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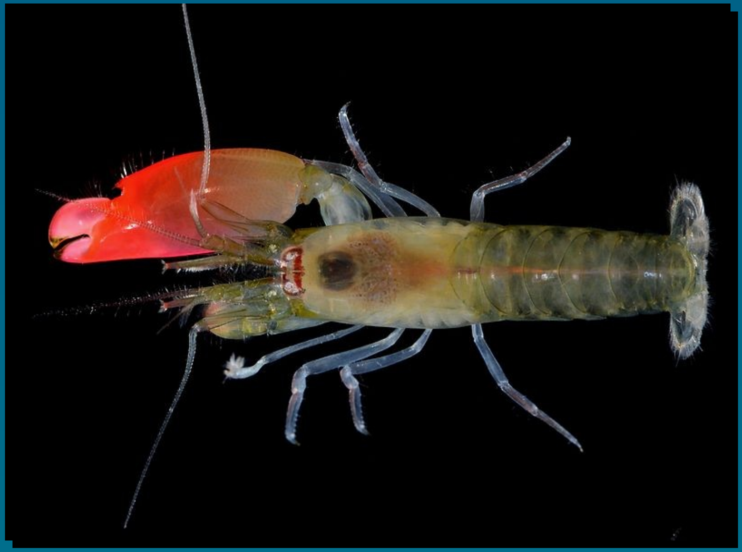
# A nonlinear technique for acoustic signal detection in impulsive noise



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# Talk structure

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- Motivation and the problem addressed
- The signal processing scheme used
- Nonlinear systems behaviours
- The correlator
- Measuring detection performance
- Results – simulated and real
- Conclusions

# Motivation

- Problem: Detecting acoustic signals underwater becomes more difficult as the signal-to-noise ratio reduces (so called weak signal case)

- Problem is not helped if the noise is impulsive

- Previous application of nonlinear chaotic systems to weak signal detection appeared spectacular[1,2]
  - Context: Single sine wave in Gaussian noise
  - Finding: “Noise immune”    (I could not repeat this!)

- PhD: Repeat prior work, find other nonlinear behaviours, apply to a range signal and noise types and then measure and compare detection performance

# General scheme

## Measuring detection performance

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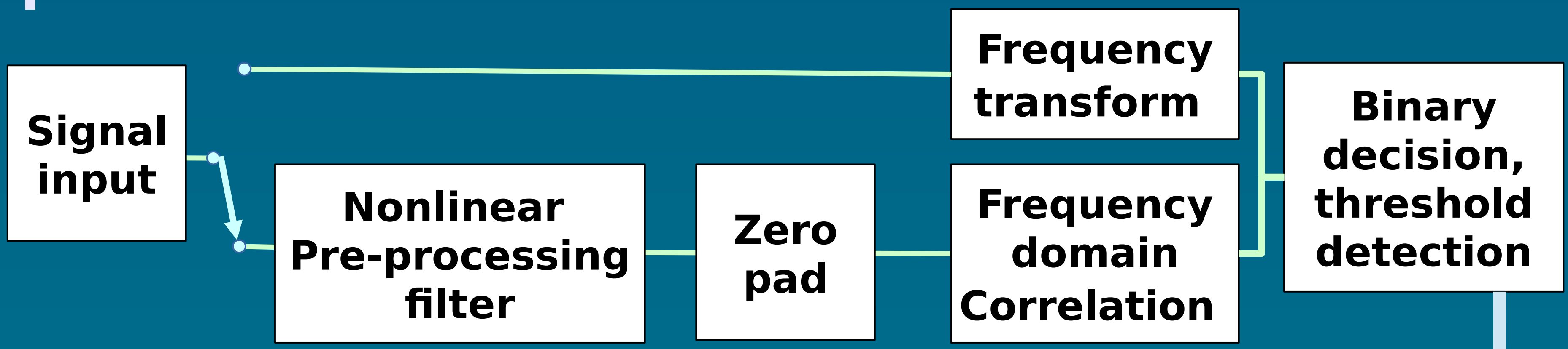


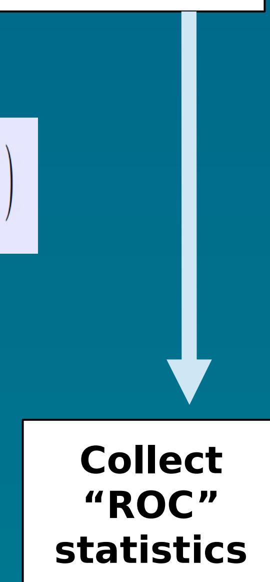


- SIGNAL INPUT: Simulated sine wave + simulated noise

$$n(t) + A\cos(\omega t + \phi)$$

- Alternates between 'signal+noise' and 'noise only'
- CORRELATOR: More later ….
- “ROC” ANALYSIS: More later ….
- NONLINEAR FILTER: Many choices available

Nonlinear Pre-processing filter

# Nonlinear systems

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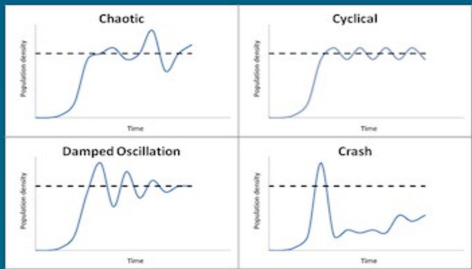
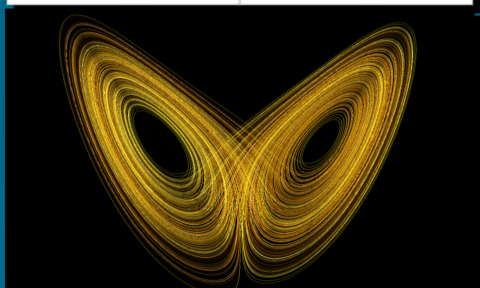


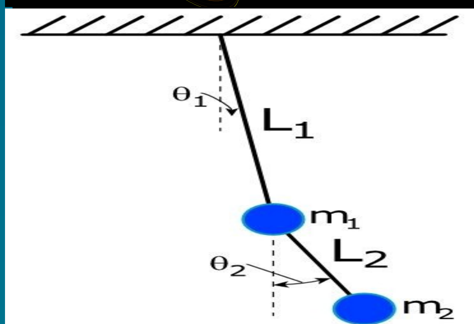

Population model

$$f(x) = rx\,(1 - x).$$



Lorenz system

$$\frac{dx}{dt} = \sigma(y - x)$$
$$\frac{dy}{dt} = x(\rho - z) - y$$
$$\frac{dz}{dt} = xy - \beta z$$



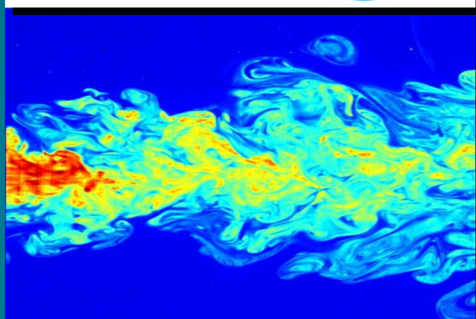

Duffing system

(Langevin system)

Inertia
Spring Force
Drive

$$\ddot{x} + \gamma\dot{x} + \alpha x + \beta x^3 = \delta \cos \omega t$$

Damping
Nonlinearity



Navier Stokes

$$\overbrace{\rho}^{\substack{\text{MASS}\\ \text{Density of}\\ \text{the fluid}}}\left(\overbrace{\frac{\partial V}{\partial t} + V\cdot\nabla V}^{\substack{\text{ACCELERATION}\\ \text{How velocity experienced}\\ \text{by a particle changes with time}}}\right) = \overbrace{\underbrace{\nabla P}_{\text{Internal}} + \underbrace{\rho g}_{\text{External}} + \underbrace{\mu\nabla^2 V}_{\text{Internal stress}}}^{\substack{\text{FORCE}\\ \text{All the forces that}\\ \text{are acting on the fluid}}}$$

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# Nonlinear system behaviours

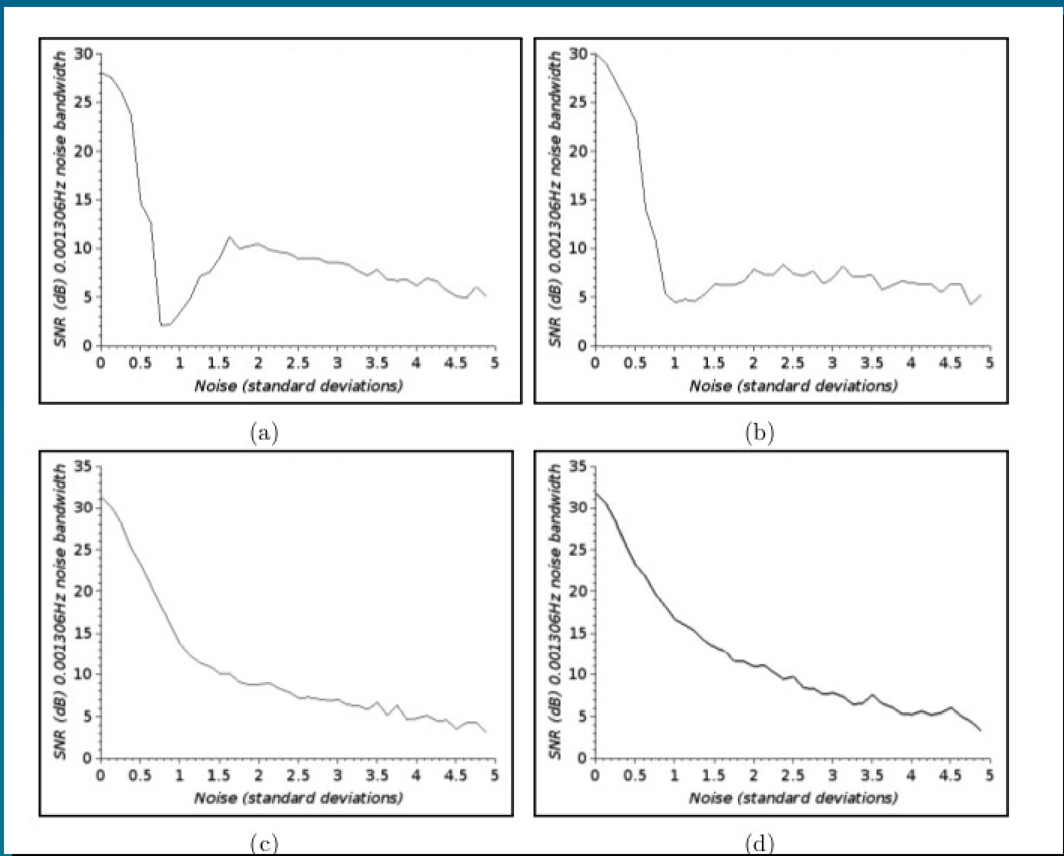
- Chose the frequency normalised Duffing system:

$$\frac{d^2x}{dt^2}+\delta\frac{dx}{dt}-\alpha x+\beta x^3=\gamma_c\cos\left(\omega_0 t\right)$$

- Looking for a 'nonlinear' property or behaviour that gives some advantage
- Two behaviours investigated in the PhD:
  - Stochastic Resonance
  - Chaos-to-stable transition

# Nonlinear behaviour:
## Stochastic Resonance[3]





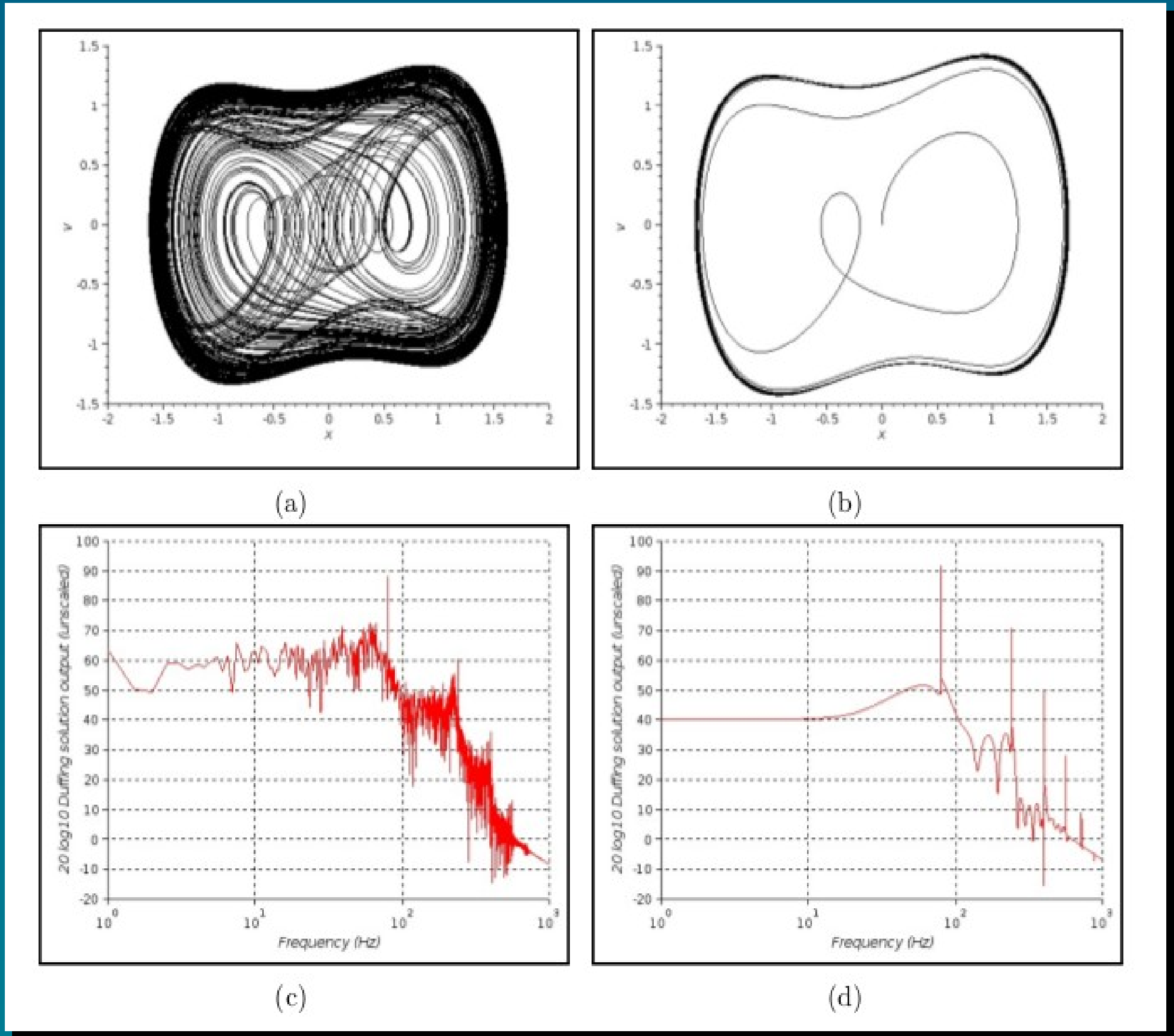

- Configure the nonlinear 'filter' at the peak
- Pre-process the input signal through the filter
- Detect as per normal
- Result: No benefit (gain) found in this application

# Nonlinear behaviour:
## Chaos-to-stable transition

### Phase Space? A quick recap

- A representation of all the states of a dynamic system
- Dimension of phase space = degrees of freedom in the system (Duffing = 2, Lorenz = 3)
- Characterised by a trajectory linking all states as the system moves between states
- Dynamic states of the Duffing system usually defined by velicity and displacement
- Reveals fixed points (stable and unstable) as well as stable loops
- Stable closed loop trajectory called a LIMIT CYCLE

# Nonlinear behaviour:
## Chaos-to-stable transition




- TOP: Phase space chaos and stable
- Stable trajectory called a LIMIT CYCLE
- BOTTOM: Spectra, chaos and stable
- The main peak rises by around 3dB

**Signal input** + **Nonlinear Pre-processing filter**

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# Implementation

- The input signal and the Duffing 'filter' combine as:

$$\frac{d^2x}{dt^2}+\delta\frac{dx}{dt}-\alpha x+\beta x^3=\gamma_c\cos(\omega_0 t)+n(t)+A\cos(\omega t+\phi)$$

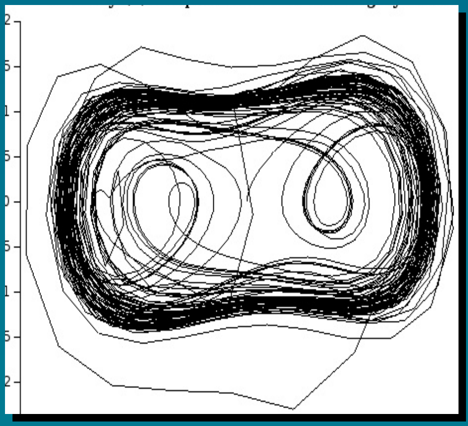
- ...recast as two first order systems and numerically solved for 'x' (timeseries), using a Runge-Kutta 4 stage fixed step method
- System configured at the point of transition, controlled mostly by the first force term amplitude (“gamma_c”)
- Addition of the input 'tips' the system into stability

Zero pad

Frequency domain correlation

# The Correlator

- On the stable limit cycle, the normalised Duffing has *nearly* constant output amplitude, with frequency
- So, make a replica limit cycle (with all the harmonics) and use the REPLICA CORRELATION coefficient as the detection parameter
- Zero pad, four-phase, transient discard, frequency domain



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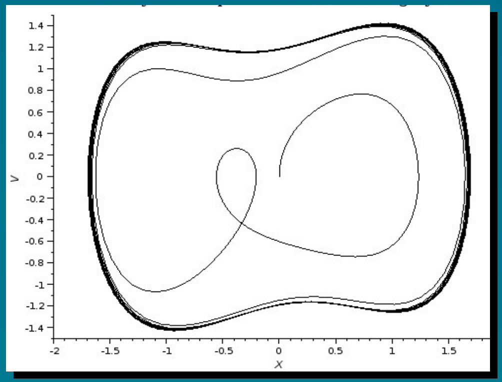


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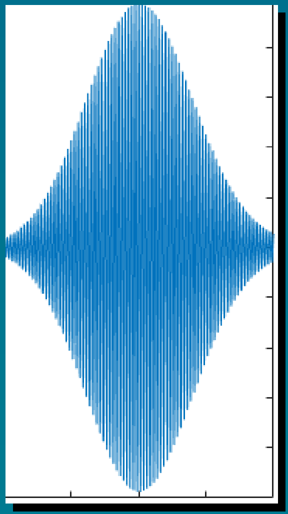
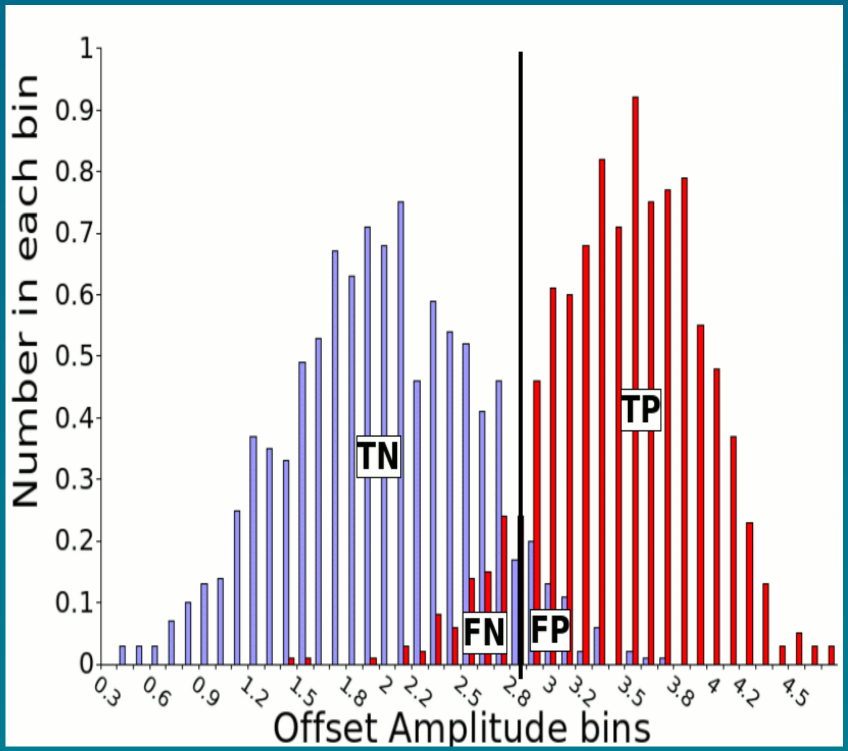


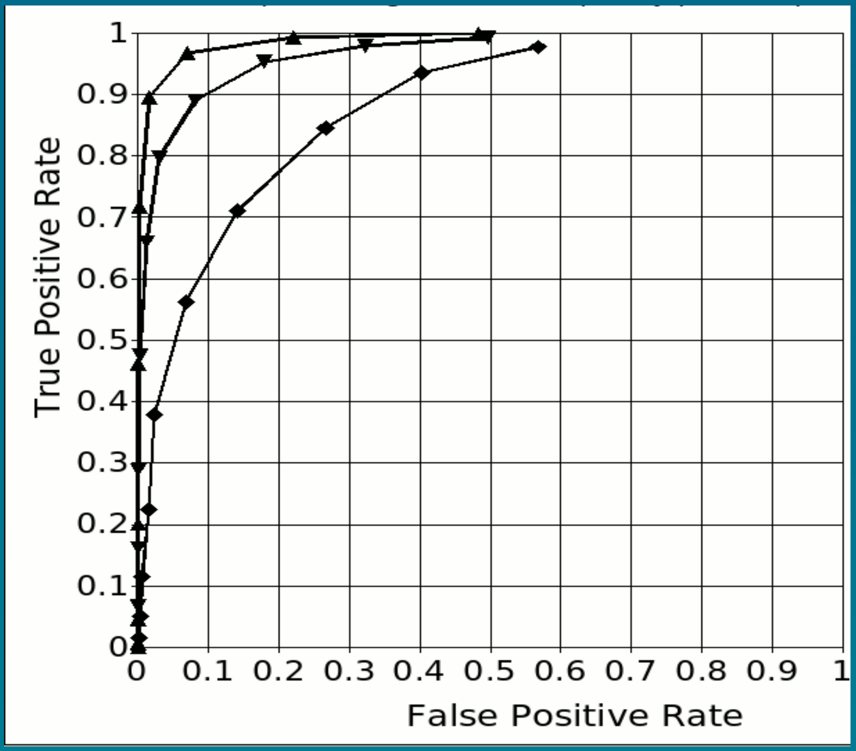
Binary decision, threshold detection

# Detection performance metric
## (Receiver Operating Characteristics)[4]

$$True\ Positive\ Rate\,(TPR) = \left(\frac{TP}{TP+FN}\right)$$

$$False\ Positive\ Rate\,(FPR) = \left(\frac{FP}{TN+FP}\right)$$



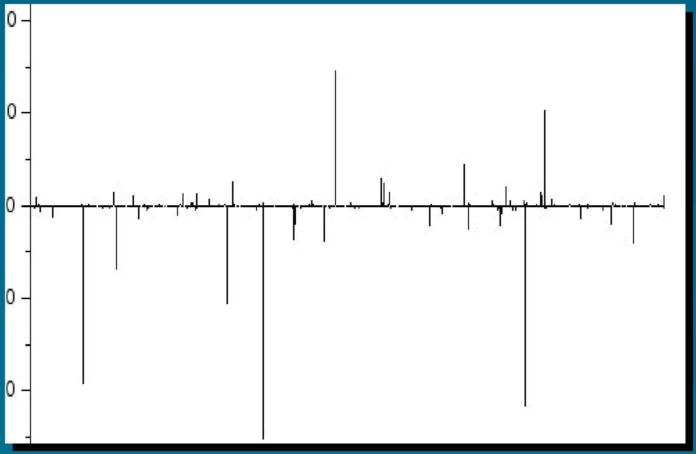
# Approach

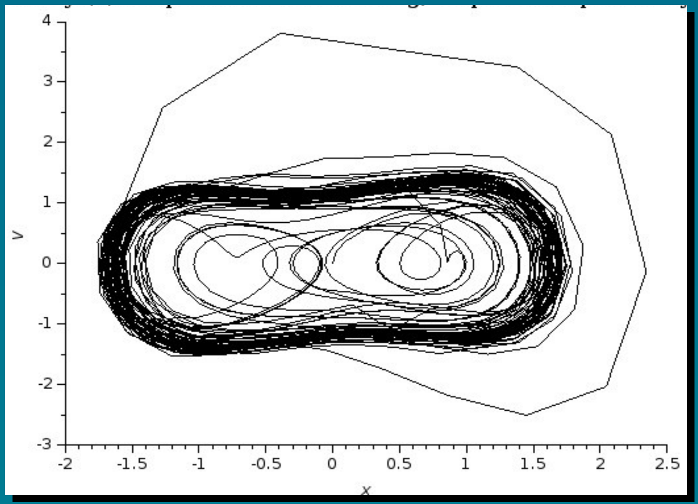
- Randomised phase ($\varphi$) ROC analysis
- Binary decision detection: signal present/absent
- PhD: Two different parameters used for ROC analysis:
  - Correlation coefficient: A novel correlation using the limit cycle as a replica
  - Amplitude: Fixed frequency bin in the Amplitude Spectral Density.
- Amplitude statistic not suitable when the Duffing pre-processing is in the SP chain. Used here, only for the detector performance comparison
- Input: Simulated single tone with additive simulated impulsive noise

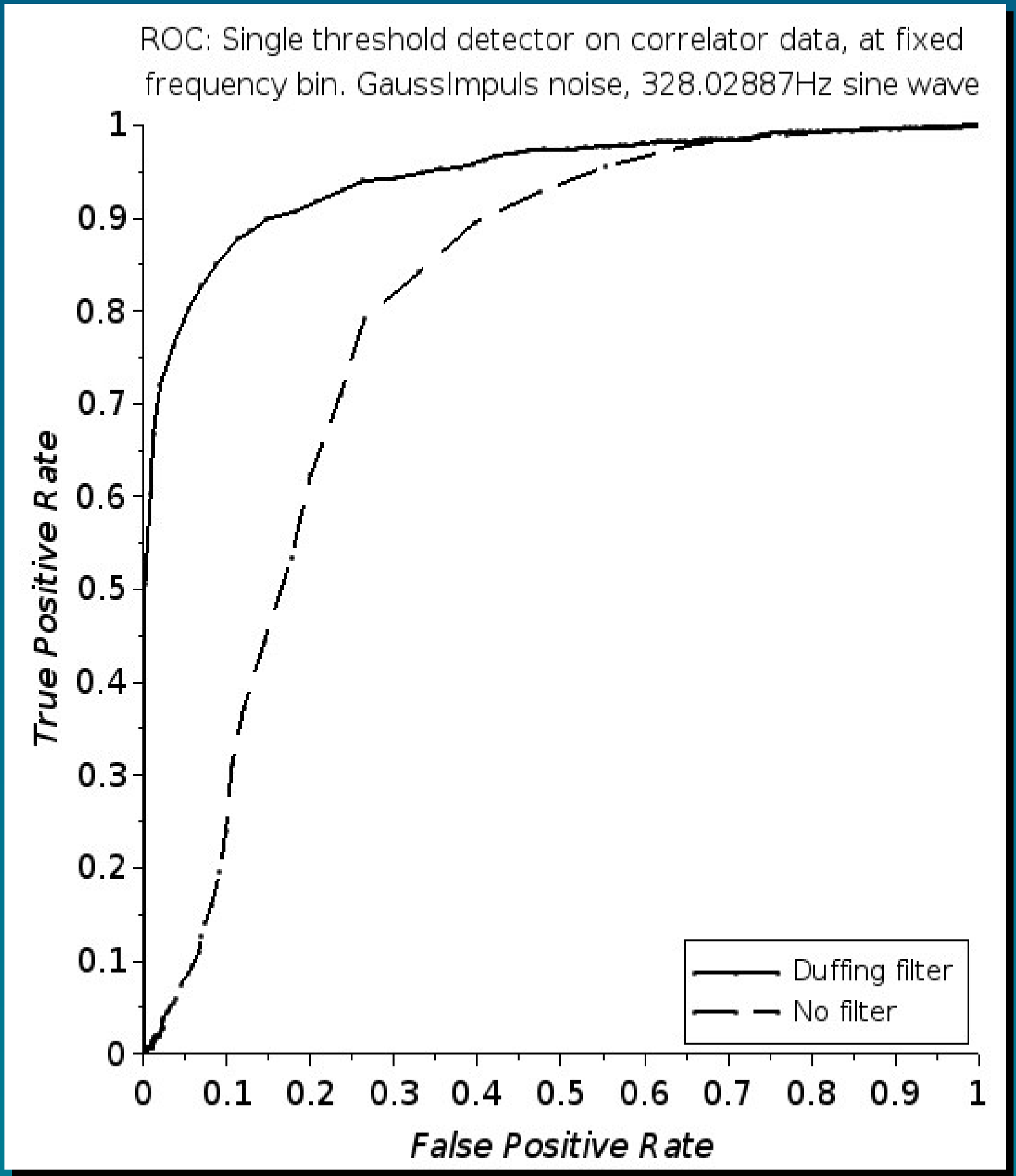
# Results



Sine wave plus only impulsive noise (Gaussian noise to power 11)



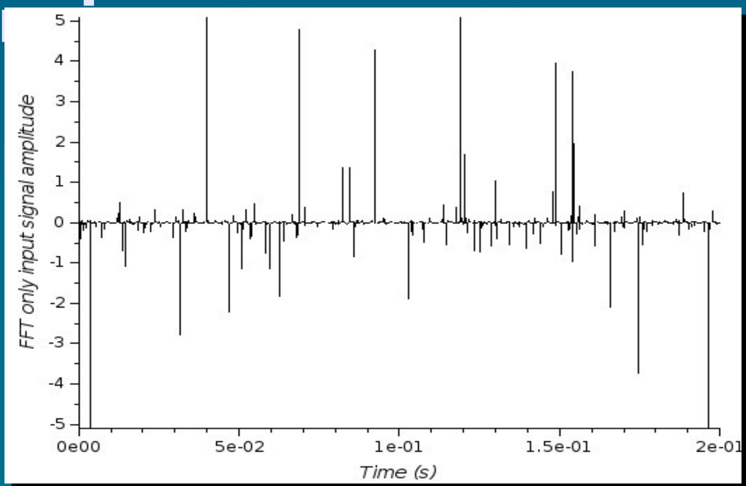


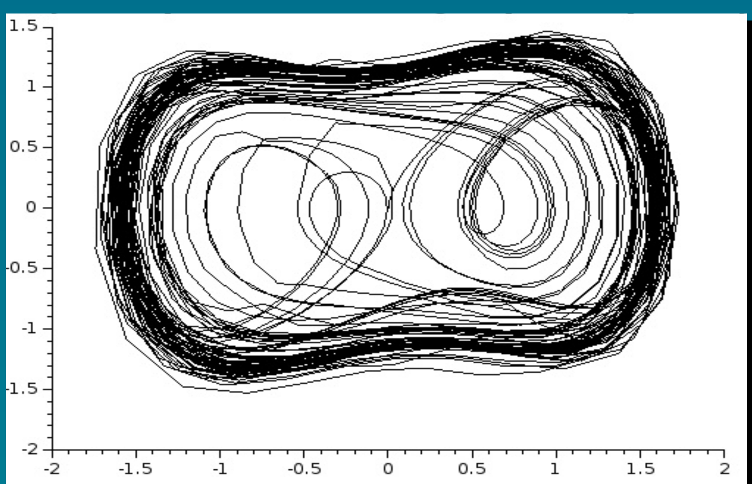



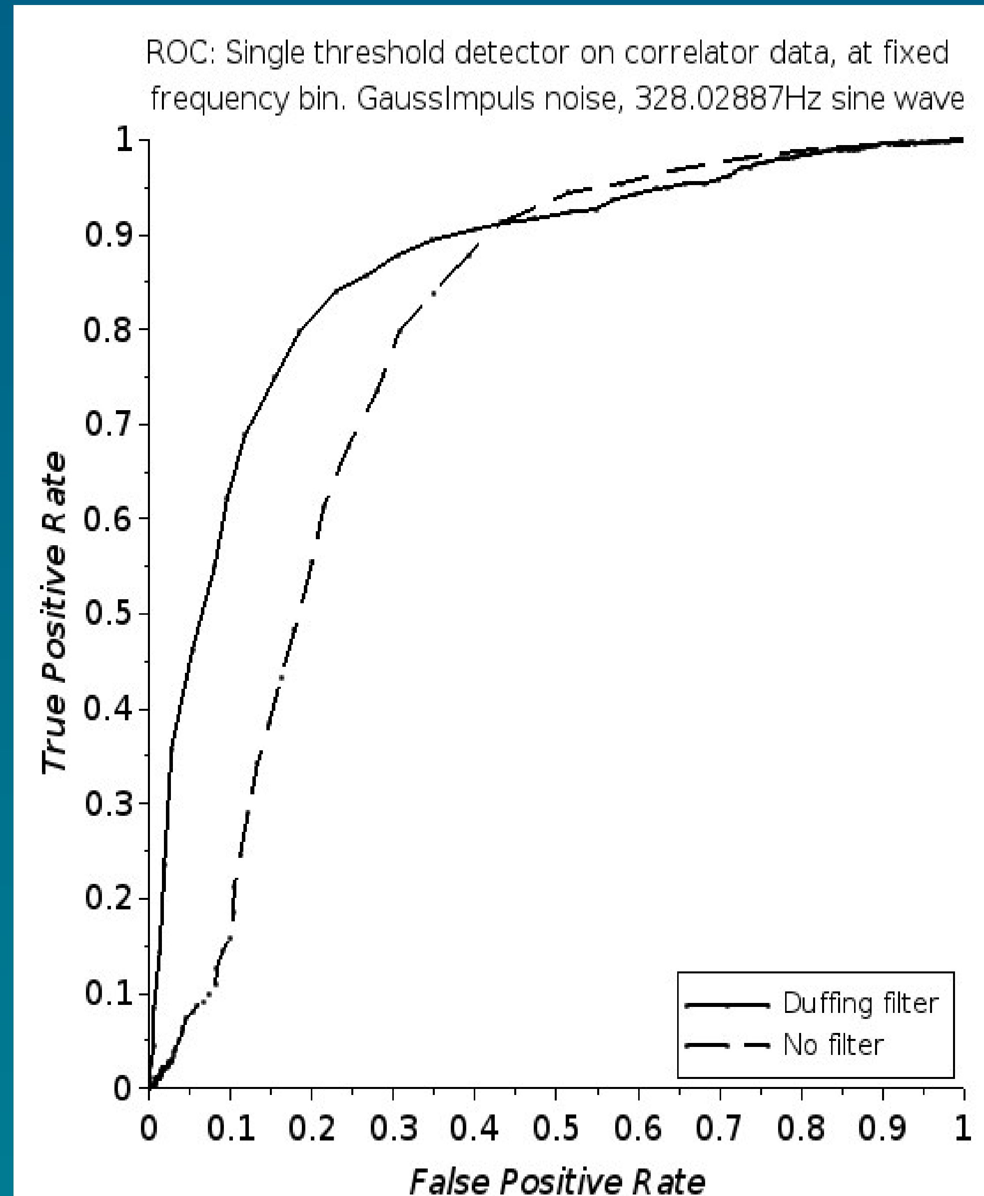
# Results



Sine wave plus impulsive noise (Gaussian noise to power 11) + **Gaussian**





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# Snapping Shrimp

Pseudo-real data

Sine wave plus snappng shrimp noise

Noise term generated by randomly  sampling short sections of the snapping shrimp timeseries data

Input signal to noise ratio controlled by varying the signal amplitude not the noise

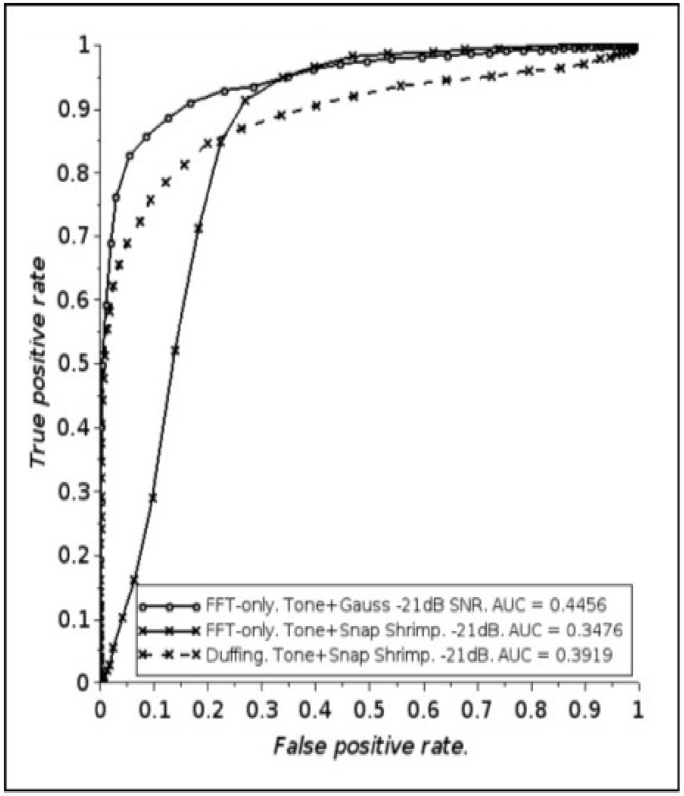


Figure 5.11: ROC curves using Monterey Bay snapping shrimp impulsive noise with an additive simulated sine wave. Two solid line curves: Basic FFT with no nonlinear pre-processing and using amplitude threshold detection. Sine wave in Gaussian white noise and sine wave in snapping shrimp impulsive noise. Dashed line ROC curve: Sine wave in snapping shrimp impulsive noise, using DAE with four-phase pre-processing and detection. RK4 solver step 0.00004, internal and input sine wave frequencies $f_0 = f = 628$Hz, internal and input sine wave amplitudes $\gamma_c = 0.812$ and $A_m = 0.0201$, replica amplitude 1.0 using 3 cycles, 200 initial transient points discarded.

# Possible next steps

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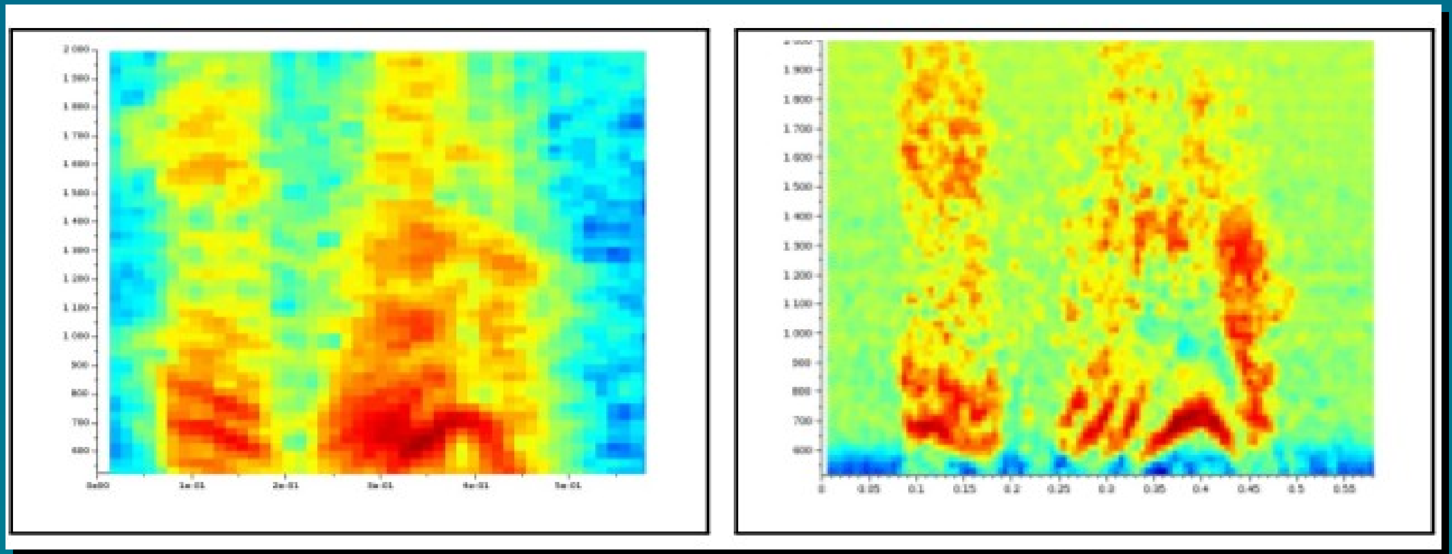
- Analyse the system to understand why impulsive noise is apparently rejected. What should we expect the nonlinear 'filter' to do to the noise?
- What range of SNR ? Suspect narrow region where 'filtering' wins
- Application: If it is real, could the detector be anything more than a narrowband 'bell ringer'?
- Test the “bank of Duffing Filters” on impulsive noise



# Conclusions

- For the limited tests conducted, a significant improvement in detection performance was found, for a CW single tone sine wave, in highly impulsive noise
- Requires more 'stress testing' and analysis to build confidence
- Initial ROC results using real snapping shrimp noise + simulated tone look promising
- Most tests to date have used simulated data, the result has not yet fully passed the test of real data

# References


[1] “Weak Signal Detection Based On Chaotic Oscillator”, D. Lui, H. Ren, L. Song, H. Li, IEEE IAS 2005, 2054-2058.

[2] “The Application of Chaotic Oscillators to Weak Signal Detection”, G. Wang, D. Chen, J. Lin, X. Chen, IEEE Transactions on Industrial Electronics, Vol. 46, No. 2, April 1999.

[3] “The Mechanism of Stochastic Resonance” R. Benzi, A. Sutera, A. Vulpiani, J. Phys. A: Math. Gen. 14 (1981) LL453-L457.

[4] “What's under the ROC? An Introduction to Receiver Operating Characteristics Curves”, D. Streiner and J. Cairney, Canadian Journal of Psychiatry, Vol 52, No 2, Feb 2007

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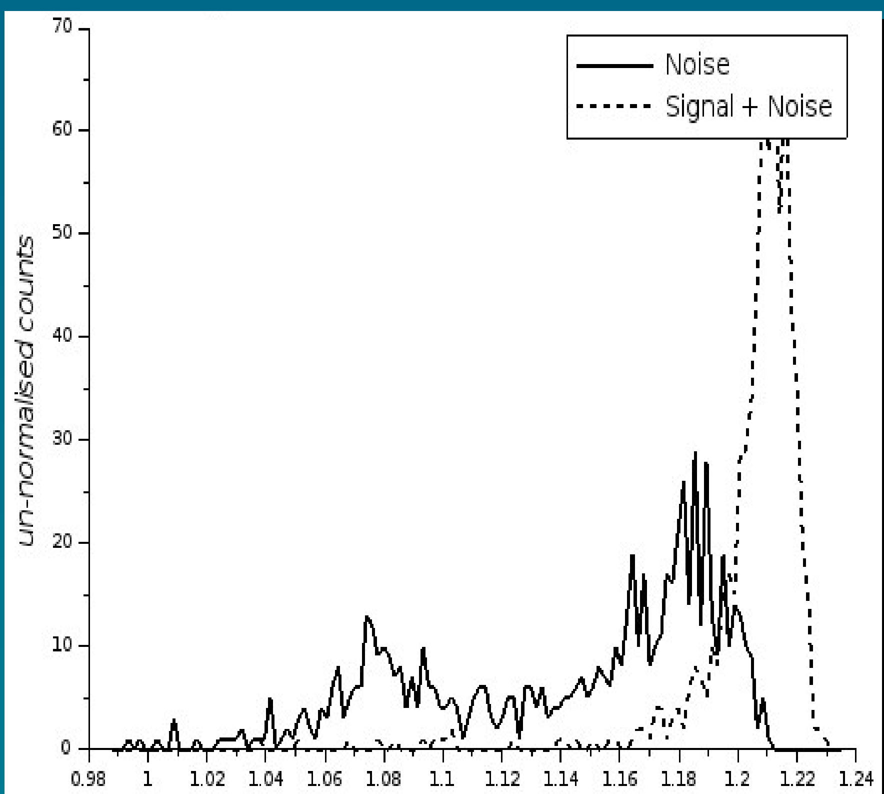
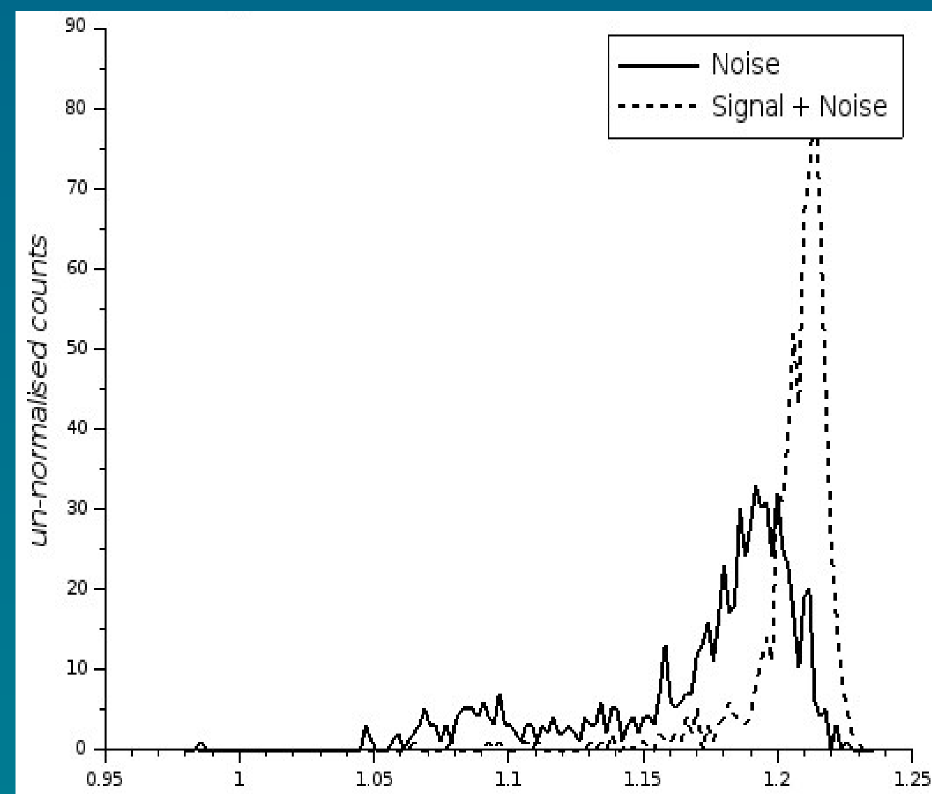
# Results

## PDF's correlation coefficient

Sine wave plus only impulsive noise (Gaussian noise to power 11)




Sine wave plus impulsive noise (Gaussian noise to power 11) **+ Gaussian noise**



- General approach:
  - Implement a signal processing chain
  - Generate simulated data
  - Compares nonlinear processing and correlation detection, to Fourier transform and amplitude thresholding detection
  - Collect detection statistics for repeated iterations
  - Calculate detection performance