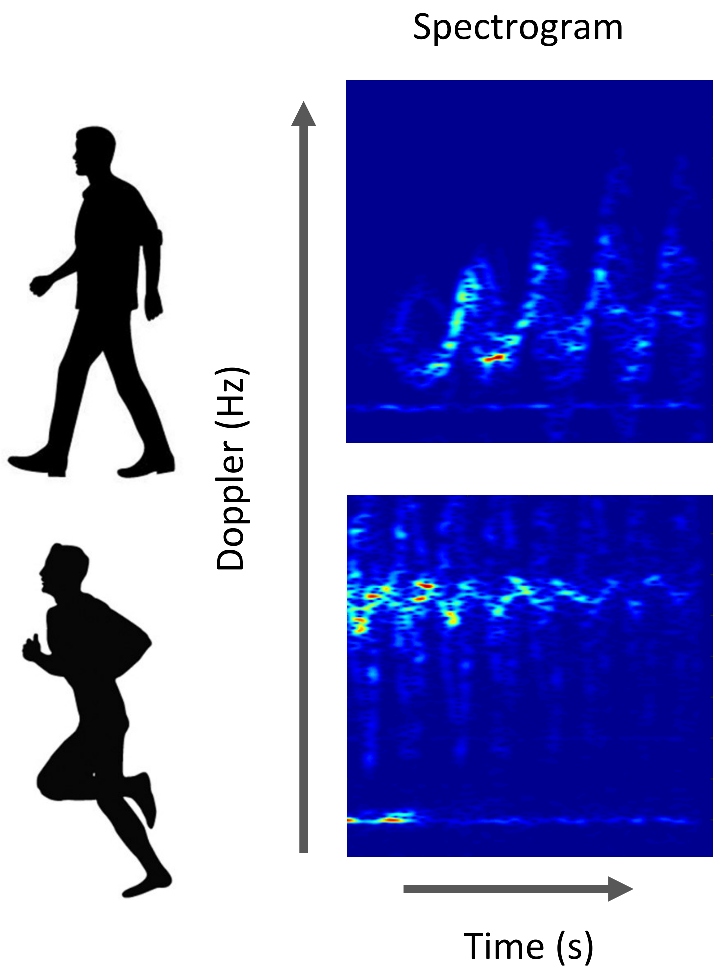
DSP CHALLENGE 3

What we learned so far

- We have seen how we are able to estimate the range of a target thanks to waveform design and matched filtering.
- We have learned how to estimate the radial velocity of a target and how to discriminate multiple targets in velocity thanks to FFTs;
- Using range and velocity information we can potentially track targets.
- Can we obtain additional targets' information in order to perform also recognition, or perform kinematic analysis?

3rd DSP Challenge



- In addition to the main motion targets might exhibit additional movements affecting the radar return;
- Additional motions introduce additional time-varying Doppler reflecting the peculiar target motion;
- Information about the targets movements allow additional applications.
- A way to extract this information is needed.

Micro-Doppler

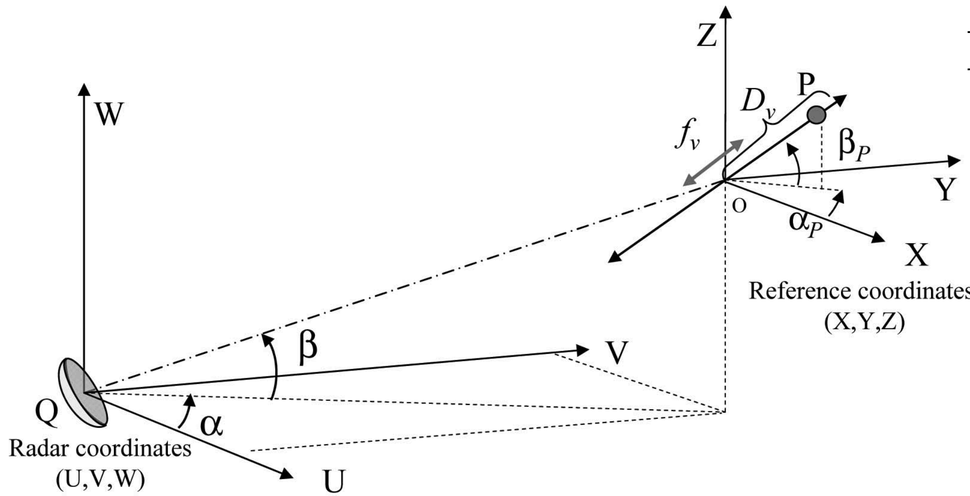
“The Micro-Doppler Signature is the intricate frequency modulation that is imparted on the backscatter signal by the moving components of a radar target.” (Chen et al., 2006)

- “Micro” is not related to the extension of the motion or to the amount of Doppler shift observed.

Micro-Doppler

- Micro-Doppler effect was introduced in laser systems;
- Used to measure small motions and vibrations;
- In laser systems a small displacement creates relatively large Doppler shifts;
- The Doppler shift is generally smaller in Radar;
- The exploitation of time-frequency analysis allowed increasing interest in mD;
- Growing interest in radar mD from late '90s;
- Since then mD has been successfully applied in a wide range of defence and civilian applications.

Micro-Doppler of a Vibrating Target



$$\Gamma = D_v$$

$$R[n] = R_0 \Gamma sin(2\pi f_v n)$$

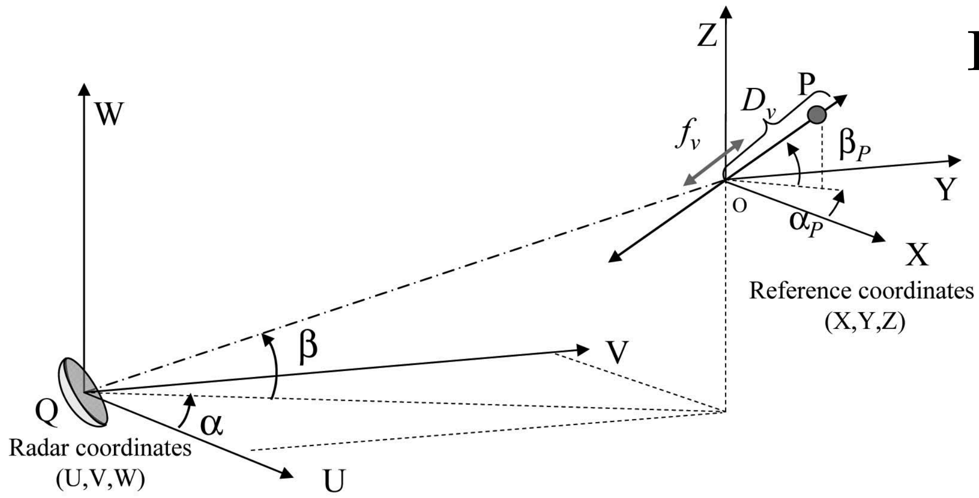
Γ is the modulus of the radial component of the vibration

The radar received signal is

$$s_r[n] = \rho \exp\{j(2\pi f_0 n + \Phi[n]\}$$

$$\Phi[n] = \frac{4\pi R[n]}{\lambda}$$

Micro-Doppler of a Vibrating Target



$$\Gamma = D_v$$

the derivative of $\Phi[n]$ leads to the time varying component of the Doppler shift, the micro-Doppler frequency

$$f_{mD}[n] = \frac{4\pi f_0 f_v \Gamma}{c} \cos(2\pi f_v n)$$

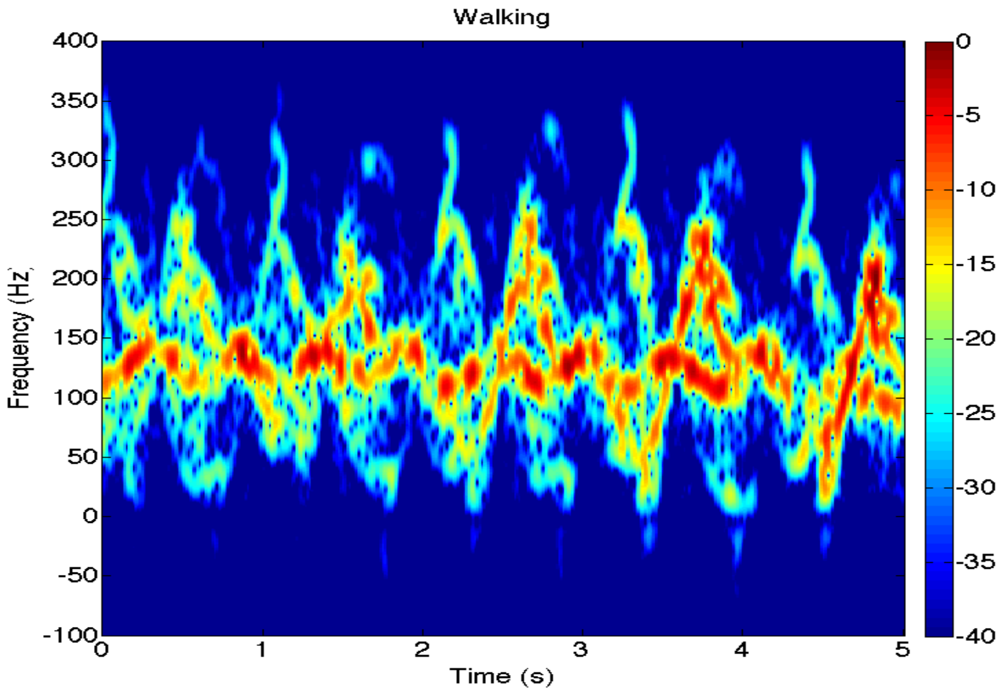
Micro-Doppler – Time Varying Doppler

- For a target with micro-Doppler, the Doppler frequency has time-varying characteristics;
- In order to extract the target's micro-motions characteristic both time and frequency information need to be observed;
- **Time Frequency Analysis is the DSP tool we need!**

Micro-Doppler Signature

- A micro-Doppler signature is the time-frequency representation of the observed/modelled micro-Doppler effect;

- Useful for visualization but principally for post-processing of the information;



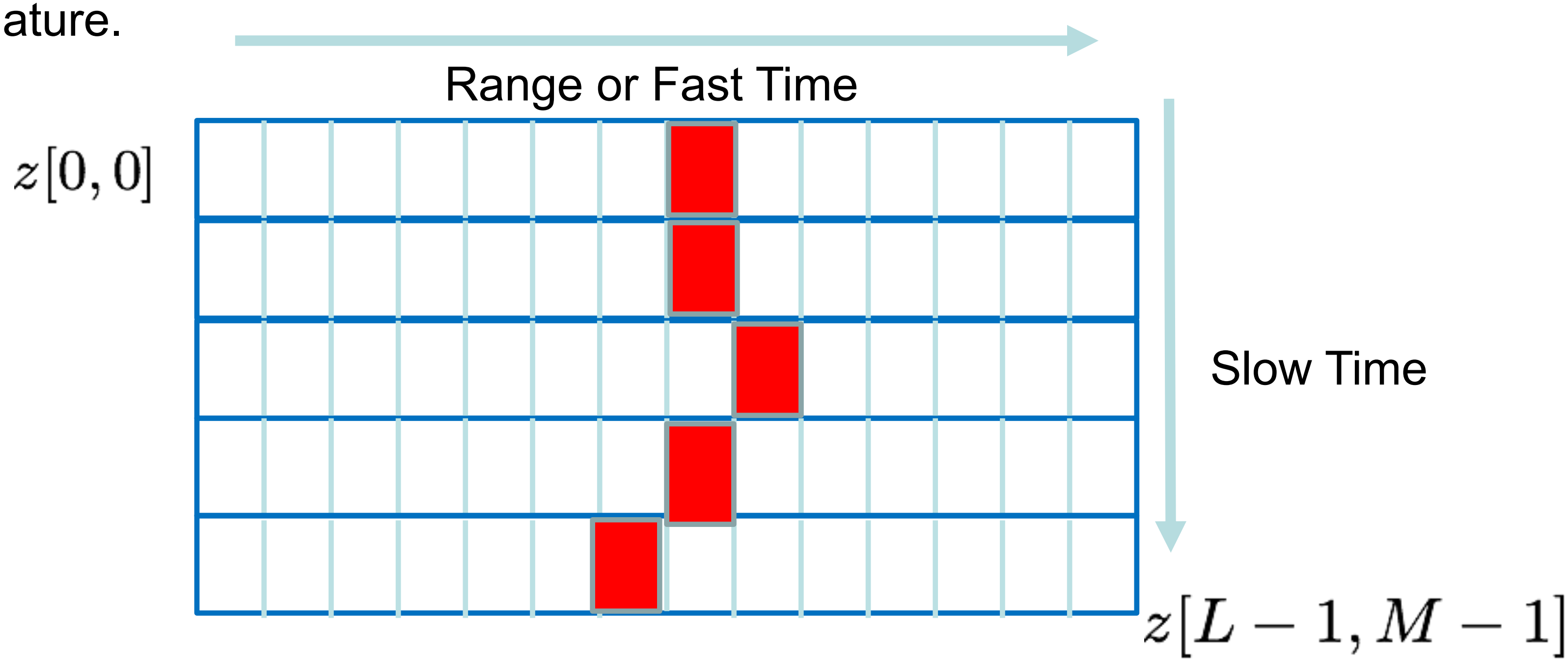
- Time-Frequency distributions are the analysis tool used to extract the signatures.

Micro-Doppler and Sampling Frequency

- The Micro-Doppler shift depends on the radar wavelength λ ;
- For example for an X band radar (λ = 3 cm), a 15 Hz vibration with amplitude of 3 mm produces a maximum micro-Doppler shift of 18.8 Hz;
- In S band (λ = 10 cm) to obtain the same micro-Doppler shift a displacement of 1 cm is needed;
- An UHF system (300-1000 MHz) used for foliage penetration can be used to detect very high shifts;
- If λ = 60 cm and a helicopter rotor blade is observed with a tip velocity of 200 m/s, the maximum shift is 666 Hz;

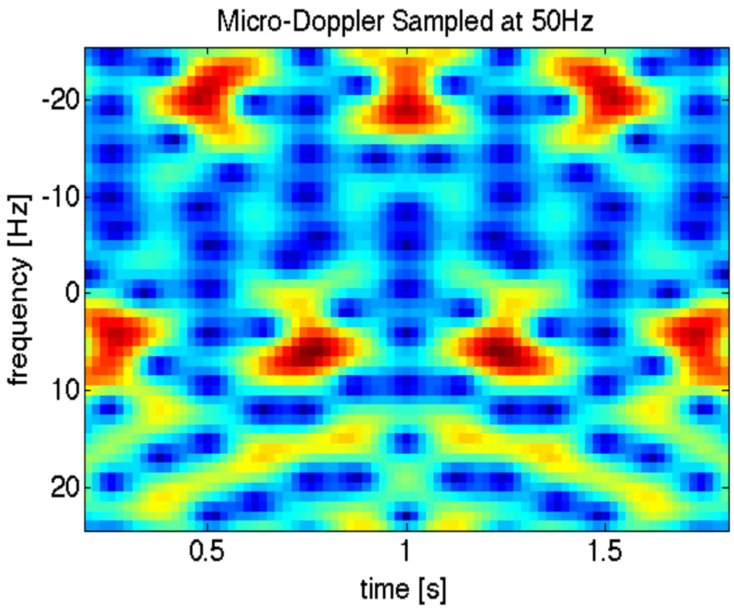
Micro-Doppler and Sampling Frequency

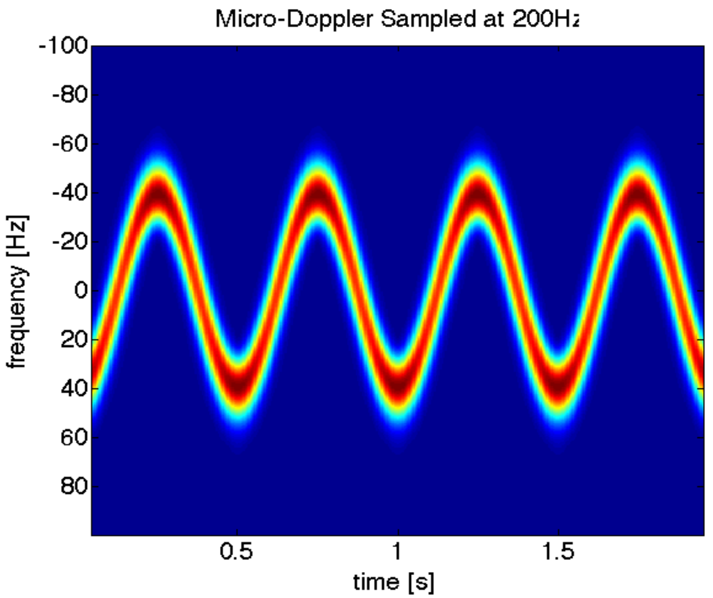
- In genaral the Micro-Doppler effect is a slow-time phenomenon;
- The relevant sampling frequency is the Pulse Repetition Frequency (PRF);
- A careful selection of the Coherent Pulse Integration (CPI) (in this case the TFD windows) interval is required to avoid aliasing and information loss;
- The micro-Doppler effect is not affected by the range resolution, however the range resolution helps the separation of different parts contributing to the micro-Doppler signature.



Micro-Doppler and Sampling Frequency

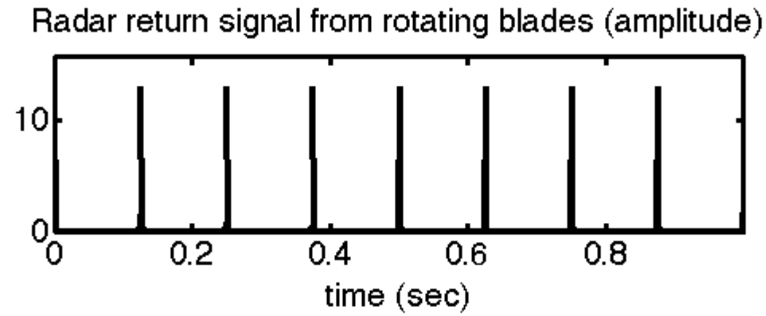
- The sampling frequency plays a fundamental role in the correct extraction of the micro-Doppler

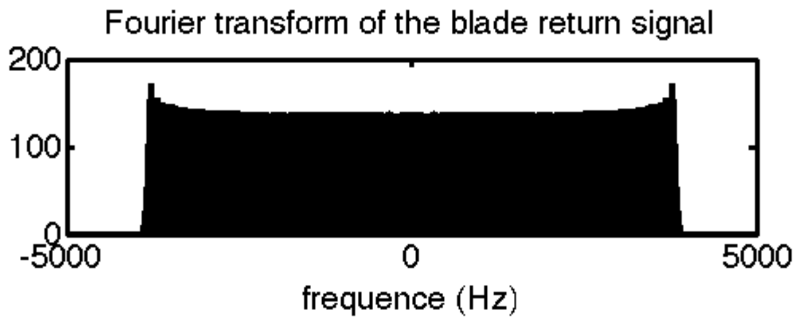


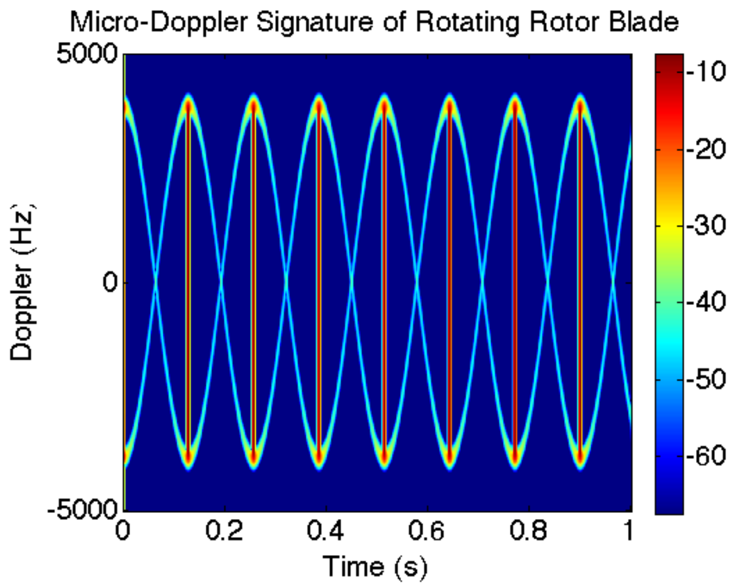


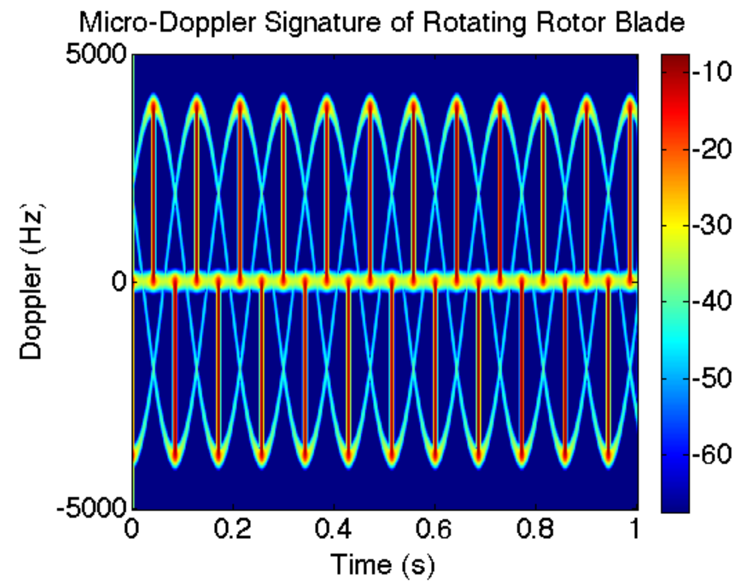
- Aliasing can cause corrupted reconstruction of micro-Doppler signature.

Helicopter rotor blade



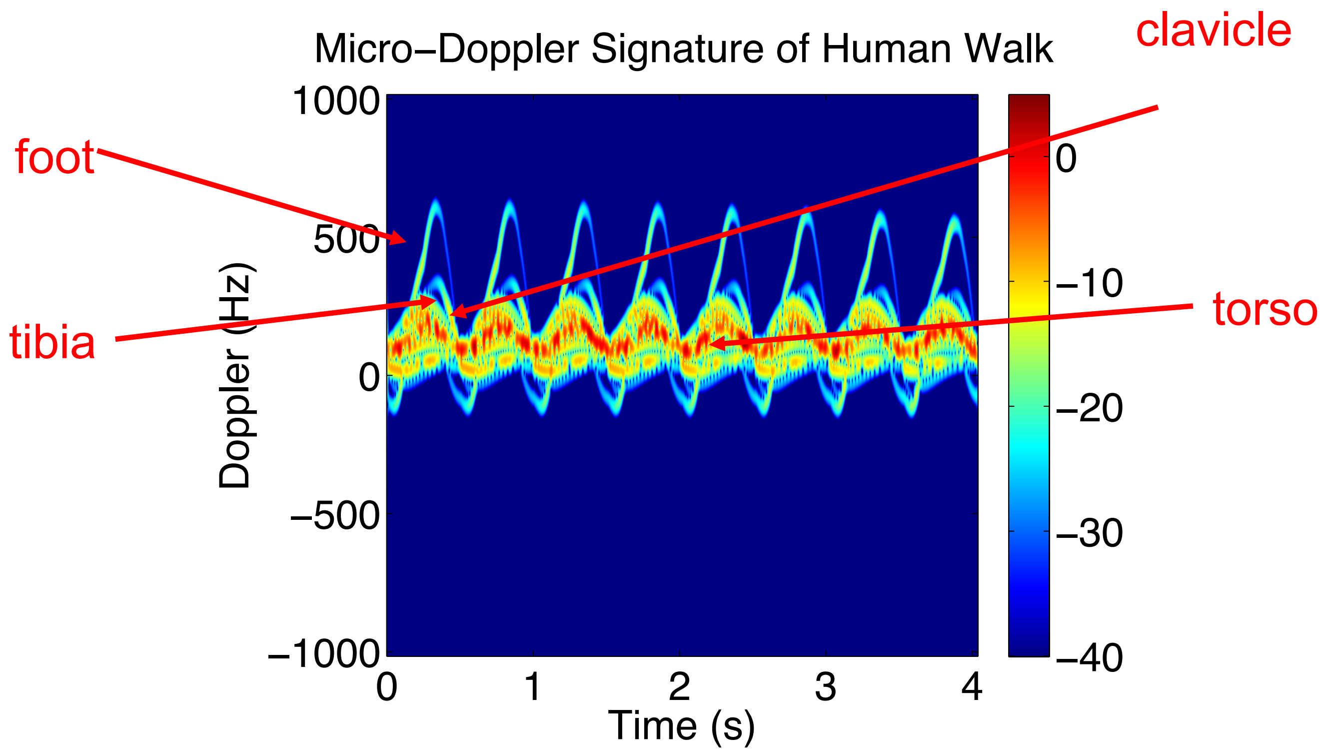






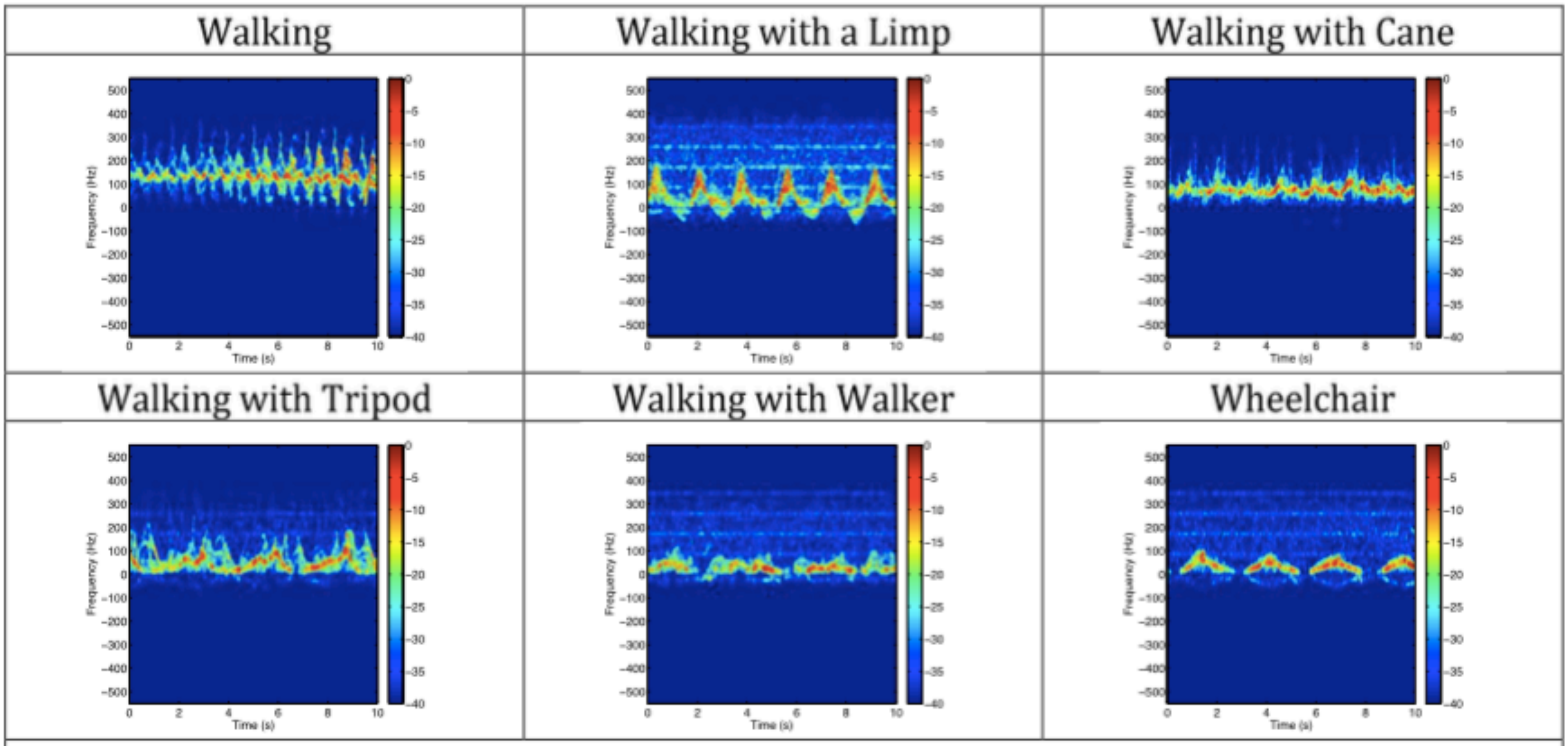
Human Gait

- The expected micro-Doppler signature is the superposition of all the contributes from all body parts and is proportional to the radial velocity

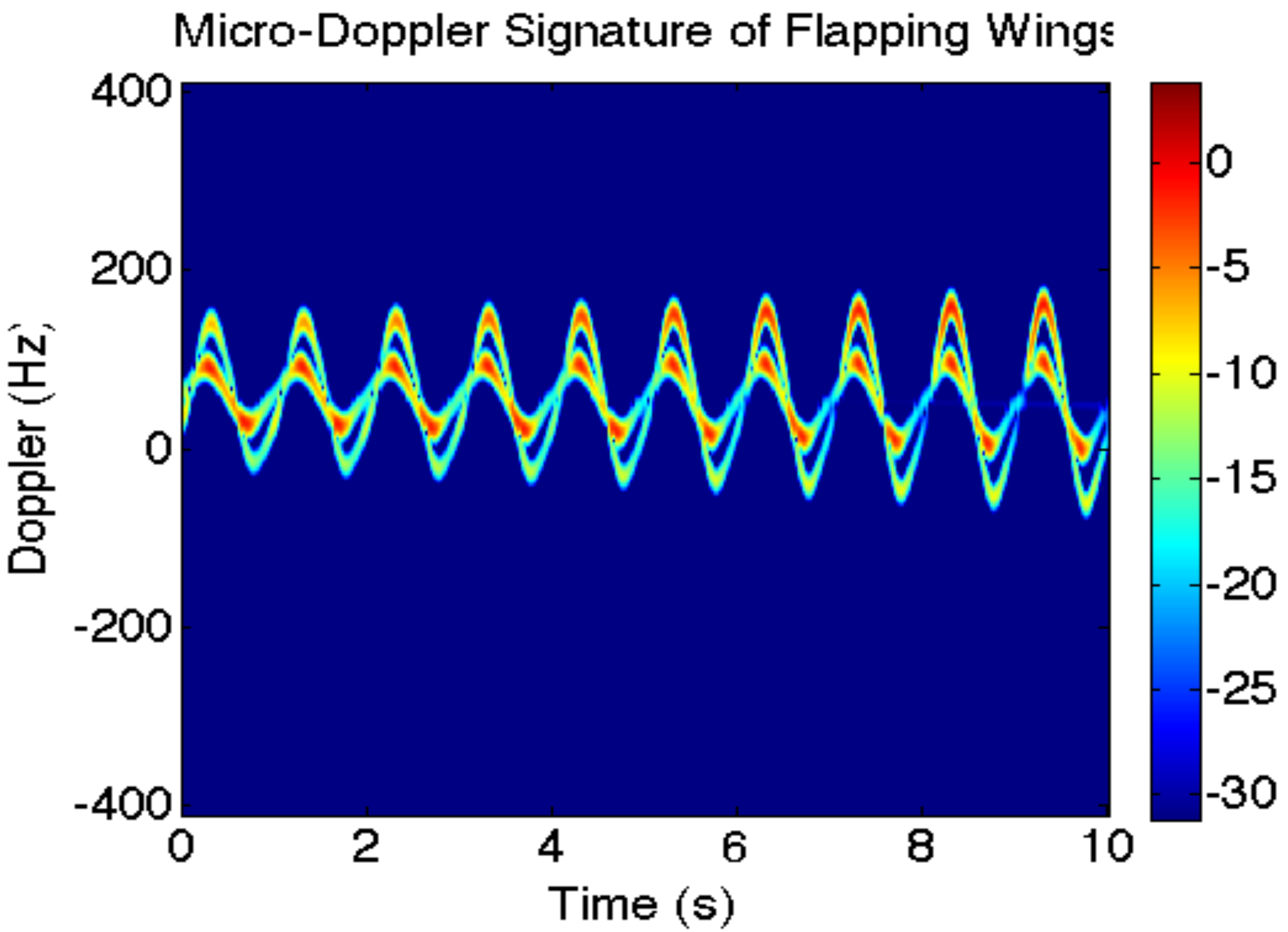


Human Activities

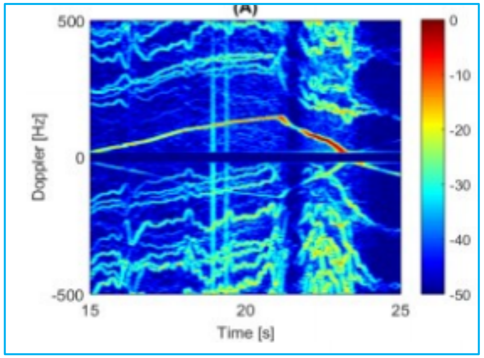
- Different Human Activities exhibit characterizing micro-Doppler signatures;

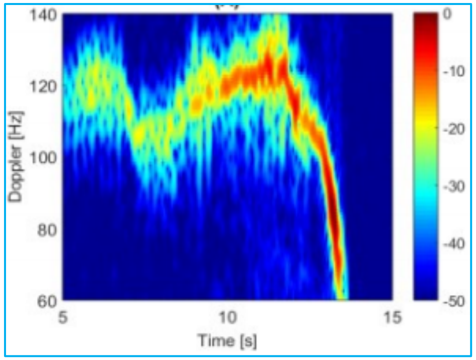


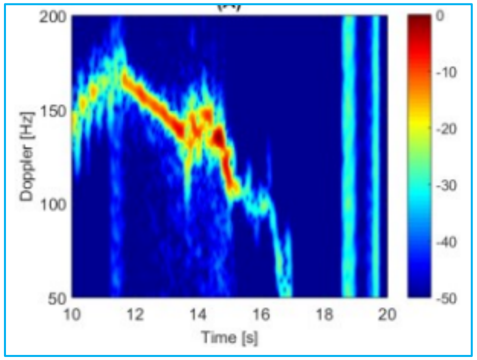
Bird Flapping



ADVANCED APPLICATIONS – UAVs vs birds

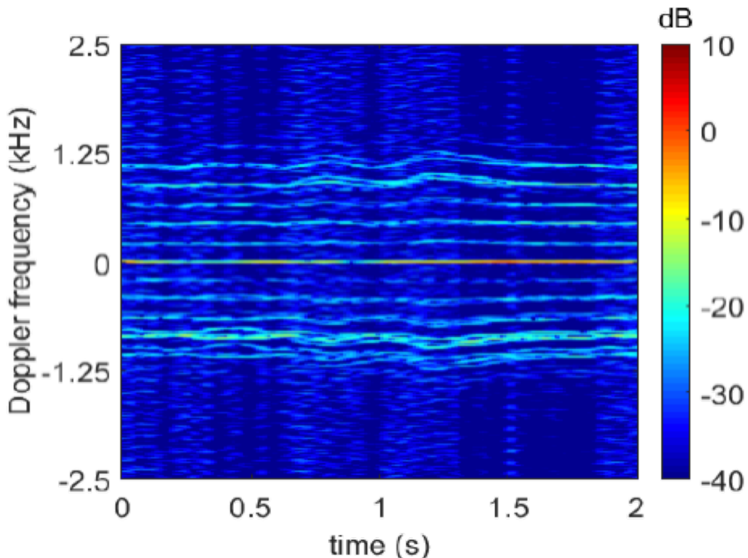




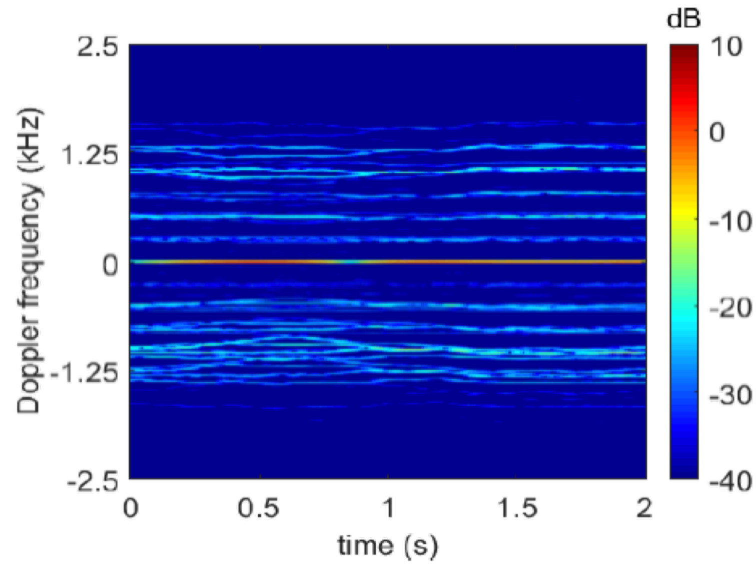


-M. Ritchie, F. Fioranelli, H. Griffiths and B. Torvik, "Monostatic and bistatic radar measurements of birds and micro-drone," 2016 IEEE Radar Conference (RadarConf), Philadelphia, PA, 2016, pp. 1-5.

ADVANCED APPLICATIONS – UAV Payload Discrimination



DJI drone - No Payload



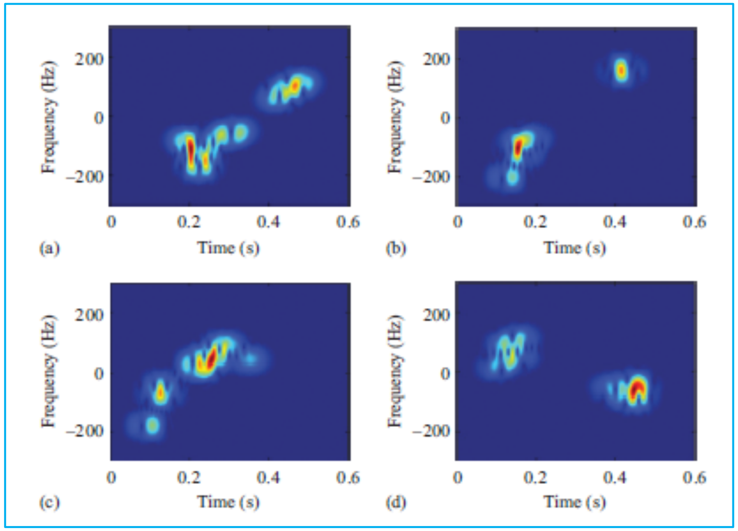
DJI drone - 500g Payload

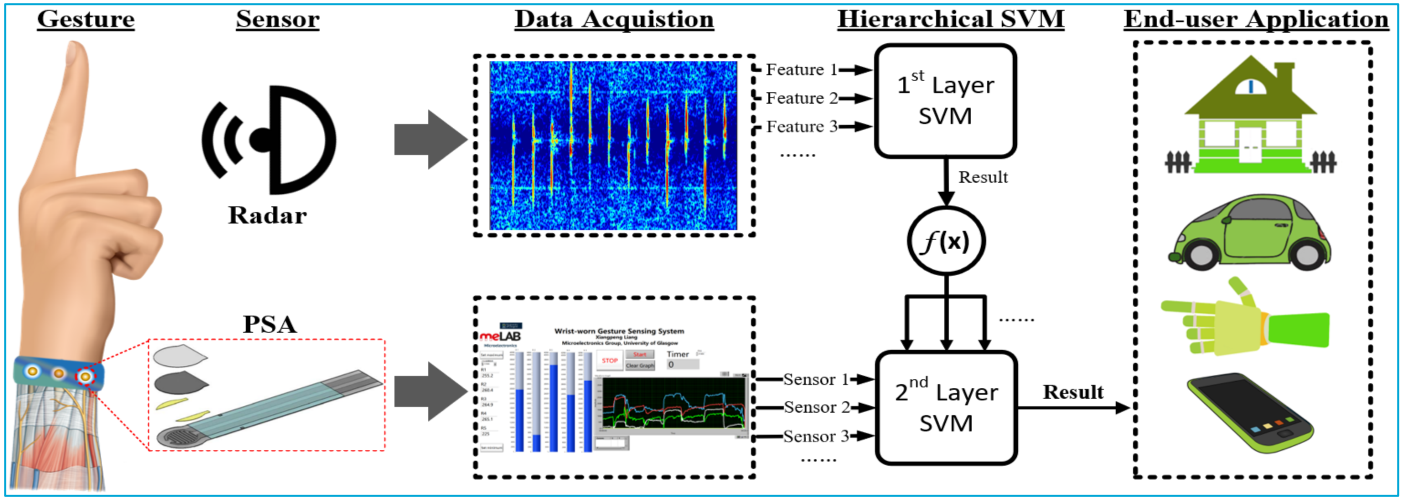
AVERAGE CONFUSION MATRIX FOR THE SIX CLASSES OF DRONES.

	unloaded	200 g	300 g	400 g	500 g	600 g
unloaded	**97.31%**	0.15%	0.23%	2.15%	0.16%	0%
200 g	1.23%	**95.08%**	1.23%	2.46%	0%	0%
300 g	4.46%	6.77%	**88.16%**	0.23%	0%	0.38%
400 g	0.08%	0%	3.15%	**95.85%**	0.92%	0%
500 g	0.08%	1.15%	0.15%	0.77%	**97.31%**	0.54%
600 g	0.54%	0%	4.77%	0.08%	12.61%	**82.00%**

ADVANCED APPLICATIONS – Hand Gesture

Reconstructed sparse micro-Doppler signal. 4 gestures including: a) hand rotation; b) beckoning; c) snapping fingers, d) flipping fingers

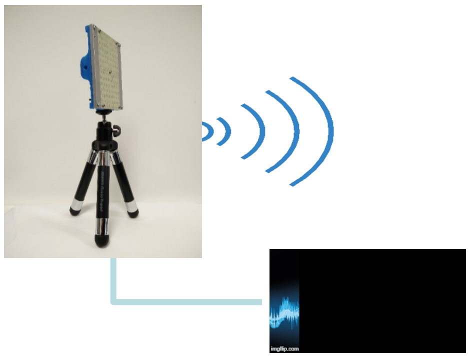


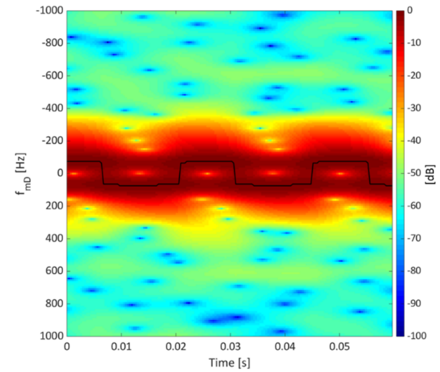


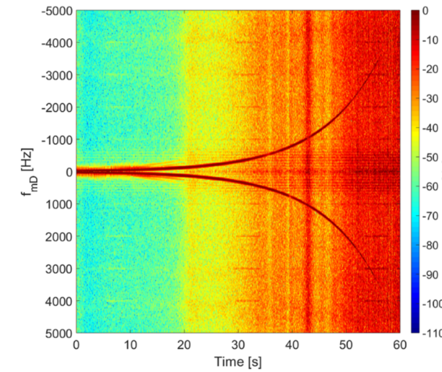
-Top image from G. Li & S. S. Ram; Chapter 3 in "Micro-Doppler Radar and its Applications", Edited by F. Fioranelli, H. Griffiths, M. Ritchie, A. Balleri, The IET, 2020.

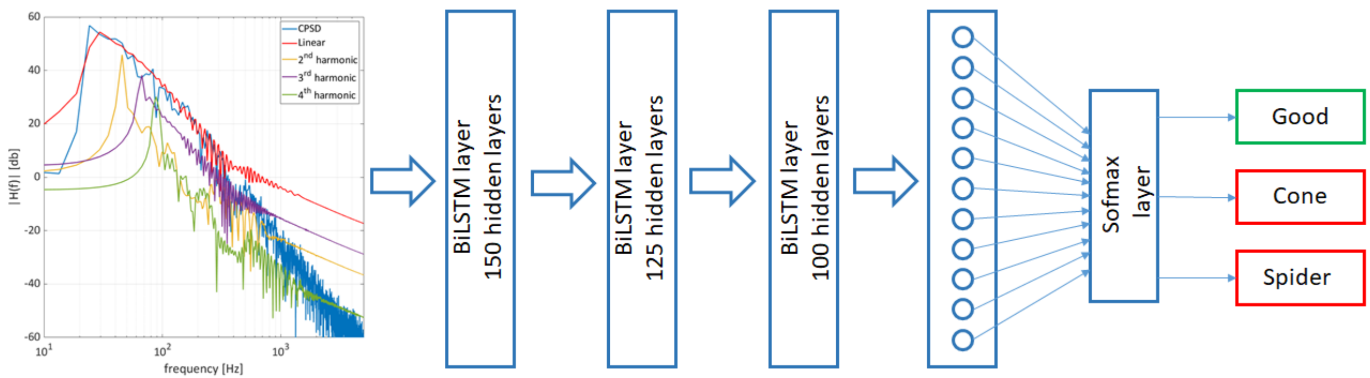
-H. Li et al., "Hierarchical Sensor Fusion for Micro-Gestures Recognition with Pressure Sensor Array and Radar," in IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, doi: 10.1109/JERM.2019.2949456.

ADVANCED APPLICATIONS – Industry 4.0









Worked Example

A 77 GHz is used for infrastructure monitoring and is observing a dam. The dam vibrates at 0.5 Hz and has a displacement of 1 mm. Sketch the micro-Doppler signature of the dam for 4 seconds of observations.

$$\Gamma = 0.001m \qquad f_v = 0.5Hz$$

The micro-Doppler of the dam is

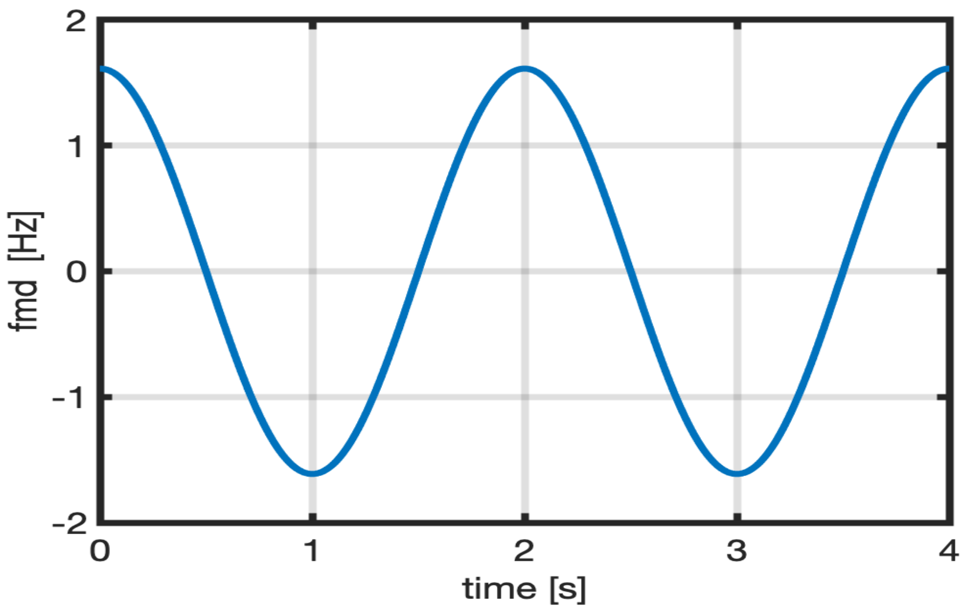
$$f_{mD}(t) = \frac{4\pi f_0 f_v \Gamma}{c} cos(2\pi f_v t)$$

Worked Example

The maximum micro-Doppler is obtained when the cosine is 1.

$$f_{mD_{max}} = \frac{4\pi f_0 f_v \Gamma}{c} \times 1 = 1.61Hz$$

So the m-D oscillates at 0.5 Hz with a max of 1.61Hz of Doppler



Micro-Doppler analysis in Matlab

```
clear all
close all
clc

% Simulation parameters

f_0 = 10e9; % carrier frequency
Gamma = .2; % component vibrating amplitude
f_v = 3; % vibrating frequency
rho = 1;  % return intensity
c = 3e8; % propagation speed
PRF =1000; % pulse repetition frequency
dur = 1; % acquisition duration
lambda = c/f_0; % wavelenght
R0 = 10000; % target range center
t = linspace(0,dur,PRF*dur); % time axis

%Simulation
R  = R0 + Gamma*sin(2*pi*f_v*t) ; % instaneous target range
phi =4*pi*R/lambda; % time varying phase
s = rho.*exp(1i*2*pi*f_0*t).*exp(1i*phi); % received signal
NFFT = PRF; % number of FFT bins in the STFT
WS = 20;  % time window size
overlap = round(0.95*WS); % overlap
```

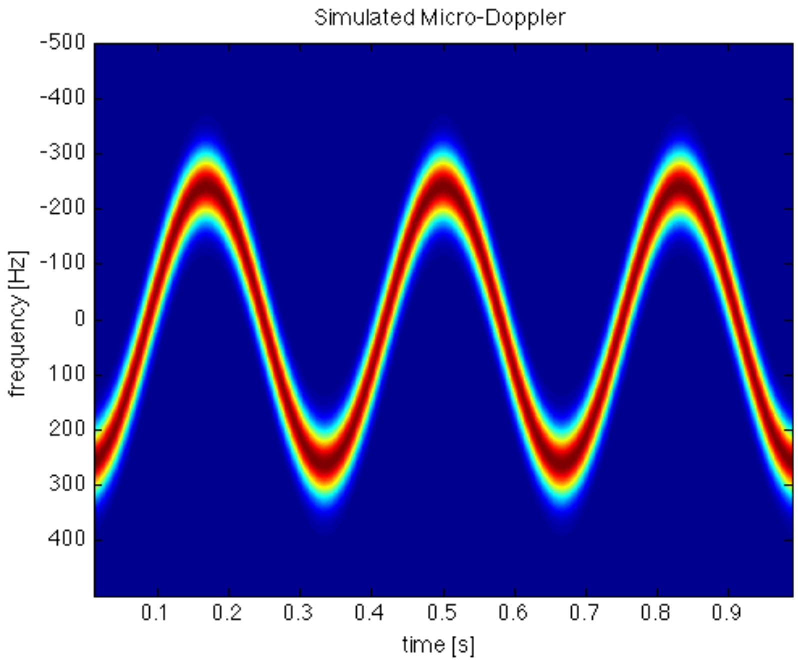
Micro-Doppler analysis in Matlab

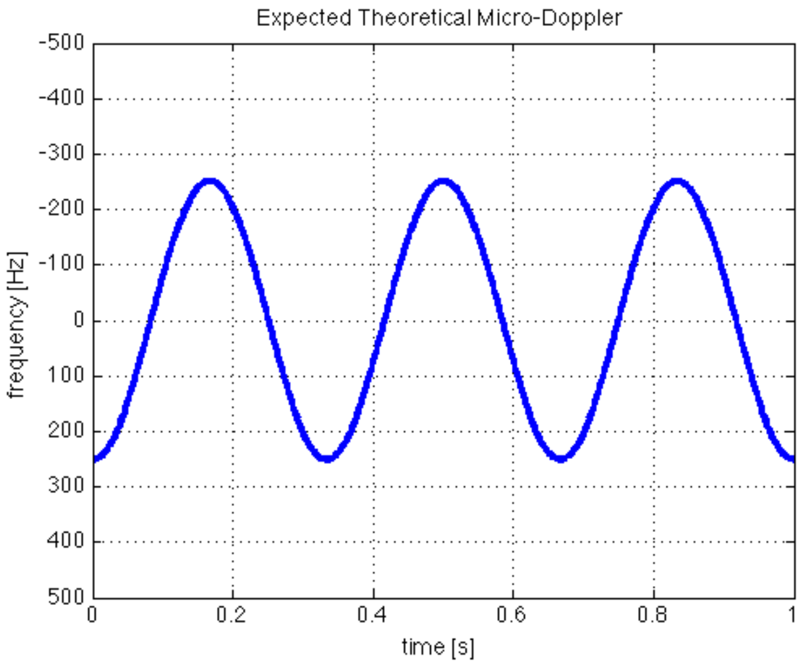
```
%Analysis
[X, F, T] = spectrogram(s,gausswin(WS),overlap, NFFT, PRF);  % spectrogram
X = fftshift(X,1); % fftshift applied to the spectrogram
F =F-PRF/2; % frequency axis adjusted
figure, imagesc(T,F, abs(X))

title('Simulated Micro-Doppler')
xlabel('time [s]')
ylabel('frequency [Hz]')

% check the theoretical MD
fmd = 4*pi*Gamma*f_v/lambda*cos(2*pi*f_v*t); % expected micro-Doppler shift
figure, plot(t,fmd, 'linewidth',4)
title('Expected Theoretical Micro-Doppler')
set(gca,'Ydir','reverse')
xlabel('time [s]')
axis([min(t) max(t) -PRF/2 PRF/2])
ylabel('frequency [Hz]')
grid on
```

Micro-Doppler analysis in Matlab





3rd DSP Challenge - Solved

- Additional movements introduce Doppler modulation that can be modelled;
- The micro-Doppler can be analyzed in the time-Frequency Domain using STFT, WVD, PVWD, etc.;
- Target recognition and kinematic analysis are possible based on the micro-Doppler information.