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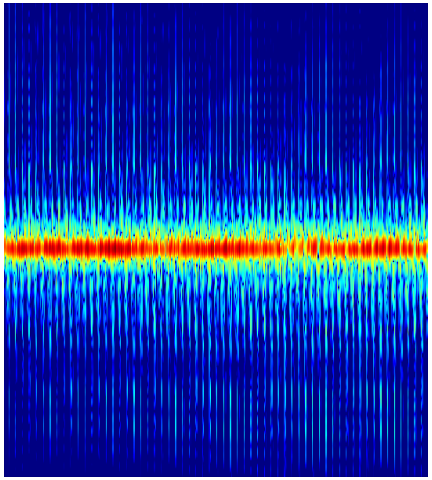
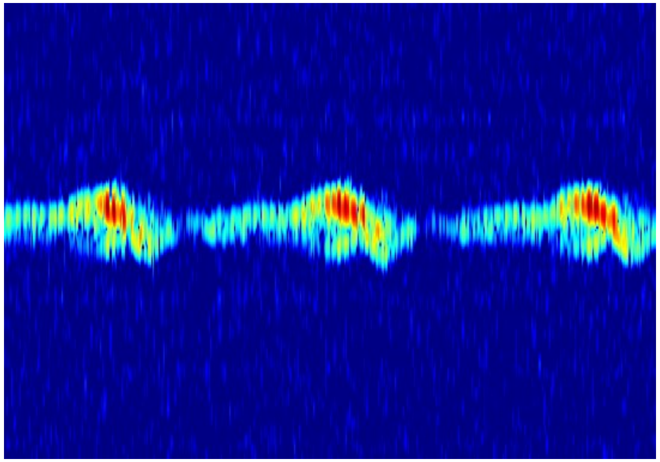
Time-Frequency Analysis of Millimeter-Wave Radar Micro-Doppler Data from Small UAVs

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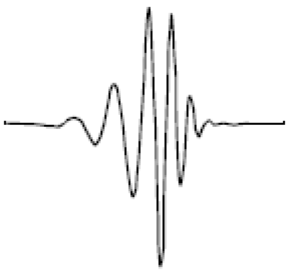
Overview

- Need for small UAV detection and classification system in defence sector
- Radar micro-Doppler signature analysis of sUAVs by STFT
- Wavelet Transform

  - *Continuous Wavelet Transform*

  - *Discrete Wavelet Transform*

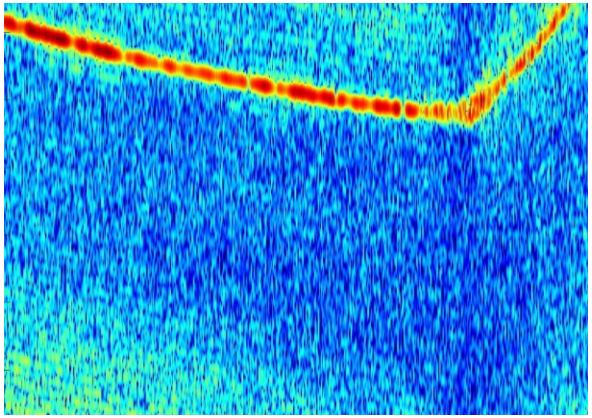
  - *Wavelet transform for sUAV data analysis*



- Experimental results (Drone and Bionic Bird)

  - *CW radar*

  - *FMCW radar*



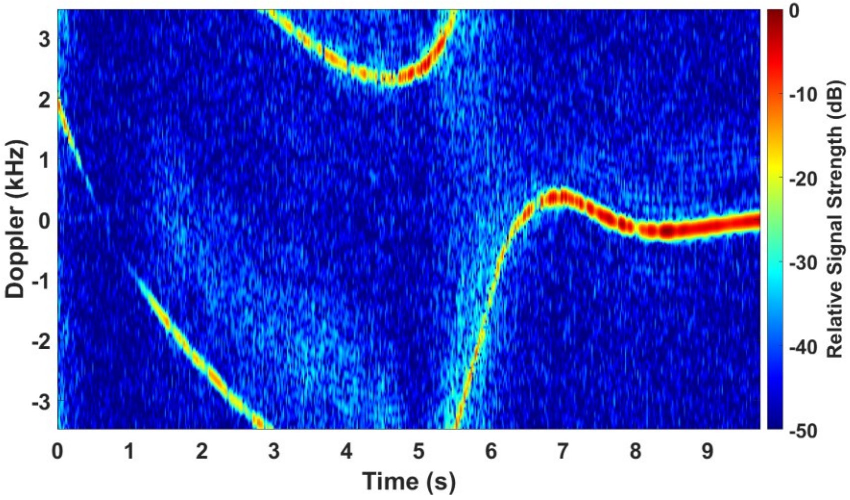
- Conclusions

Need for small UAV detection and classification system in defence sector

- Consumer drones have become readily available to the general public
- A user with malicious intent can use it for dropping/transferring explosives or contraband, illegal video recording etc.
- A novice user can create problems unintentionally which may disrupt a citizen's privacy/safety or create damage to an important facility
- There is a need for reliable, compact and low cost drone detection and classification system in the market

Radar micro-Doppler signature analysis of sUAVs by STFT

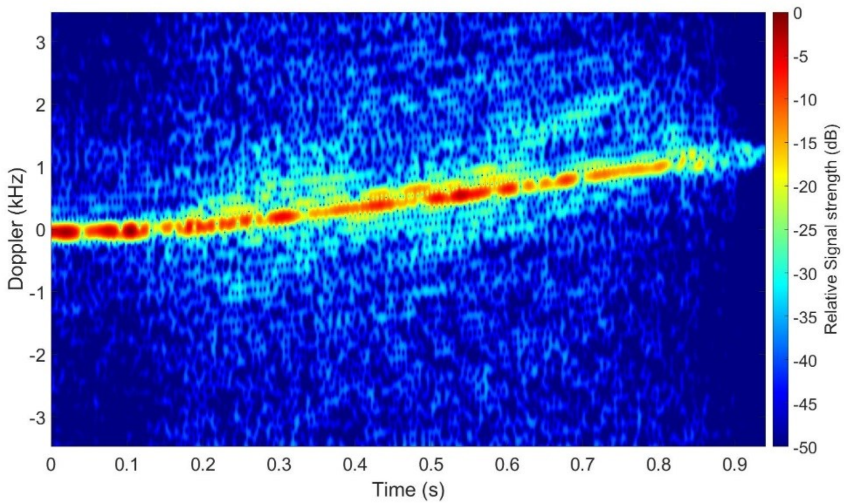
- Joint time-frequency analysis methods are mainly used for analysing micro-Doppler signals
- The most widely used technique is the linear analysis method, named the Short-Time Fourier Transform (STFT)
- Very intuitive, illustrates the variation in signal frequency content over time
- Millimeter-wave radar can produce high fidelity micro-Doppler returns from a sUAV due to the very fast rotating propeller blades

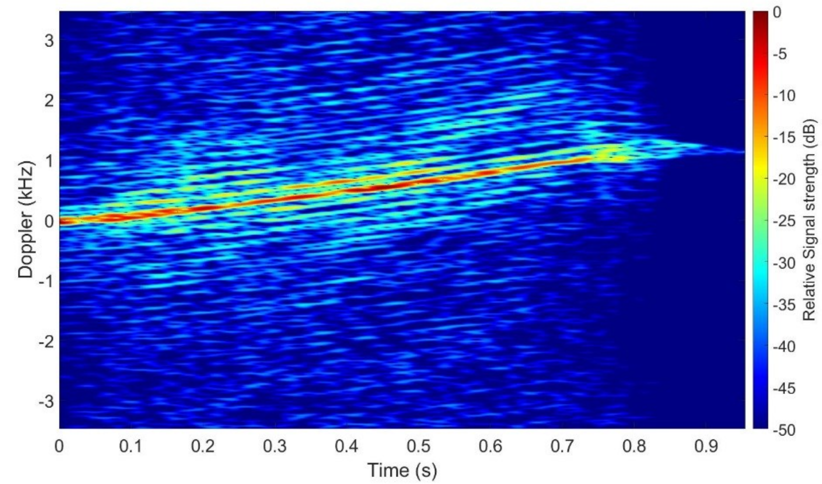


Spectrogram of a flying UAV

Radar micro-Doppler signature analysis of sUAVs by STFT

- In STFT, there is a trade-off between time and frequency resolution
- Different window lengths used in the STFT reveal different features





Spectrograms obtained by using different STFT window length revealing different features (HERM lines, blade flashes)

* *Using different window lengths for feature extraction can increase computational load*

Wavelet transform

- Uses wavelets instead of sines/cosines as the basis function
- Wavelets are localized both in time and frequency
- The localization is achieved by means of scaling or dilation (frequency localization) and shifting or translation (time localization)
- The resultant analysis is represented by a scalogram, which shows the energy distribution of the signal in different scales (revealing different frequency components) over time
- Capability to extract Doppler signatures of fast moving objects (i.e. sUAV propeller blades)

Wavelet transform

Continuous Wavelet Transform (CWT)

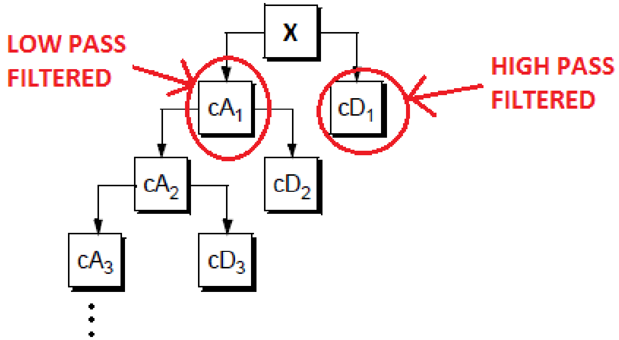
$$CWT(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-b}{a}\right) dt$$

- *a* and *b* are the scaling and shifting parameters respectively
- ψ^* is the complex conjugate of the mother wavelet
- *x(t)* is correlated with the different scaled versions of the wavelet function as well as the wavelet being shifted along the time axis
- The Haar (or Daubechies 1, 'db1') wavelet has been used to analyse data here

Wavelet transform

Discrete Wavelet Transform (DWT)

- The discretization is done in terms of integer powers of 2 (*2^j, j=1, 2, 3,…)*
- By performing multi-level DWTs, the original signal can be decomposed into various components corresponding to different frequencies



- The high-pass outputs are defined as the detailed coefficients and the final low-pass output defines the approximation coefficients
- A 5-level wavelet decomposition process,

$$x = cd_1 + cd_2 + cd_3 + cd_4 + cd_5 + ca_5$$

(The first five components correspond to detailed coefficients and the last one corresponds to approximate coefficients)

Wavelet transform

Wavelet Transform for sUAV data analysis

- Combination of CWT and DWT have been used to analyze the micro-Doppler signatures of the millimeter-wave radar data (in 3 steps)

Step 1- Perform wavelet decomposition (4-6 levels) on the phase coherent radar return signal.

Step 2- Select cd1 and/or cd2 and performing CWT to attain micro-Doppler feature.

Step 3- Select the final low-pass output and perform CWT to get bulk Doppler feature.

Millimeter-wave radars used for micro-Doppler measurements

94 GHz FMCW/CW radar 'T-220'

- *94GHz FMCW / CW*
- *+18 dBm*
- *B up to 1.8GHz*
- *Dual antenna fan beam*
- *0.92°Az x 3.00° El (40.5dBi)*
- *CP only (odd bounce)*
- *NF ~ 6dB*
- *70dB Tx-Rx isolation*
- *Staring or slow pan*
- *Very low phase noise*
- *DDS chirps*

94 GHz FMCW radar 'NIRAD'

- *94GHz FMCW*
- *+20 dBm*
- *B up to 600 MHz*
- *Single antenna pencil beam*
- *0.74°Az x 0.87° El (42.5dBi)*
- *CP, V, H or 45^0 (co- and x-pol)*
- *NF_{eff} ~ 26.5 dB (Tx-Rx leakage)*
- *R^3 filter*
- *10 Hz PPI rate or Staring*
- *Low phase noise*
- *DDS chirps*

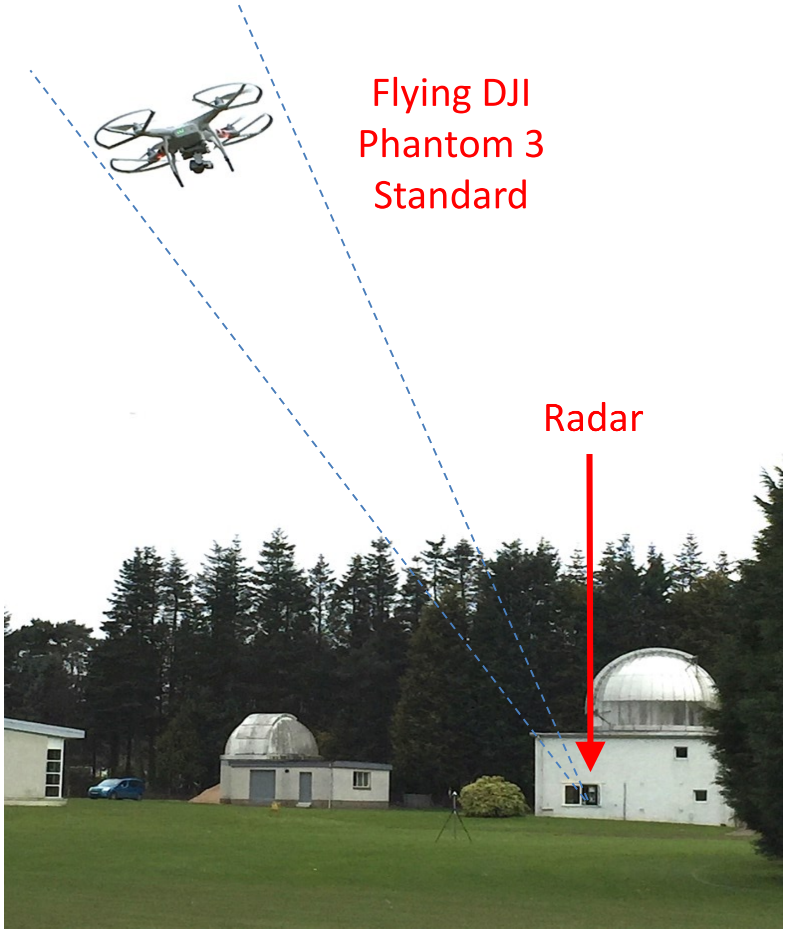
sUAVs used for data collection

- *DJI Phantom 3 Standard*

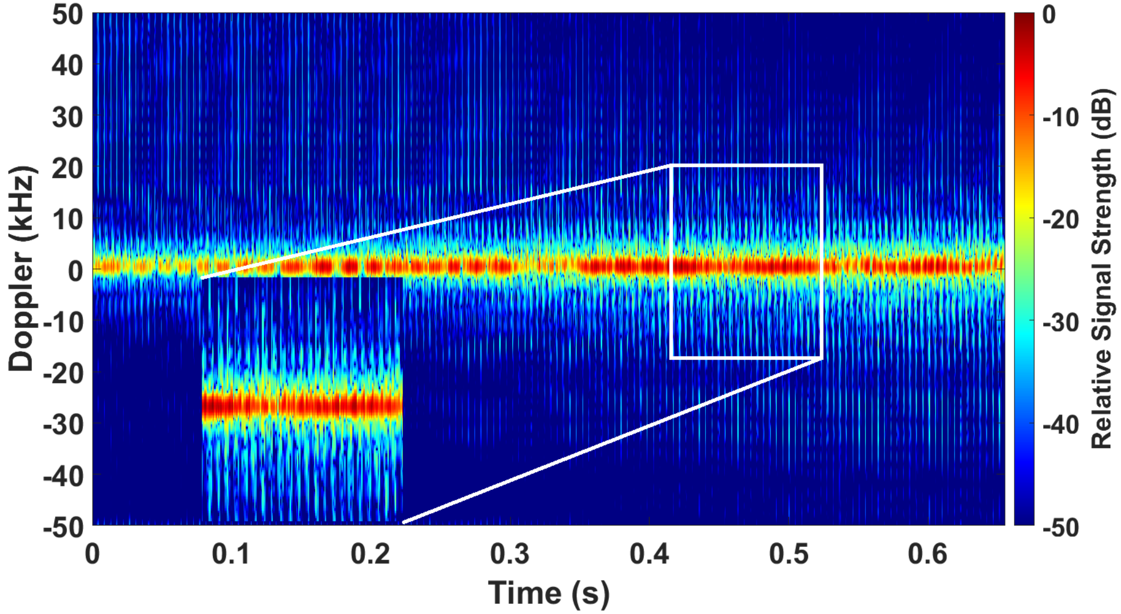
https://www.dji.com/phantom-3-standard

- *Bionic bird biomimetic drone*

http://www.mybionicbird.com/?lang=en



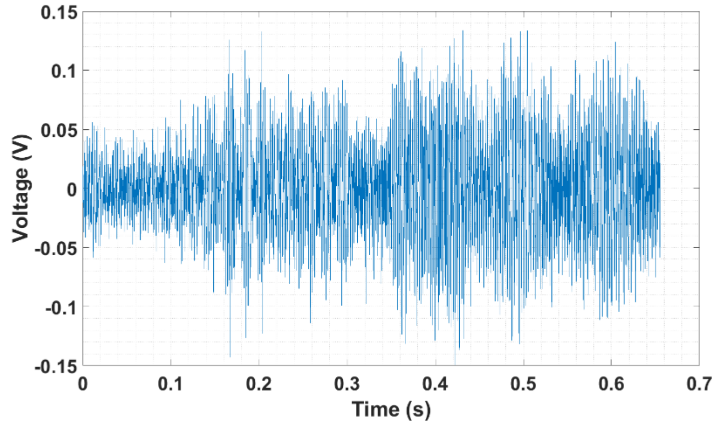
CW radar data (DJI Phantom 3 Standard)- Spectrogram



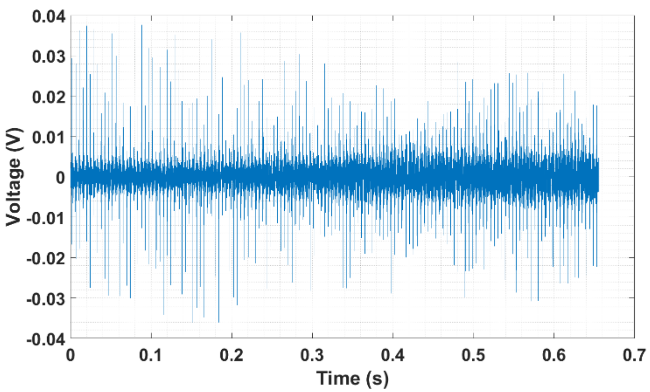
Spectrogram of hovering DJI phantom with blades attached to only one rotor

- Conventional STFT with Gaussian windowing is used
- The Phantom was ~20 m away from the radar

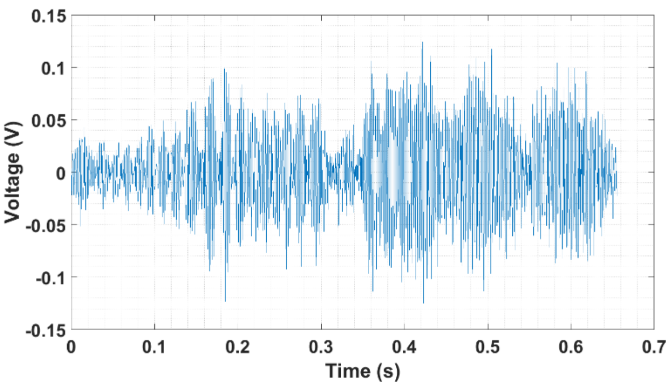
CW radar data (DJI Phantom 3 Standard)- 6-level wavelet decomposition



Real part



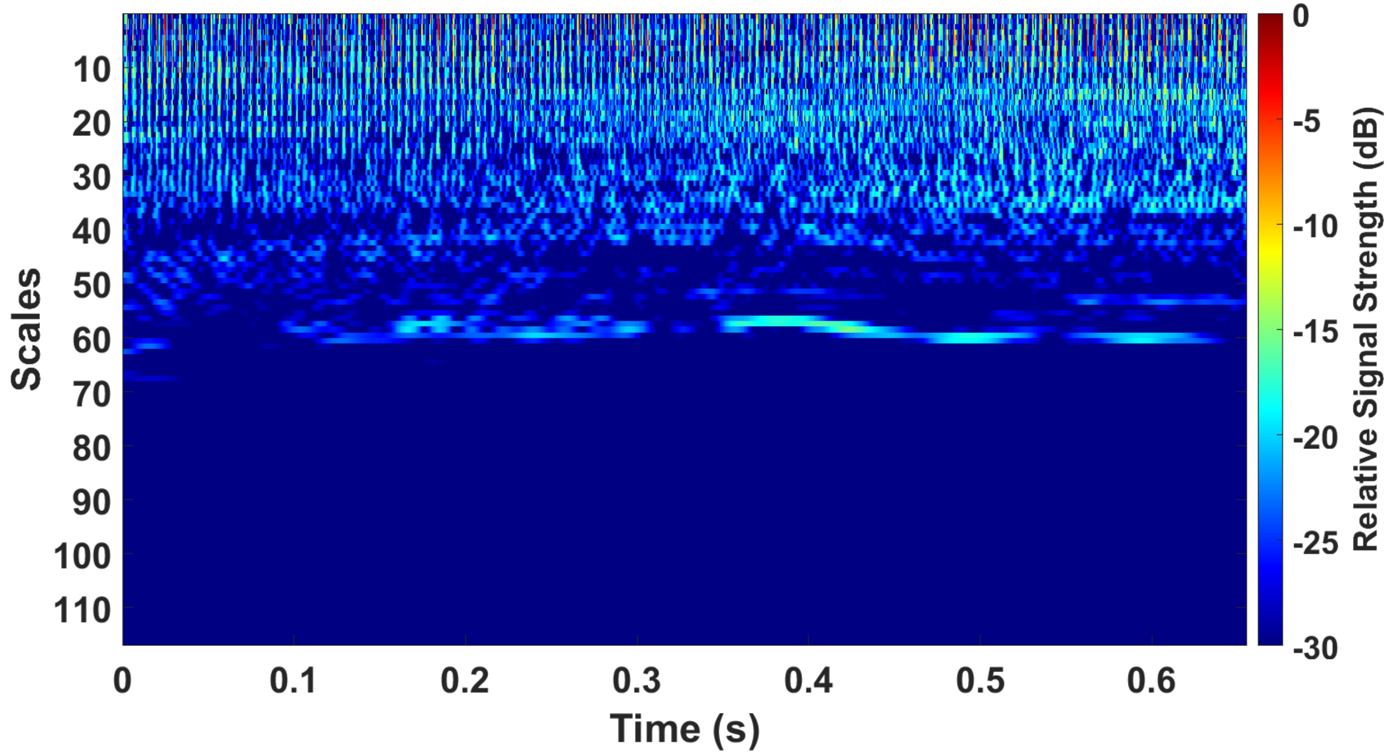
High Frequency component, cd_1



Low frequency component, ca_6

- Most of the signal energy is concentrated in bulk velocity component

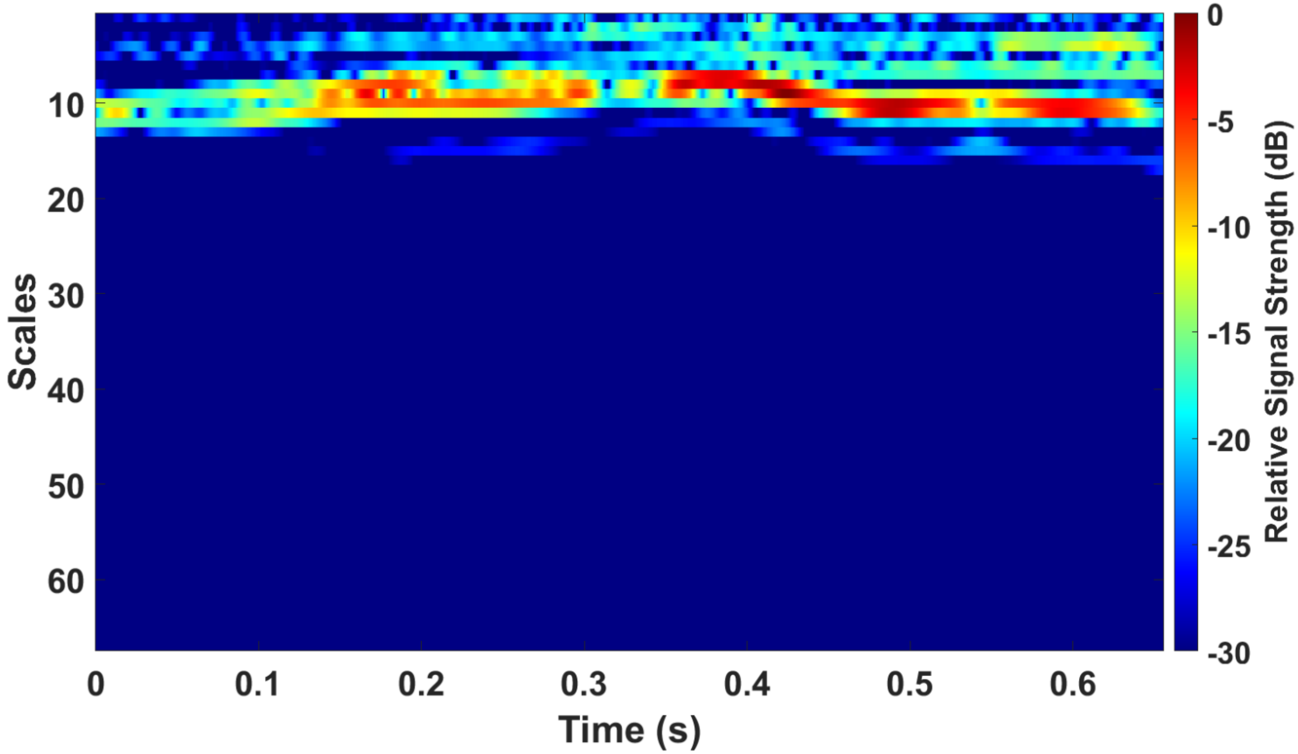
CW radar data (DJI Phantom 3 Standard)- Scalogram, high frequency component



Scalogram of the high frequency component, cd_1. The blade flashes are observed

** The scaling parameter is discretized in terms of $2^{1/v}$. Here, v is greater than 1, hence the scale factor is always positive*

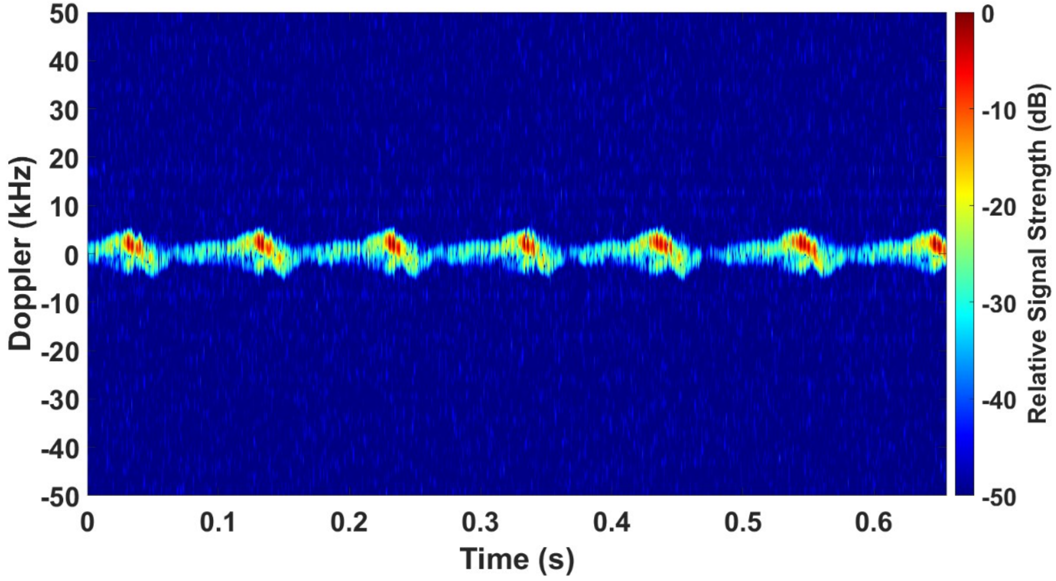
CW radar data (DJI Phantom 3 Standard)- Scalogram, low frequency component

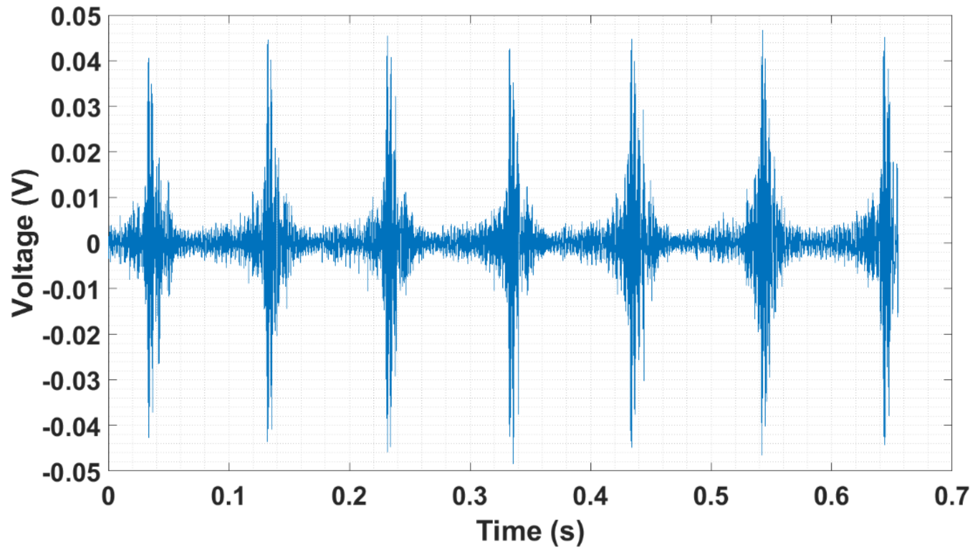


Scalogram of the low frequency component, ca_6. Zero Doppler components are observed

** The bulk-Doppler and micro-Doppler (due to propeller blade rotation) components are hence separated*

CW radar data (Bionic bird)- Spectrogram

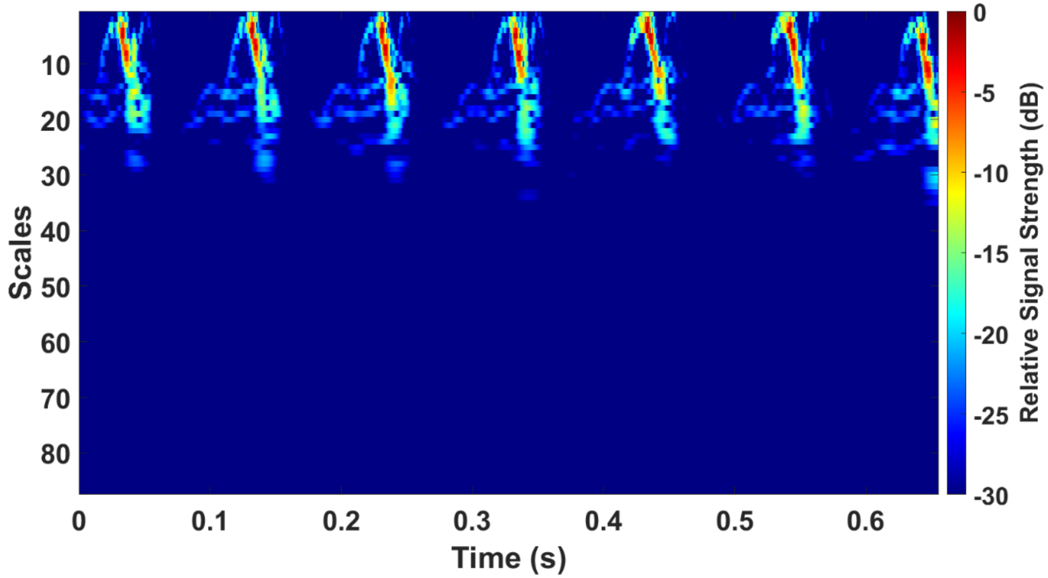




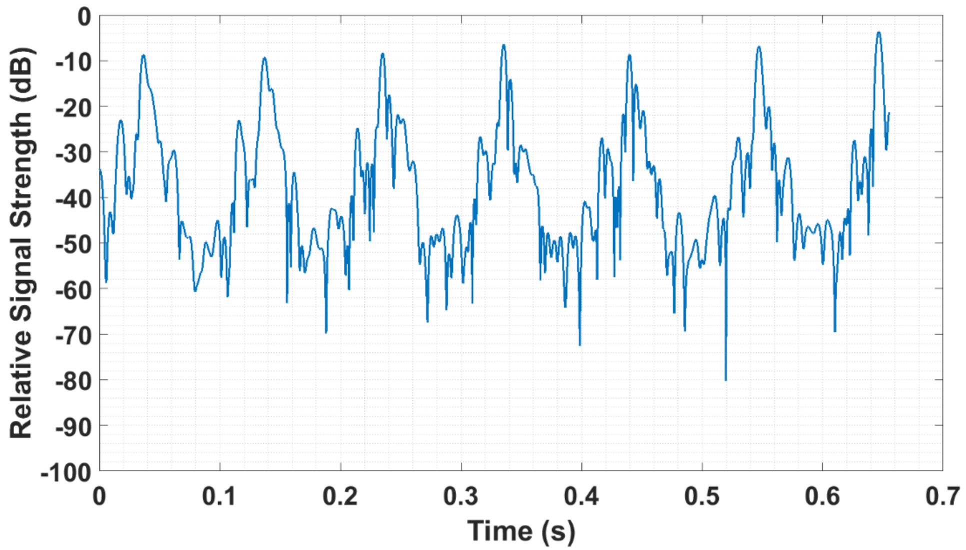
- Spectrogram of the Bionic Bird flapping wings. The periodic motion of the wing beats is clearly observed

- the real part of the corresponding time-domain signal. Negligible bulk Doppler

CW radar data (Bionic bird)- Scalogram

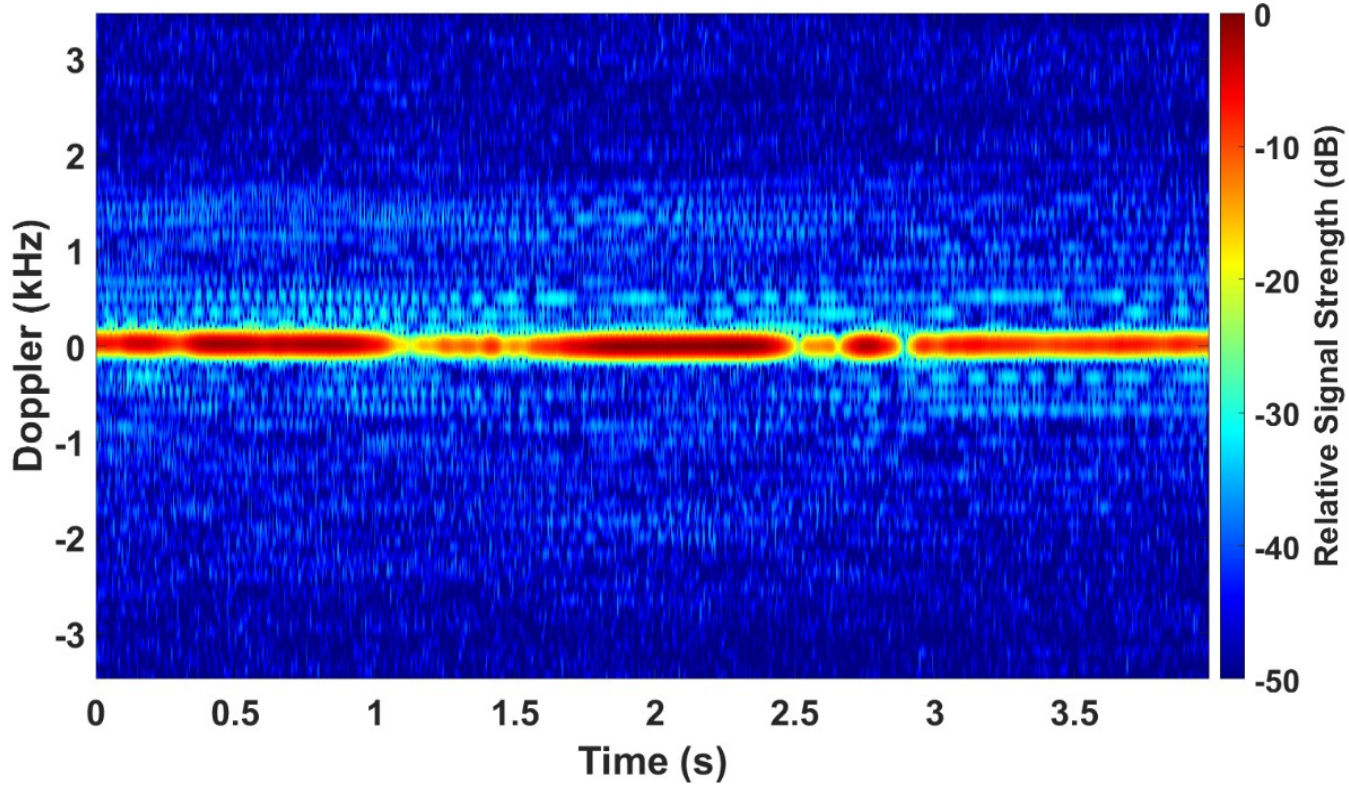


- Scalogram of the same data showing wing beats. 4-level wavelet decomposition is performed



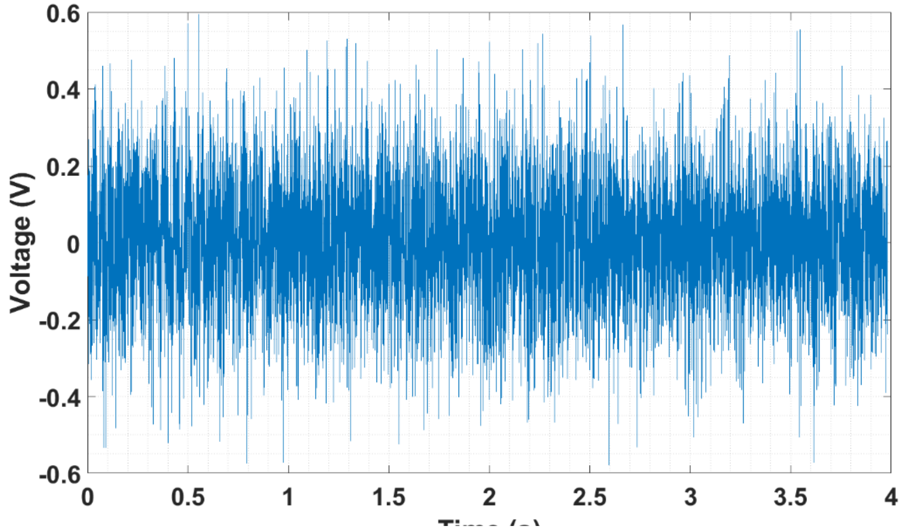
- Time slice of the 10th scale

FMCW radar data (DJI Phantom 3 Standard)-Spectrogram

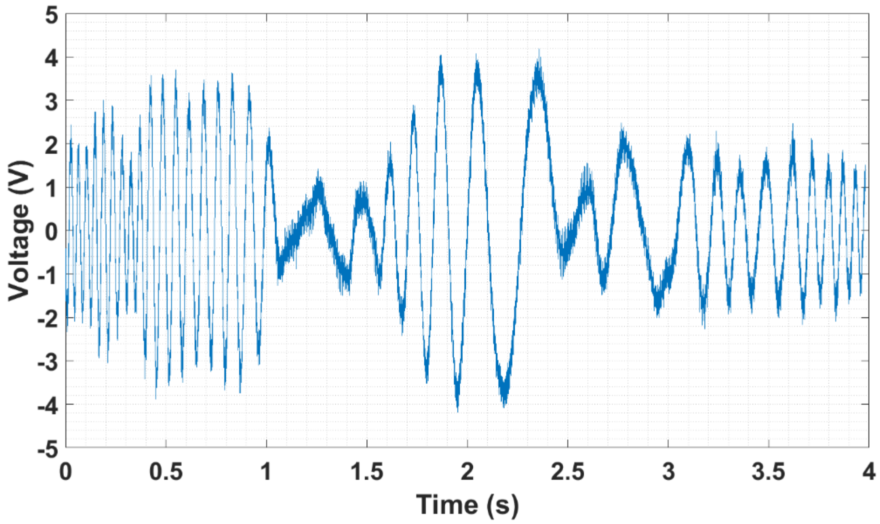


- All 4 rotor blades rotating
- Both micro-Doppler and bulk Doppler signatures are observed, but neither is fully resolved

FMCW radar data (DJI Phantom 3 Standard)- 6-level wavelet decomposition

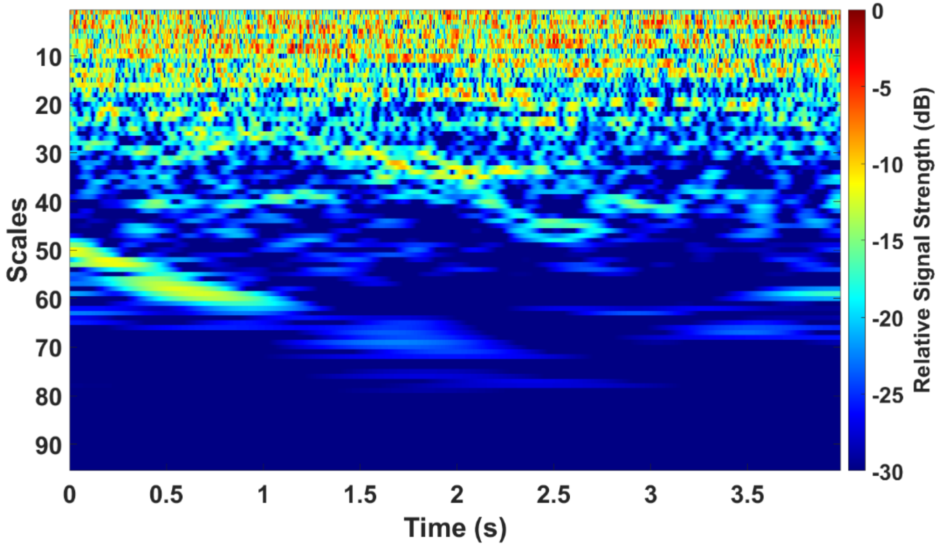


- Real part of the deramped signal of the sUAV return. 6-level wavelet decomposition performed

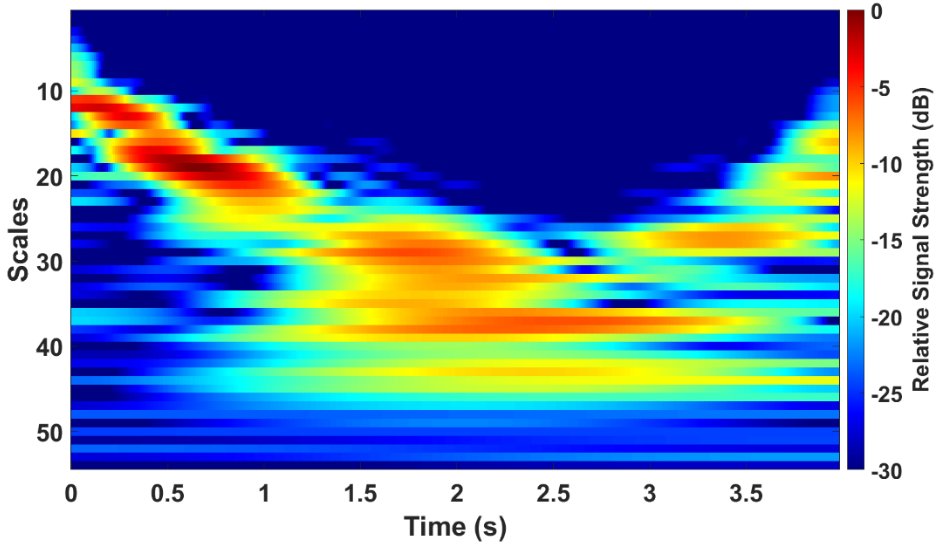


- High frequency component, cd_2, first iteration did not suppress the low frequency part entirely, hence cd_2 is chosen

FMCW radar data (DJI Phantom 3 Standard)- Scalogram



- Scalogram of the high frequency component (top), cd_2, showing the micro-Doppler features of the sUAV



- Scalogram of the low frequency component (bottom), $ca_{6.}$ Micro-Doppler features are filtered out in this case

Conclusions

- Spectrograms provide very good visualization of the micro-Doppler features
- Combination of wavelet decomposition and scalograms obtained by CWTs can be used for separating the micro-Doppler information
- The wavelet transform method can be used to feed a classifier with unique sUAV micro-Doppler characteristic
- The computational complexity
  - Fast wavelet transform $O(n)$
  - Fast Fourier transform $O(n.log_2(n))$
- For real-time sUAV detection operation, the proposed method has the potential to be more efficient in terms of false alarm rate and computational load

Acknowledgements:-

- Colleagues at University of St Andrews
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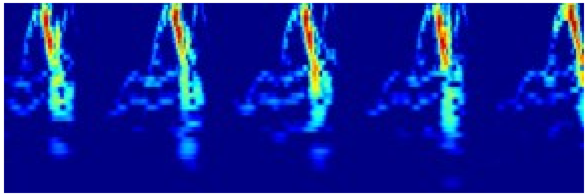

Thank you! Any questions?

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