Fundamentals of Forced Oscillation Detection

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Outline

- Fundamental of Forced vs Modal Oscillations
- Importance of Detecting even Small Forced Oscillations
- Oscillation Detection – just an old Radar/Sonar Problem
- Why is knowing the Underlying Noise Spectrum is Important? Setting the threshold
- Periodic Forced Oscillation Detection and Performance
- Other Approaches to Identifying Forced Oscillations
- Power Detectors vs Periodic Oscillation Detectors

Fundamentals of Forced Oscillations vs Modal Oscillations

- Remember back to your second circuits course[(1)]

  3 different classification of a response
  - Total Response = Forced Response + Natural (Modal) Response
  - Total Response = Zero State Response + Zero Input Response
  - Total Response = Steady State Response + Transient Response

- Also have a stochastic problem
  - part of the response is a random process (e.g. ambient noise)
  - Remember a random process is best described by in power spectrum

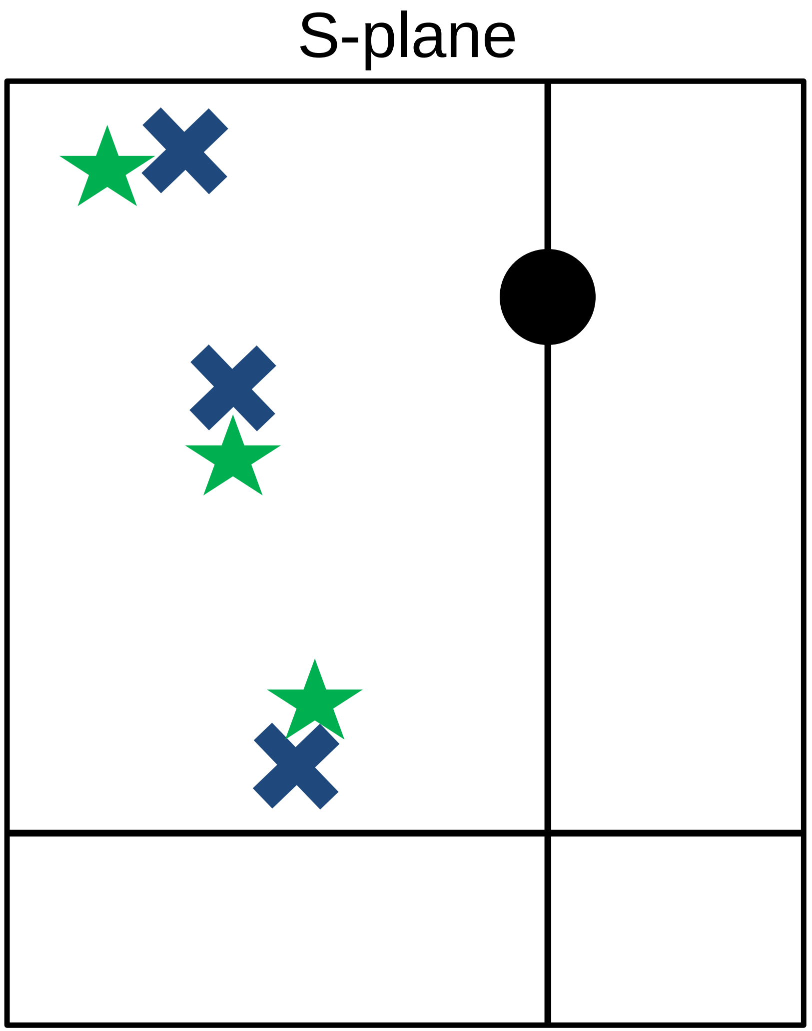
(1) Lathi's book Linear Systems and Signals

Forced Response vs Natural (Modal) Response

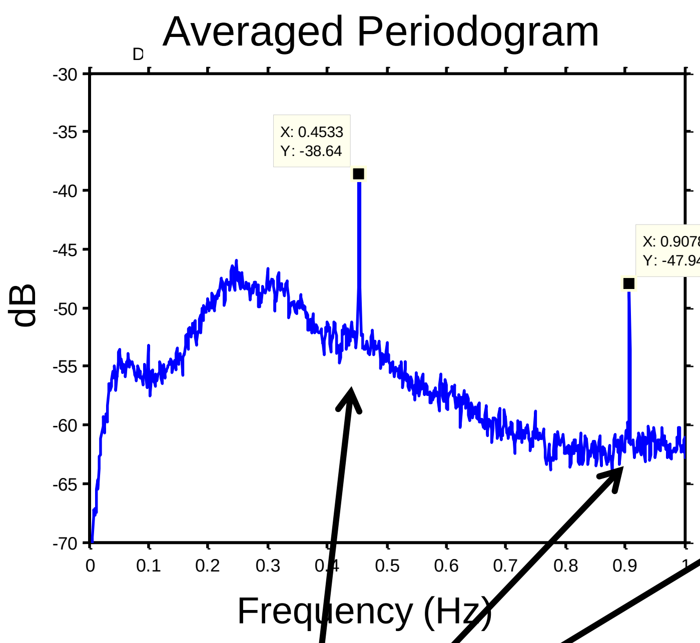
- Forced Response – portion of response associated with the driving excitation of the system
  - Periodic Forced Oscillation: approximately sinusoidal forced response, possibly with harmonics
- Natural (Modal) Response – portion of response associated with the modes (poles) of the system
- Problem: From measured synchrophasor data need to
  - Estimate modes, and
  - Detect forced oscillations
- We obviously care about the large forced oscillations but what about the small ones?

Impact of FO on Standard Mode Meters

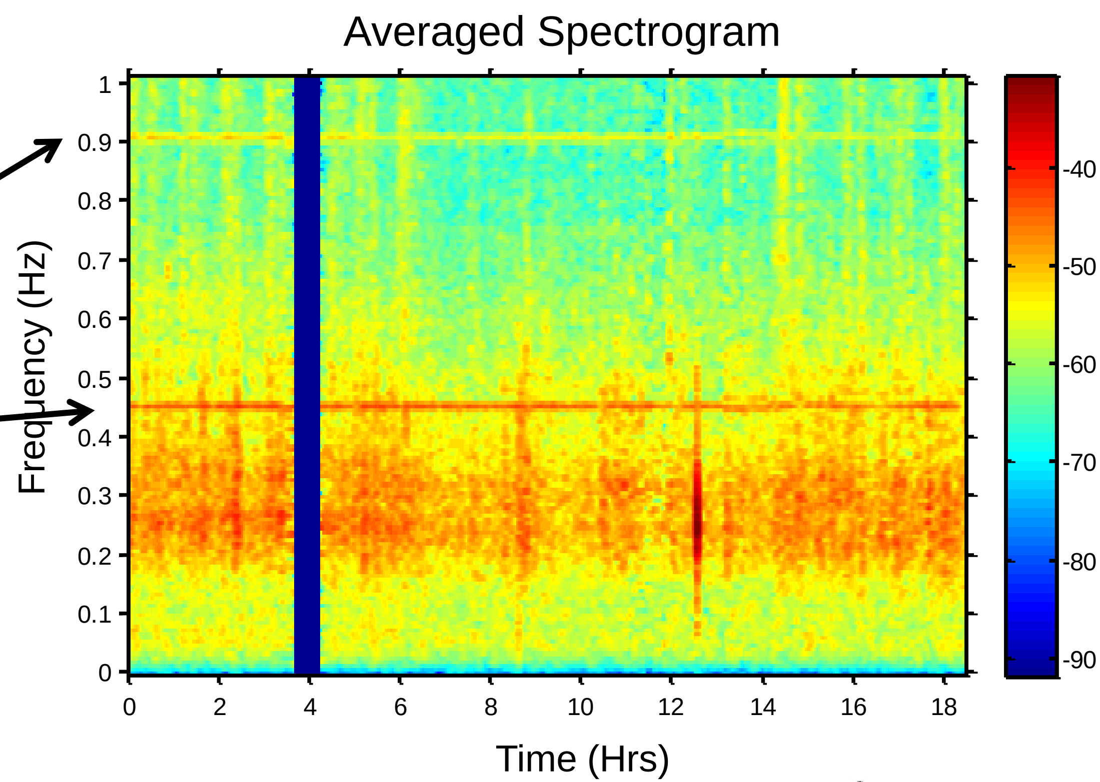
- Green Stars – True Modes
- Blue X's estimated modes under ambient conditions
- What if a sinusoidal FO is present in the data?
- The estimated mode can be biased toward the forced oscillation!



Small Eastern Intertie Periodic Forced Oscillation



- Note: not visible in time domain above ambient noise
- Visible throughout EI
  Much Less than 1 MW in Amplitude!



0.45 Hz and 0.90 Hz
Forced Oscillations

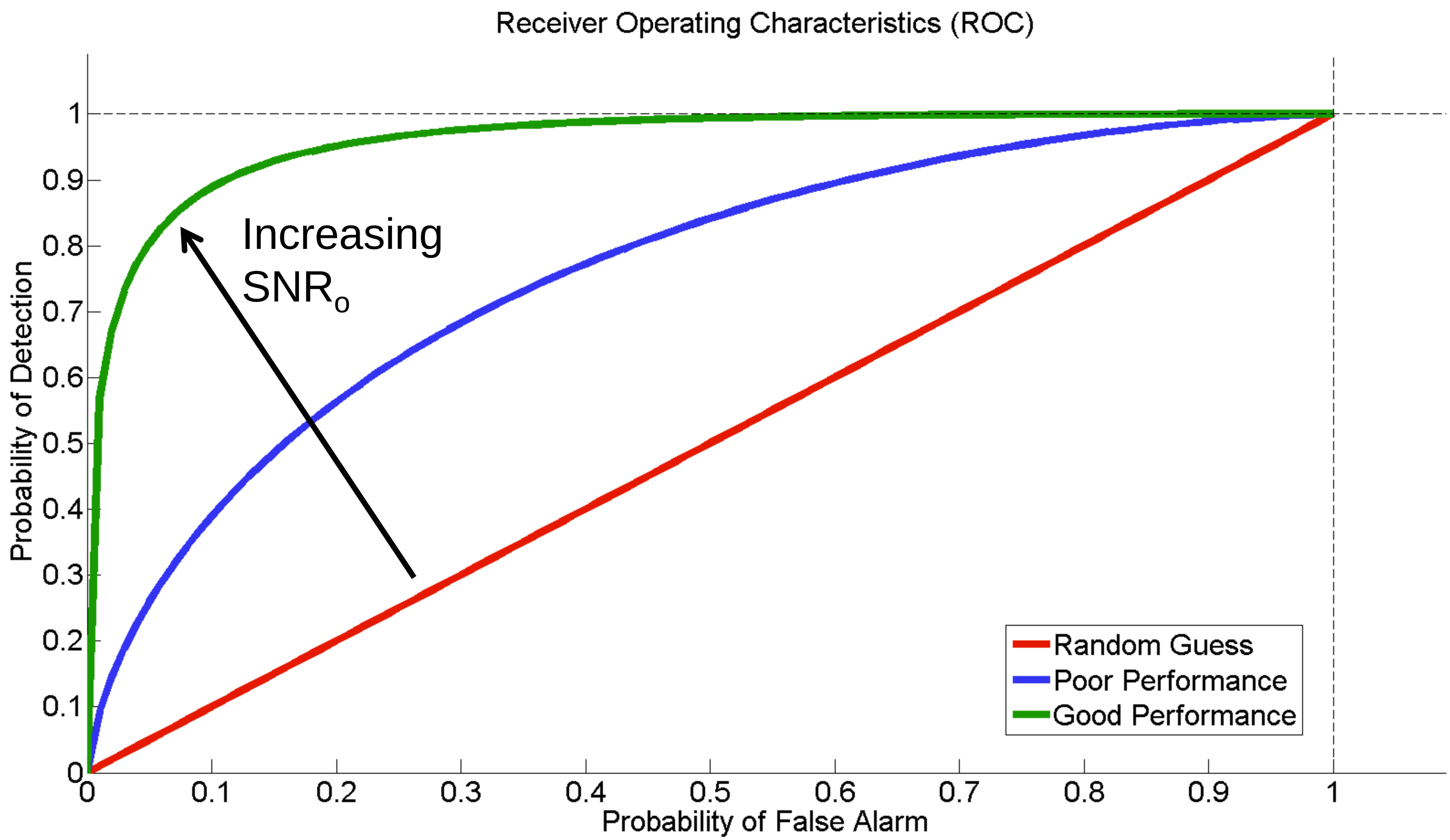
Oscillation Detection – Old Radar/Sonar Problem

- Oscillation Detection is not a new problem. Other disciplines like Radar/Sonar have been doing this for decades.
- Really it is a detection of oscillations in noise problem
- A major difference is that in the Power System case, the oscillation is usually in highly colored (ambient) noise
- Colored noise vs white noise
  - For white noise the power is evenly spread across frequency
  - For colored noise it is not.

Important Detection Terms and Concepts

- "Probability of Detection" – the probability of correctly identifying that an oscillation is occurring.
- "Probability of a False Alarm" – probability of concluding an oscillation is occurring when it is not.
- "Probability of a Miss" – probability of saying there is no oscillation when there actually is. (P_m=1-P_d)
- "Threshold" – a value set by the user defining the cutoff between saying Present or Not Present!
- There is a trade off between the Probability of Detection and False Alarm.
  - Can always make Probability of Detection higher but at the cost of also making Probability of False Alarm higher

Probability of Detection vs False Alarm



Forced Oscillation Detection and Estimation

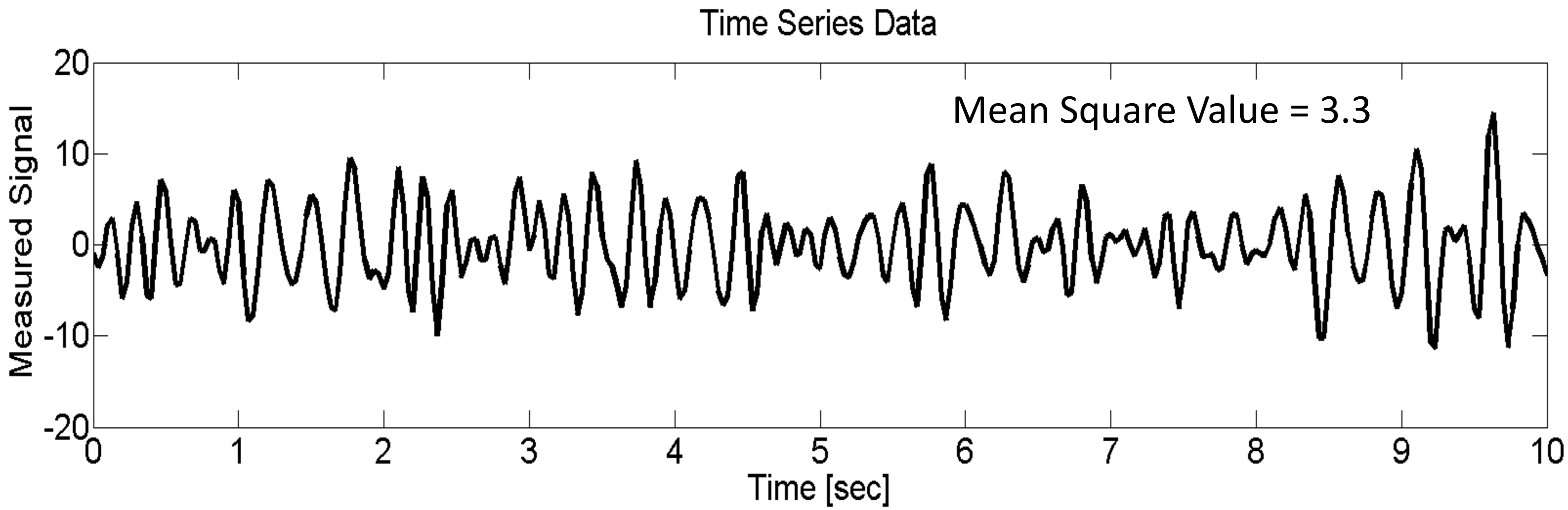
- Identifying a forced oscillation is both a Detection and Estimation Problem.
- What needs to be detected and estimated
  - Detect: the presence of an oscillation
  - Estimated:
    - Amplitude or mean square value (MSV or Power) of the oscillation
    - Start time and duration of oscillation
    - Frequency of the oscillation
    - Possibly harmonics
    - Location of the oscillation
    - Etc.
- What drives the performance of the detector/estimator?
- How do you set the threshold?

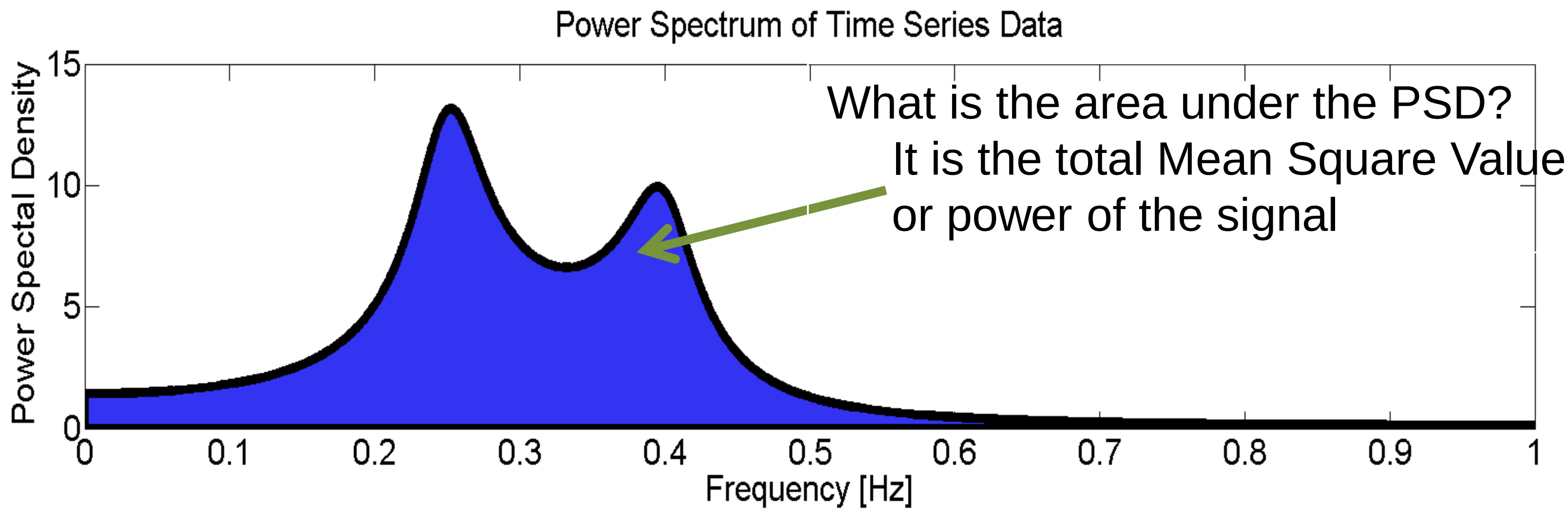
What Drives the Detector/Estimator Performance

- Amplitude or mean square value of oscillation
  - Obviously the larger the oscillation the easier to detect/estimate
- Start time and duration of oscillation
  - The longer the time duration the easier to detect/estimate
- Ambient Noise
  - The more noise the more difficult to detect/estimate, we'll say more in a minute
- Analysis Method

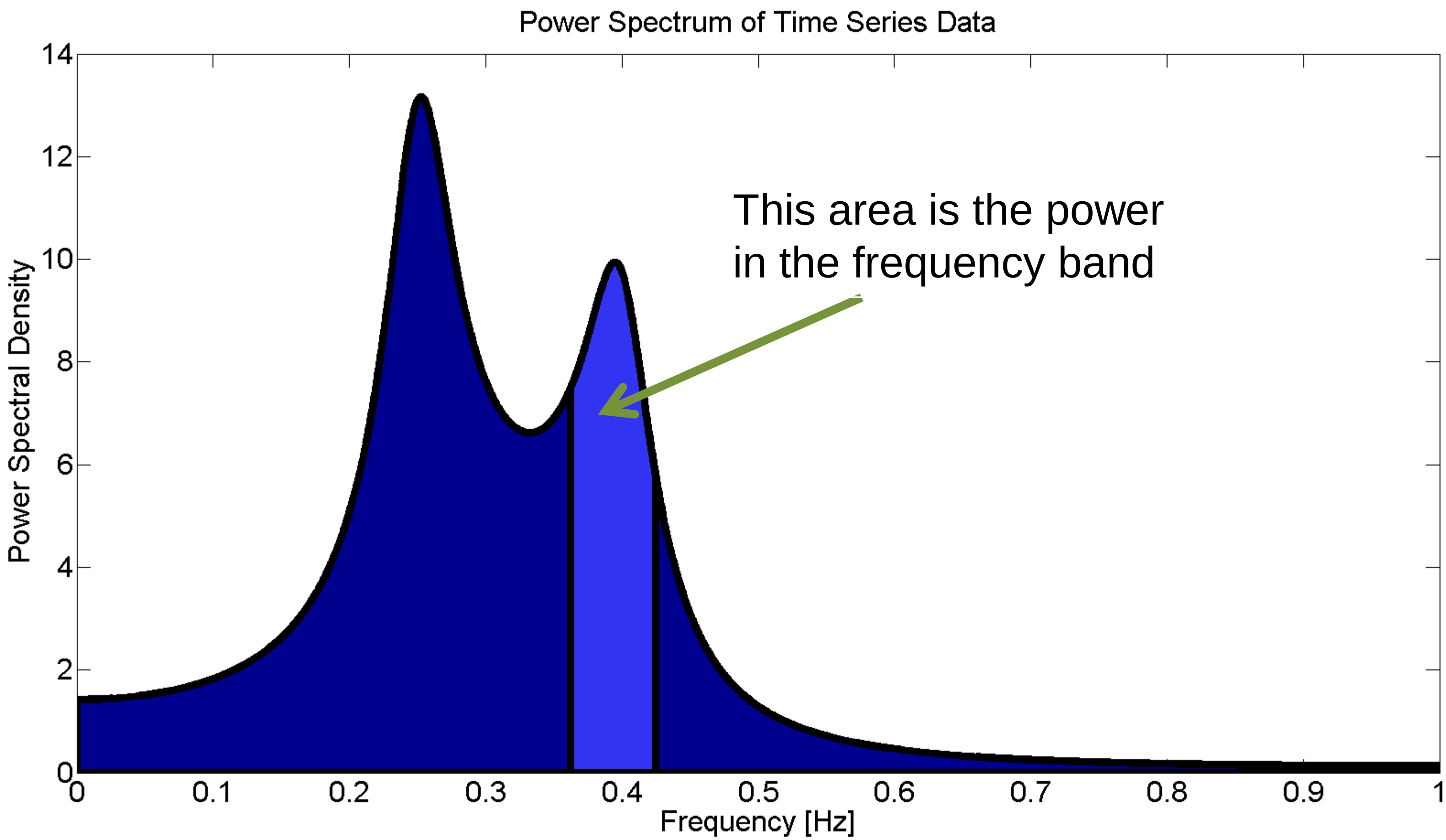
Also, knowing the power spectral density allows one to set the Threshold for a given probability of false alarm!

Ambient Noise Power Spectral Density: What does it tell us?





Why knowing the Underlying Ambient Noise Spectrum is Important!



Periodic Forced Oscillation Detection
Hypothesis Test For Periodic Forced Oscillation

Measurement

Null Hypothesis

Ambient Noise

$$H_o:\ \ y(k) = x(k) \qquad k = 0,1,\cdots,(K-1)$$

$$H_1:\ \ y(k) = x(k) + s(k) \qquad k = 0,1,\cdots,(K-1)$$

Alternative Hypothesis

Sinusoid or Sum of Sinusoids

So what is the decision rule?

- Intuition suggest if I have a sharp peak at a certain frequency in the periodogram (absolute value of windowed FFT squared) of the data that it could be a periodic forced oscillation.
- Under Ambient noise conditions the simple periodogram is on average the power spectral density of the ambient noise.
- Thus fundamentally the test is comparing the simple periodogram of the measured signal to the power spectral density of the noise.
- Formally this approach has its origins in Statistics and Statistical Signal Processing (Radar/Sonar). But intuitively it also makes sense.

So what is the decision rule?

Decide a Forced Oscillation is Present if

$$\hat{\phi}_y(\omega_m) \geq \gamma(\omega_m) \quad for\ some\ \omega_m\ in\ frequency\ band\ of\ interest$$

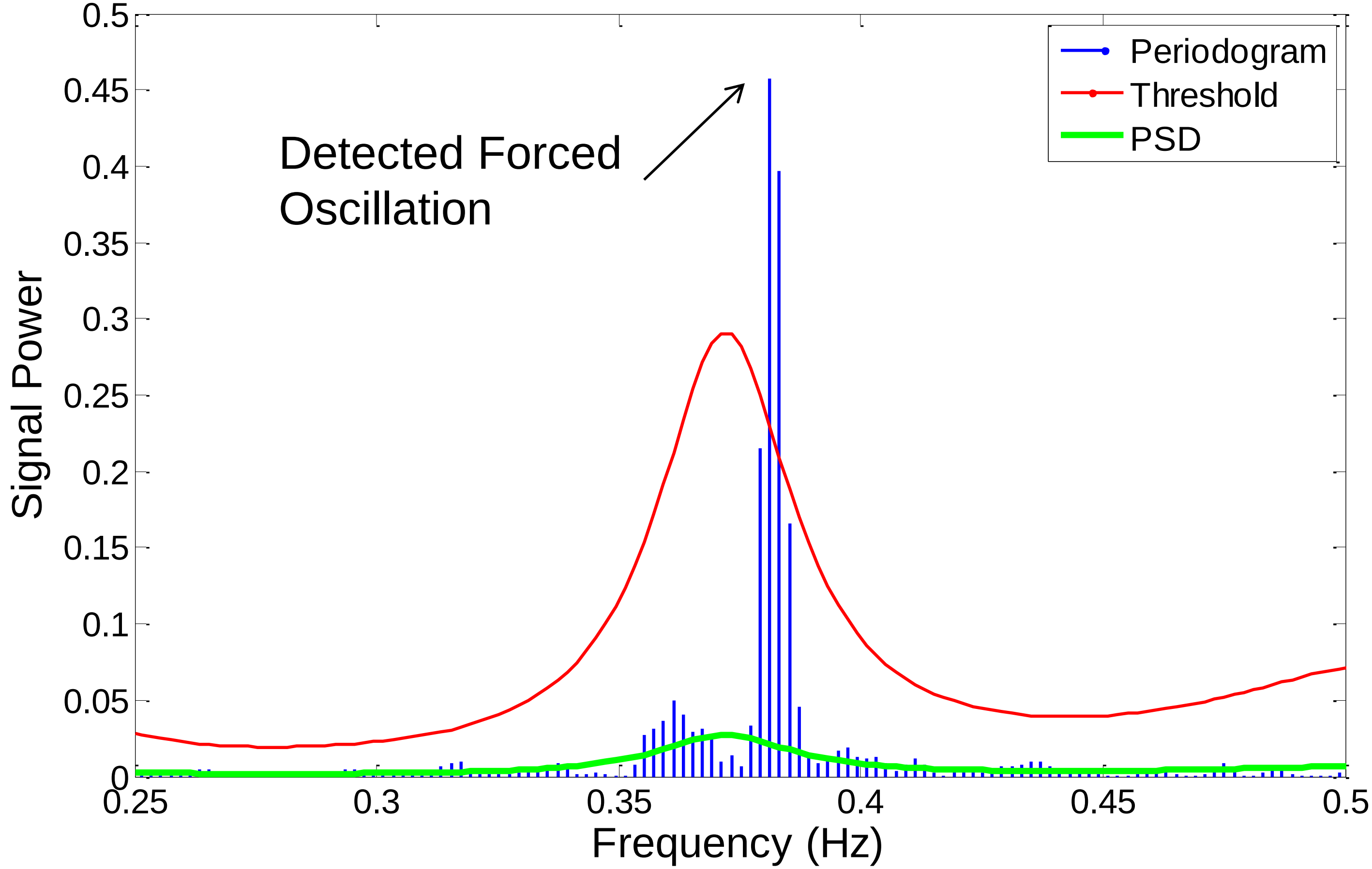
Test Statistic = windowed simple periodogram

Threshold = scaled version of ambient noise spectrum

$$\hat{\phi}_y(\omega_m) = \frac{1}{KU}\left|\sum_{k=0}^{K-1} y(k)v(k)e^{-j\omega_m k}\right|^2$$

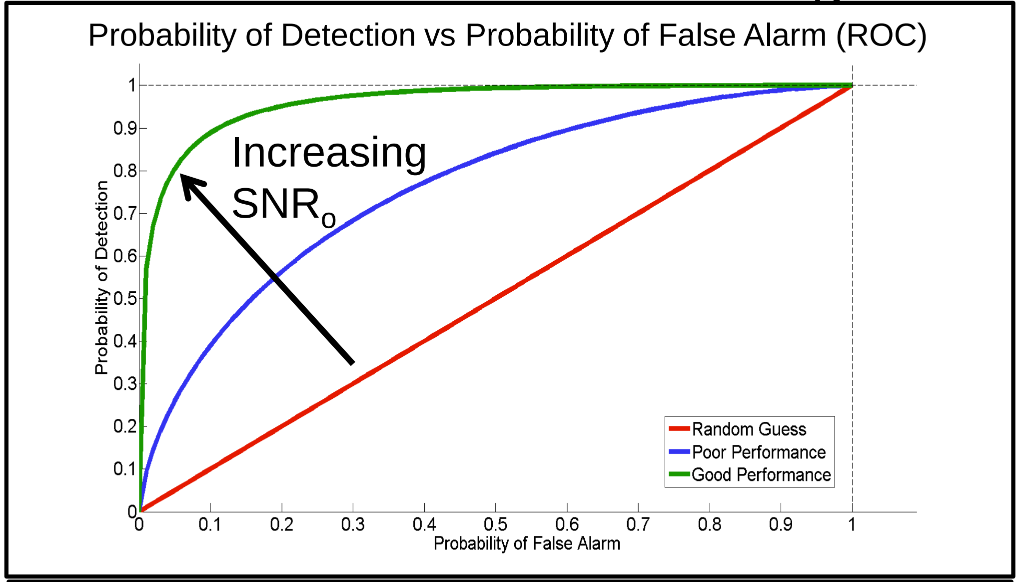
$$\gamma(\omega_m) = \phi_x(\omega_m)\ln\left(\frac{B}{P_{FA}^{max}}\right)$$

Example



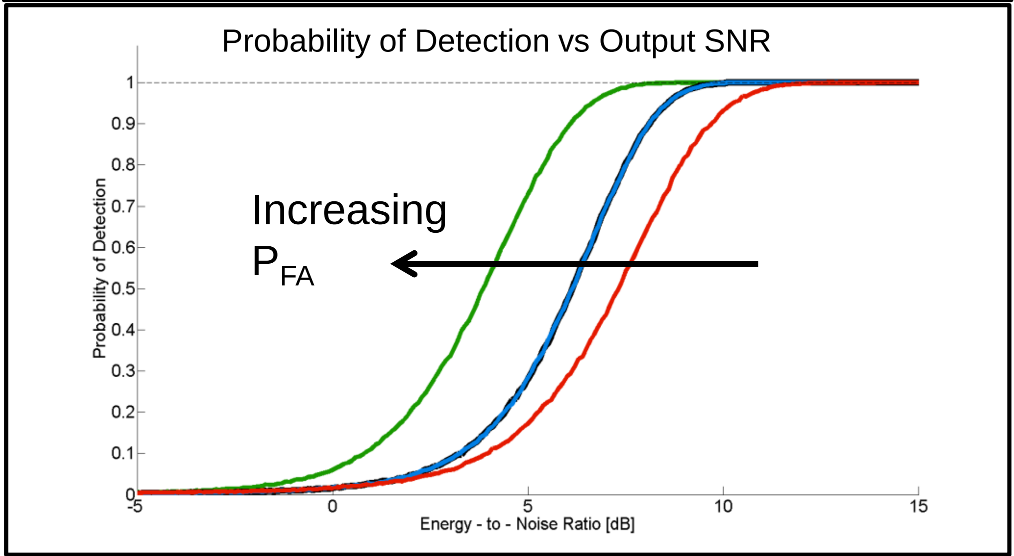
Periodogram
Threshold
PSD
Detected Forced Oscillation
Signal Power
Frequency (Hz)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.25
0.3
0.35
0.4
0.45
0.5

So how well does it perform, i.e. what is the P_D?



Probability of Detection is a function the Output SNR and the Probability of False Alarm

$$P_D = Q_{2\times SNR_o}^{\chi_2'^2}\left(2ln\left(\frac{B}{P_{FA}^{max}}\right)\right)$$



- Q is right tail of non-central Chi-square distribution
- Monotonic Increasing Function of
  - ❑ SNR$_o$
  - ❑ PFA

What influences Output SNR?

$$SNR_o = \frac{A^2}{2\phi_x(\omega_m^{FO})} \times \mu \times \rho \times \frac{CG^2_{[\epsilon,\eta]}}{2U}$$

Output SNR

Ratio of Sinusoid Mean Square Value to Ambient Noise Spectrum

Time duration Of Forced Oscillation

Percent of analysis Window containing Forced Oscillation

Function of Window

Summary Of Periodic Oscillation Detection

- Compute Threshold
- Compute Test Statistic – Windowed Periodogram
- Apply Hypothesis Test
- Note:
  - Can Use Multiple Detection Windows
  - User sets P_{FAmax}
  - Performance described by P_d vs SNR_o curves
- See paper for more details on windows, zero-padding and use of multiple windows

J. Follum, J.W. Pierre, "Detection of Periodic Forced Oscillations in Power Systems," *IEEE Trans on Power Systems*, vol. 31, no. 3, pp. 2423-2433, May 2016.

Other Approaches to Identifying Forced Oscillations

- Periodic Oscillation Detectors
- Energy Detector in Band
- Multi-Channel Methods – coherency detectors
- Matched Filter Detectors
- High Resolution Spectral Estimators

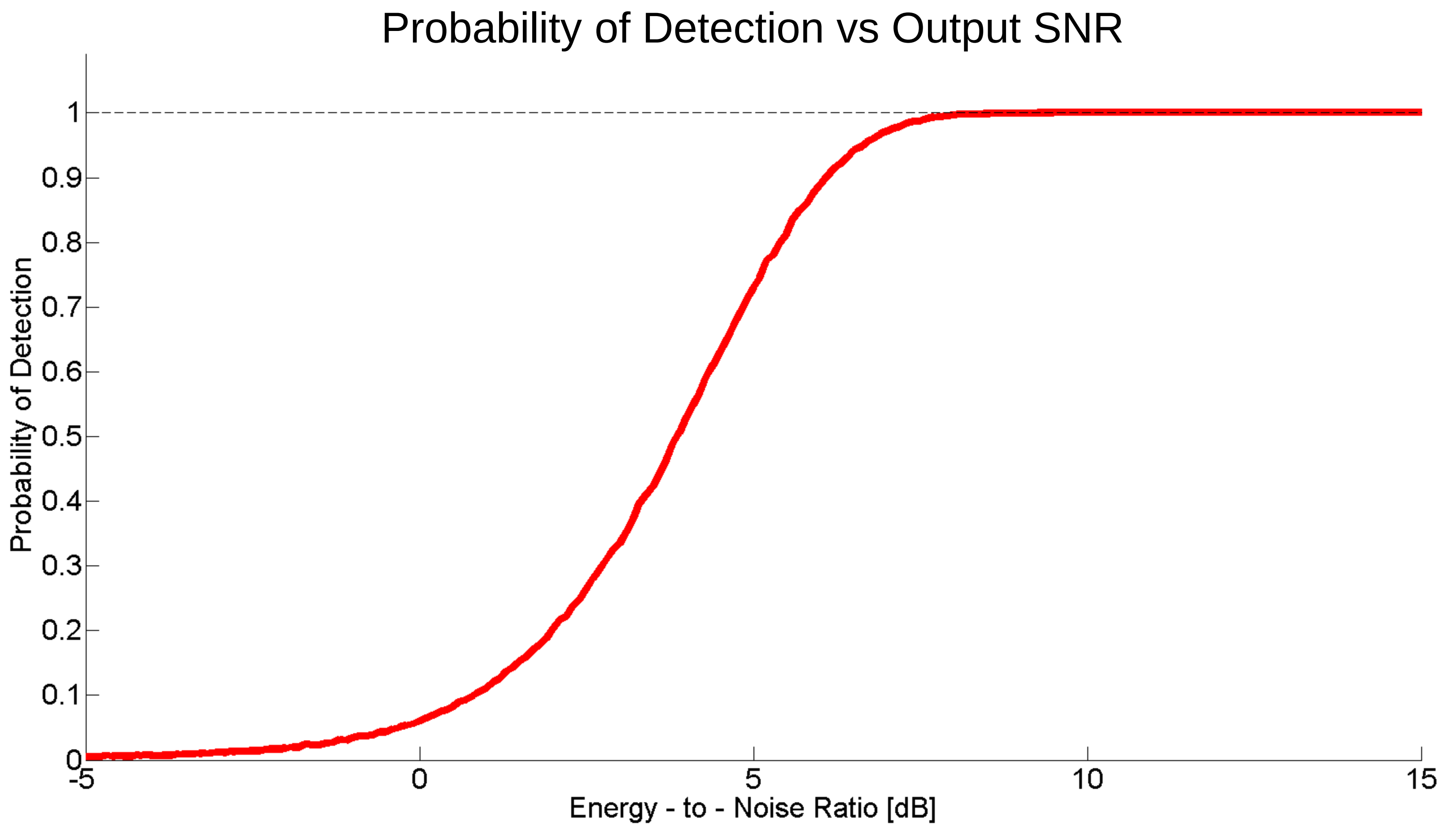
Oscillation vs Energy Detectors

- Energy Detectors – detects the power (MSV) in a frequency band, and possibly start-time and duration.

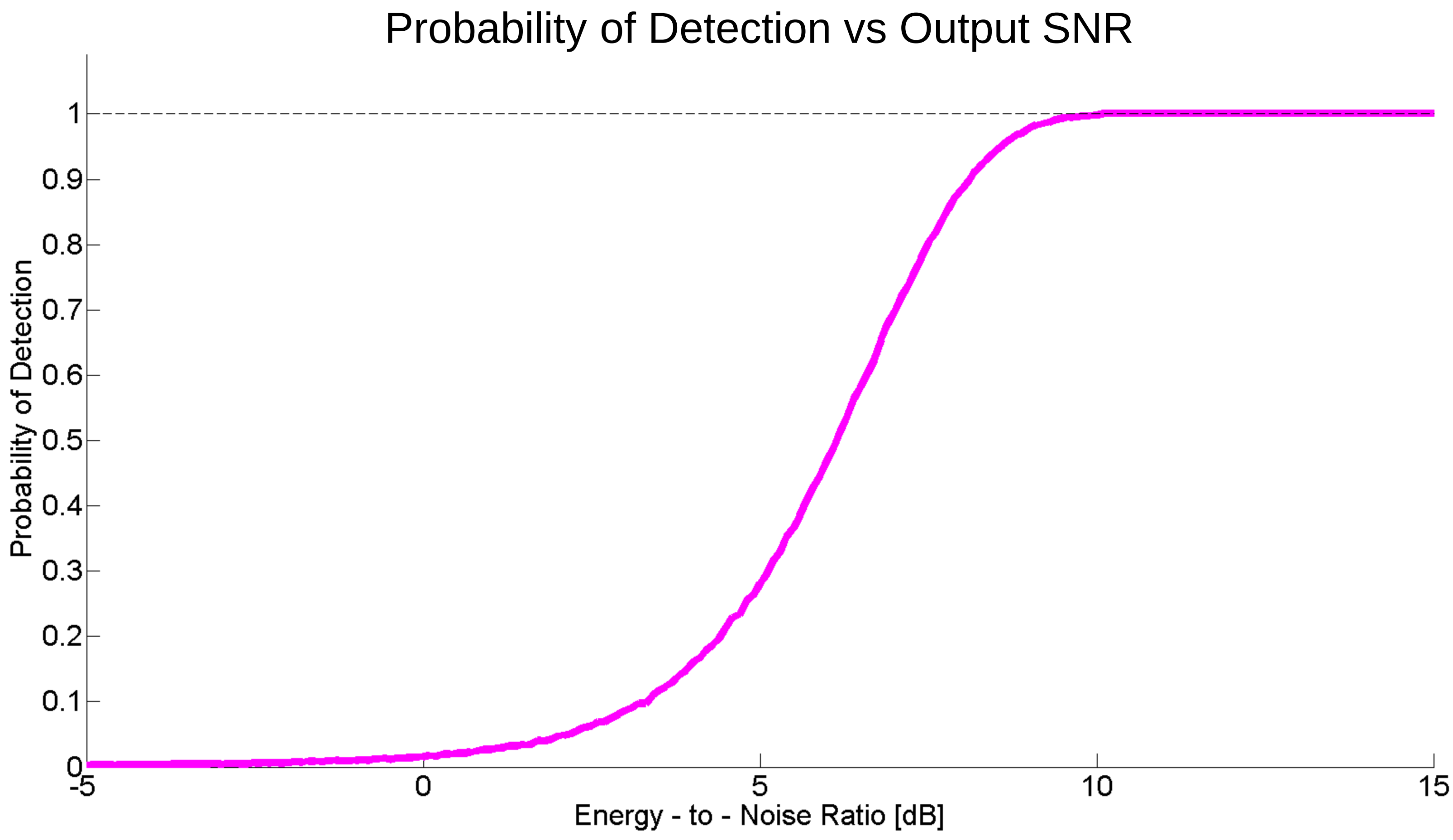
- Periodic Oscillation Detectors – detects oscillations including frequency, amplitude (or MSV), and possibly start-time, and duration.

- What are the advantages and disadvantages of each?
  - Remember narrower the band, the less noise!

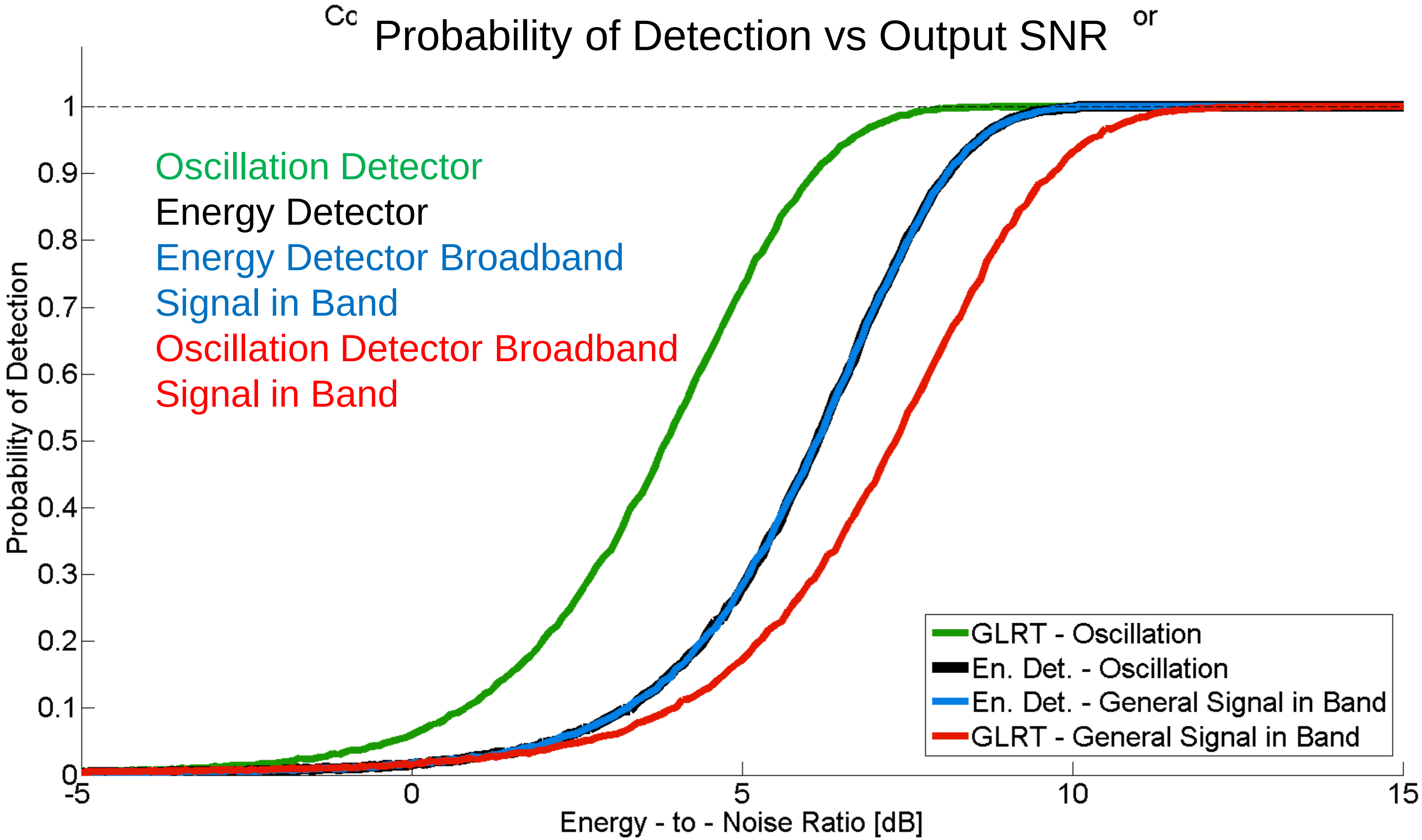
Periodic Oscillation Detector



Power Detector



Comparison


Cc
Probability of Detection vs Output SNR
or
Oscillation Detector
Energy Detector
Energy Detector Broadband
Signal in Band
Oscillation Detector Broadband
Signal in Band
Probability of Detection
Energy - to - Noise Ratio [dB]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-5
0
5
10
15
GLRT - Oscillation
En. Det. - Oscillation
En. Det. - General Signal in Band
GLRT - General Signal in Band

Take Aways

- Forced Oscillation and Modal Oscillations are different phenomenon
- Can simultaneously estimate modes and forced oscillations
- Even small forced oscillations are problematic because they can mislead standard mode meters
- Knowing or having a good estimate of the ambient power spectral density can help set detection thresholds
- Theory is well established including performance
- Both power and oscillation detectors have advantages, some combination may provide useful insights

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