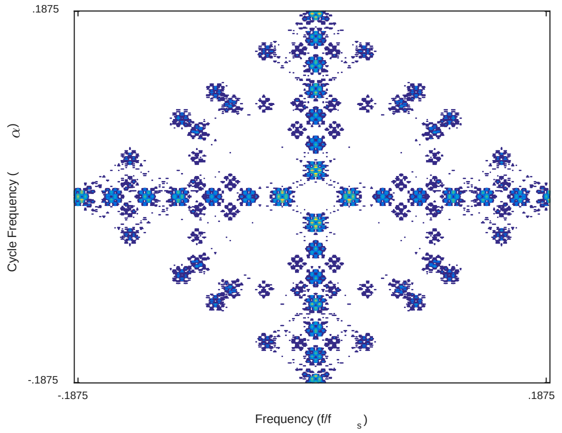
Cyclostationarity in LPI Waveforms

- Furthermore the repeating structure of LPI waveforms gives rise to unique values for the spectral correlation density which is related to the cyclic autocorrelation $R_x^\alpha(\tau)$

$$S_x^\alpha(f) = \int_{-\infty}^{\infty} R_x^\alpha(\tau) e^{2\pi \bar{i} f\tau} d\tau$$

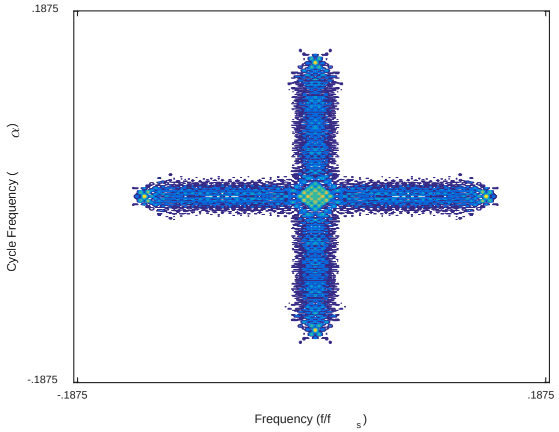
- This can be estimated for a short-time digital signal $x[n]$ and used for classification

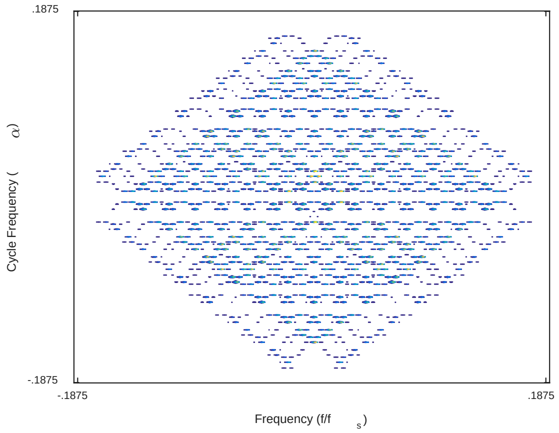
Example SCD



Costas

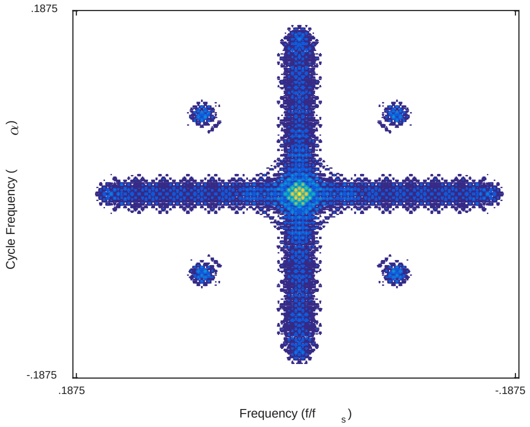
FMCW





Polyphase

Polytime

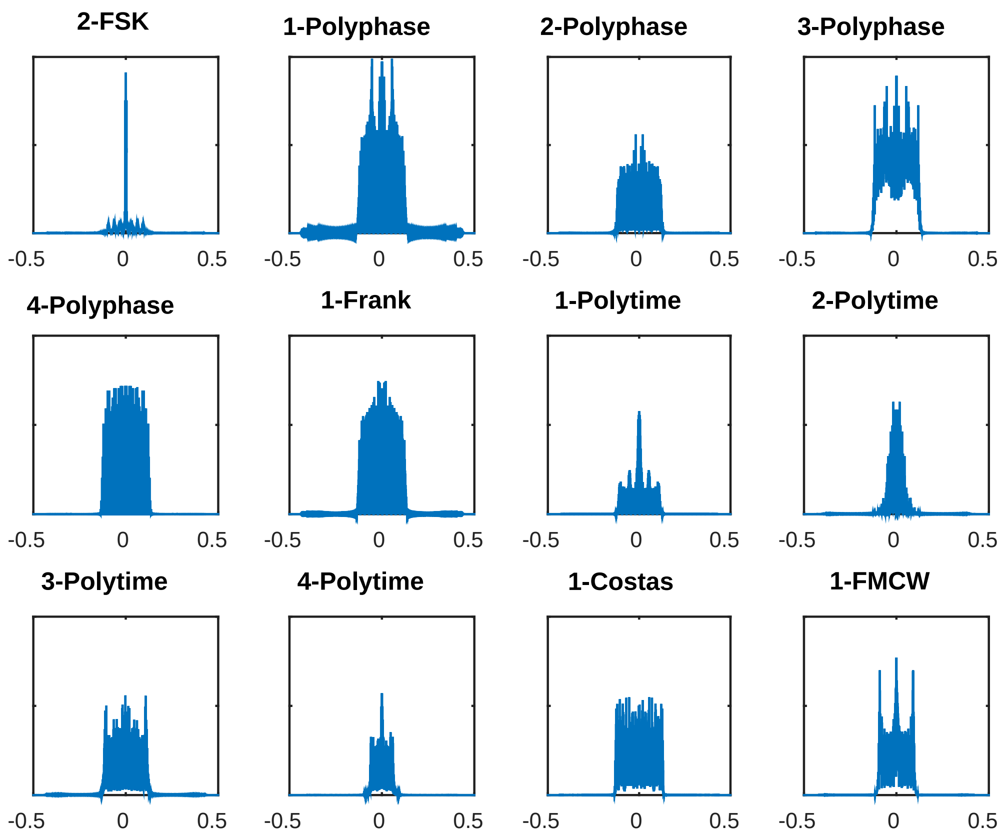


SCD of LPI Waveforms

- Signal to noise ratio (SNR) is given from the standpoint of a non-cooperative receiver

- To generalize classification, waveform parameters (# of phase states, pulse period, etc.) are randomized and classified as the same waveform

Alpha Profiles

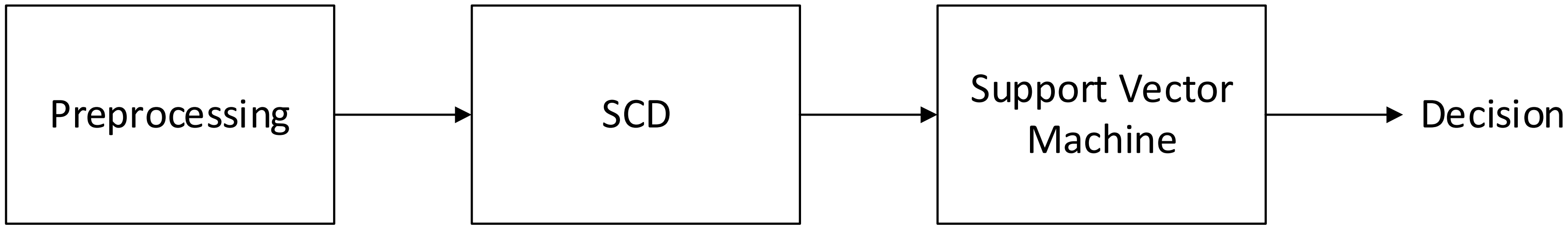


Classification of LPI Waveforms

Classification Structure

- LASSO used to determine which points in the alpha profile are most important
- Support vector machine (SVM) trained with most important points

System Description



Results

Results

TABLE I
CONFUSION MATRIX FOR -5 dB SNR

	2FSK	P1	P2	P3	P4	Frank	T1	T2	T3	T4	Costas	FMCW
2FSK	47	0	0	0	0	0	0	0	0	0	0	0
P1	0	10	7	4	3	8	4	2	6	4	1	1
P2	0	2	8	5	8	7	2	2	7	7	0	0
P3	1	0	12	10	3	7	0	1	2	10	1	1
P4	0	6	9	5	5	8	4	0	6	9	1	0
Frank	0	3	12	4	3	9	5	0	4	9	0	0
T1	0	3	7	4	5	8	20	0	1	2	0	0
T2	0	1	3	7	1	5	4	18	3	2	0	0
T3	0	5	10	4	4	5	1	2	6	9	2	0
T4	0	5	2	4	6	7	5	2	5	17	1	0
Costas	0	7	8	5	3	3	2	2	4	1	16	0
FMCW	0	0	9	1	2	1	2	0	3	2	1	28

Results

TABLE II
CONFUSION MATRIX FOR 10 dB SNR

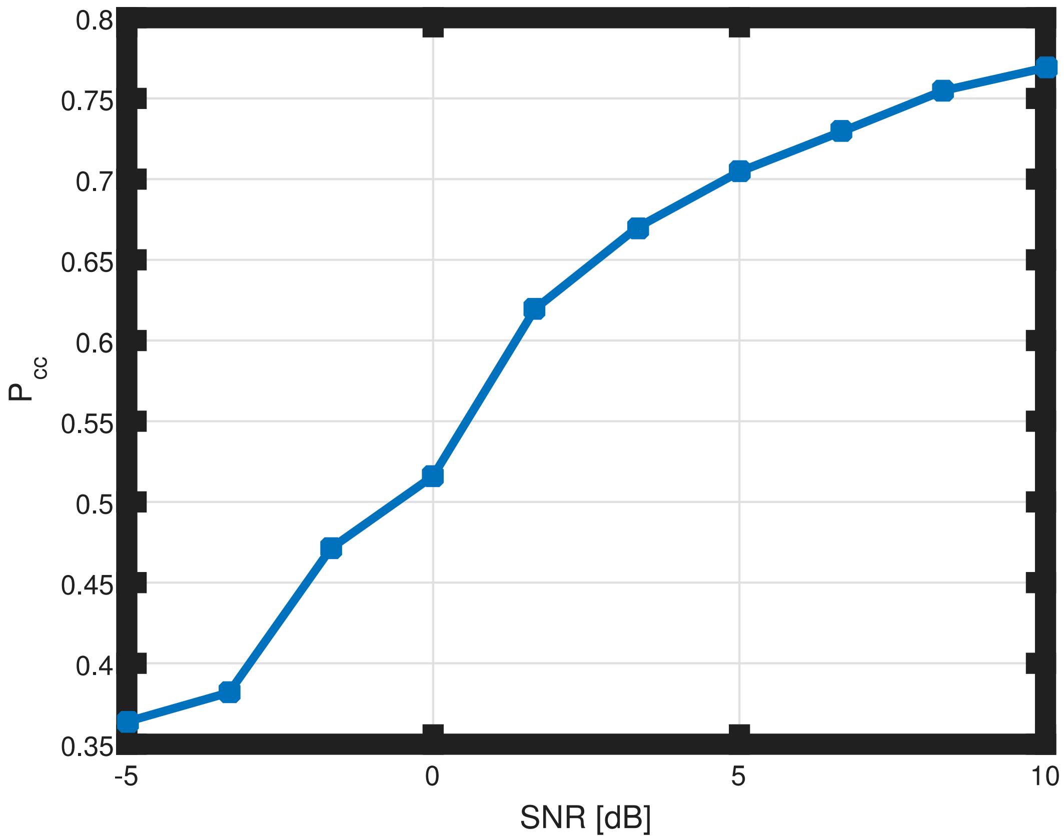
	2FSK	P1	P2	P3	P4	Frank	T1	T2	T3	T4	Costas	FMCW
2FSK	47	0	0	0	0	0	0	0	0	0	0	0
P1	0	36	0	0	0	0	0	0	0	1	3	12
P2	0	0	32	0	0	0	0	0	0	3	4	0
P3	0	0	0	21	0	0	0	0	0	12	5	7
P4	0	0	0	0	12	0	0	3	0	13	15	10
Frank	0	0	0	0	0	10	0	1	0	9	2	20
T1	0	0	0	0	0	0	46	0	0	0	2	0
T2	0	0	0	0	0	0	0	51	0	0	0	0
T3	0	0	0	0	0	0	1	0	32	2	5	0
T4	0	0	0	0	0	0	1	1	2	51	0	0
Costas	0	0	0	0	0	0	0	0	0	0	51	1
FMCW	0	0	0	0	0	0	0	0	0	0	0	56

Results

TABLE III
CONFUSION MATRIX FOR -5 TO 10 dB SNR

	2FSK	P1	P2	P3	P4	Frank	T1	T2	T3	T4	Costas	FMCW
2FSK	499	0	0	0	0	0	0	0	0	0	0	0
P1	0	204	26	13	12	18	31	18	38	35	29	65
P2	0	10	226	9	13	17	64	17	25	105	21	12
P3	1	3	35	199	9	15	20	23	13	132	17	35
P4	0	14	51	15	66	19	26	52	31	136	49	58
Frank	0	12	35	8	5	97	48	23	22	135	32	77
T1	0	8	37	19	12	16	375	0	8	9	18	1
T2	0	4	20	16	6	9	14	390	7	7	2	1
T3	0	24	33	11	11	25	20	18	220	65	36	21
T4	0	10	37	13	11	19	22	9	17	351	1	0
Costas	0	10	15	6	10	7	10	4	10	9	428	7
FMCW	0	2	11	1	3	2	2	0	3	2	1	484

Results



Conclusions

- Many LPI Radar signals are similar in the time domain
- Classification can be done using spectral correlation (SCD)
- With support vector machine-based classification, 35 percent correct classification can be achieved between 13 waveforms

Questions

- Any questions?