Doppler Measurement

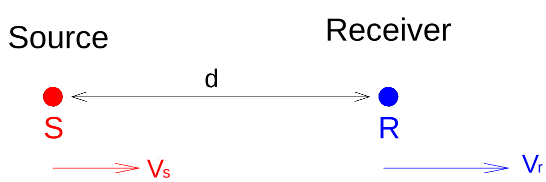
Introduction

- The apparent difference between the frequency at which sound or light waves leave a source and at which they reach an observer caused by relative motion of the observer and the wave source
- First described in 1842 by Christian Doppler
- Acoustic examples include the apparent difference in frequency of a motor vehicle approaching and receding from an observer
- EM examples include the red shift of most galaxies due to the expansion of the universe
- The principle is generally used to determine the velocity of one object relative to another

"I love hearing that lonesome wail of the train whistle as the magnitude of the frequency of the wave changes due to the Doppler effect."

Doppler Frequency Shift Movie

Definition of Directions



Doppler Frequency Shift

- It is shown in the notes that the relationship between the velocities of the source and receiver and the transmit and receive frequencies is

$$f_r = \frac{c - v_r}{c - v_s} f_s$$

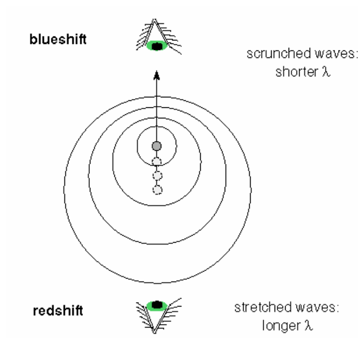
- The Doppler shift is the difference between the transmitted and received frequency

$$f_d = f_r - f_s = \left(\frac{c - v_r}{c - v_s} - 1 \right) f_s = -\frac{v_r - v_s}{c - v_s} f_s$$

- For EM radiation where $v_s << c$ this reduces to

$$f_d = f_r - f_s \approx -\frac{v_r - v_s}{c} f_s = -\frac{v_r - v_s}{\lambda_s}$$

Higher frequency



Lower frequency

Example

- An electromagnetic source operating at 77GHz (λ = 3.9mm) and a sound source operating at 90kHz (λ = 3.9mm) are each moving at a speed of 30m/s, what is the Doppler shift observed by a stationary observer in each case
- For the EM radiation

$$f_d = -\frac{v_r - v_s}{c - v_s} f_s = -\frac{0 - 30}{3 \times 10^8} 77 \times 10^9 = 7.7kHz$$

$$f_d \approx \frac{v_s}{\lambda} = \frac{30}{3.9 \times 10^{-3}} = 7.7kHz$$

- For the sound

$$f_d = -\frac{v_r - v_s}{c - v_s} f_s = -\frac{0 - 30}{340 - 30} 90 \times 10^3 = 8.7kHz$$

An Enigma (so far)

S → R →	S ← R →	S → R ←	S ← R ←
$f_r = -\dfrac{c - v_r}{c - v_s} f_s$	$f_r = -\dfrac{c - v_r}{c + v_s} f_s$	$f_r = -\dfrac{c + v_r}{c - v_s} f_s$	$f_r = -\dfrac{c + v_r}{c + v_s} f_s$
f_d = -2.42kHz	f_d = -4.57kHz	f_d = 4.85kHz	f_d = 2.28kHz

For the following values

c = 340m/s

v_r = 30m/s

v_s = 10m/s

f_s = 40kHz

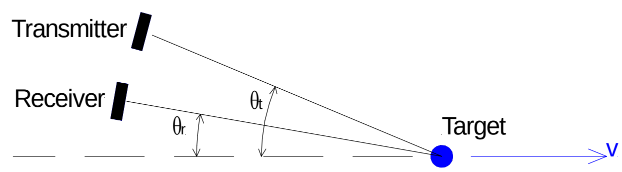
Doppler Geometry (v<<c)

- In most Doppler sensors, both the receiver and transmitter are stationary and they illuminate a moving target
- This is equivalent to the receiver moving away from the transmitter at a velocity $v.\cos\theta_t$ + $v.\cos\theta_r$ if $v<<c$
- For separated transducers this is

$$f_d = -\frac{f_s v}{c}\left(\cos\theta_t + \cos\theta_r\right)$$

- And for co-located transducers where $\theta_r = \theta_t = \theta$

$$f_d = -\frac{2 f_s v}{c}\cos\theta = -\frac{2v}{\lambda_s}\cos\theta$$



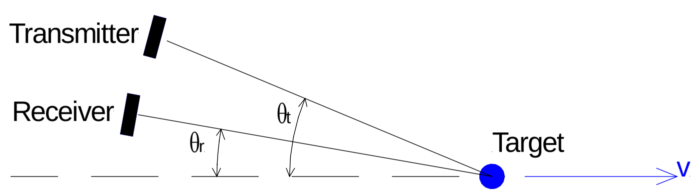
Doppler Geometry (v<c)

- For separated transducers this is

$$f_r = \frac{c - v\cos\theta_r}{c + v\cos\theta_t} f_s$$

$$f_d = f_r - f_s$$

- And for co-located transducers where $\theta_r = \theta_t = \theta$ just replace the two angles with the common offset angle



Doppler Frequency Extraction

- For a transmitter signal of the form

$$x_t(t) = \xi_t \cos(\varpi_s t)$$

- The corresponding echo received from a moving target will be

$$x_r(t) = \xi_r \cos([\varpi_s + \varpi_d]t + \phi)$$

where ϕ - phase term dependent on the distance to the target (rad)
$\varpi_s = 2\pi f_s$ (rad/s)
$\varpi_d = 2\pi f_d$ (rad/s)

- Mixing (multiplying) the two signals

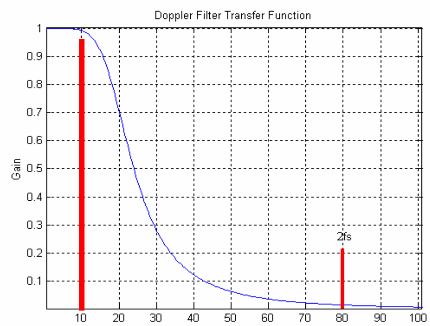
$$x_t(t)x_r(t) = \xi_t\xi_s \cos(\varpi_s t)\cos([\varpi_s + \varpi_d]t + \phi)$$

$$= \frac{\xi_t\xi_r}{2}\{\underbrace{\cos(\varpi_d t + \phi)}_{\text{Doppler}} + \underbrace{\cos([2\varpi_s + \varpi_d]t + \phi)}_{\text{Component at } 2f_s}\}$$

Filtering

- As we are not interested in the signal at $2\varpi_s$ it is filtered out using a lowpass filter as shown in the figure

$$x_d(t) = \frac{\xi_t\xi_r}{2}\cos(\varpi_d t + \phi)$$

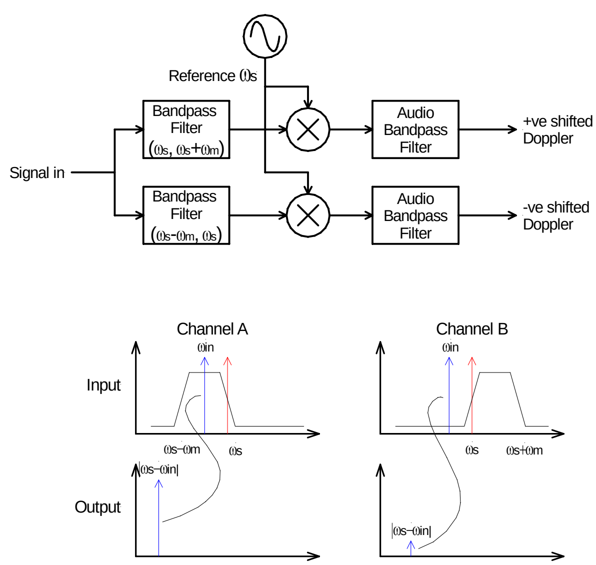


- In Doppler ultrasound applications, there is also a large static return from non moving targets that will be 40 to 50dB larger than the Doppler signal. This is often filtered out using a high pass filter

Doppler Direction Discrimination

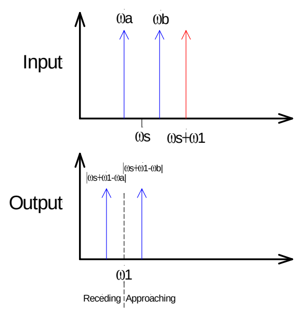
- The mixing process described in the previous slides can only provide an absolute difference in frequency. It contains no information regarding the direction of motion
- The following are the most common techniques used to preserve the direction information
  - Sideband filtering
  - Offset carrier demodulation
  - In phase / Quadrature demodulation
- In the descriptions remember that
  - $\varpi_d > 0$ Target velocity towards the sensor
  - $\varpi_d < 0$ Target velocity away from the sensor

Sideband Filtering

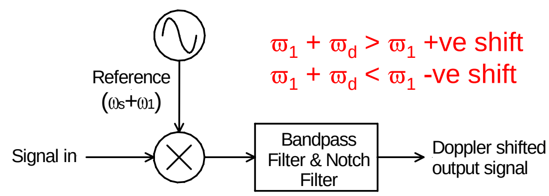


Offset Carrier Demodulation

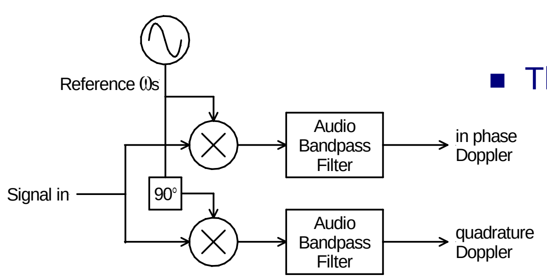
- Instead of mixing down to baseband, the received, Doppler shifted signal is mixed with a reference signal $\varpi_s + \varpi_1$ where $\varpi_1 < |\varpi_s + \varpi_{bmax}|$
- After filtering to remove the signal at $2\varpi_s$, in the absence of a moving target, the resultant is a signal at a frequency ϖ_1 which is removed with a notch filter
- If the target is moving, then the frequency will shift upwards if it is approaching, and downwards if it is receding



$\varpi_1 + \varpi_d > \varpi_1$ +ve shift
$\varpi_1 + \varpi_d < \varpi_1$ -ve shift



In Phase and Quadrature Demodulation

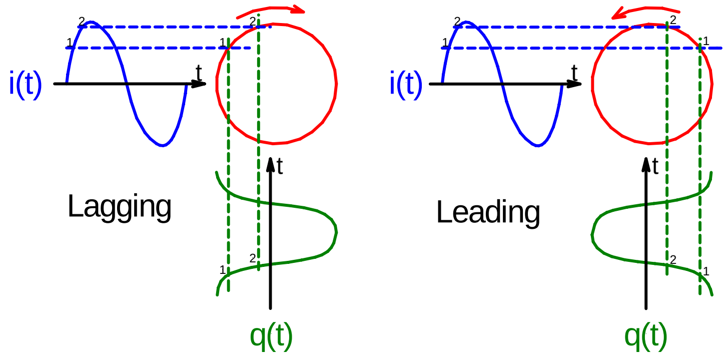


- The output signals are

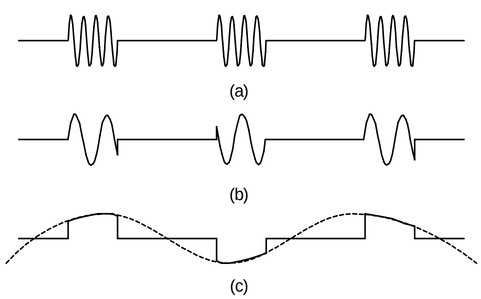
$$i(t) = \cos(\omega_d t + \phi)$$
$$q(t) = \sin(\omega_d t + \phi)$$

- If $q(t)$ is retarded by $\pi/2$ with respect to $i(t)$ the target is approaching
- If $q(t)$ is advanced by $\pi/2$ with respect to $i(t)$ the target is receding

Lissajous Representation of IQ Signals

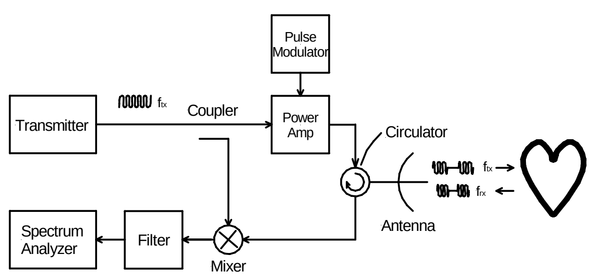


Pulsed Doppler Principles

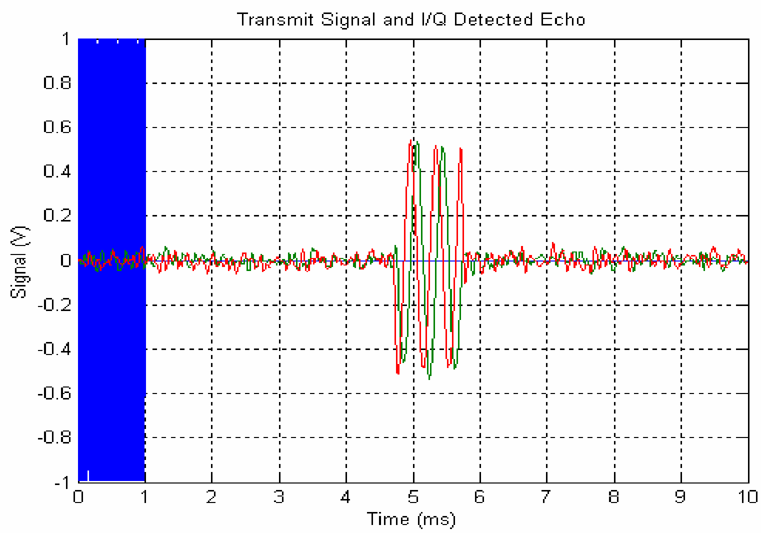


Combines aspects of TOF range measurement with Doppler velocity measurement

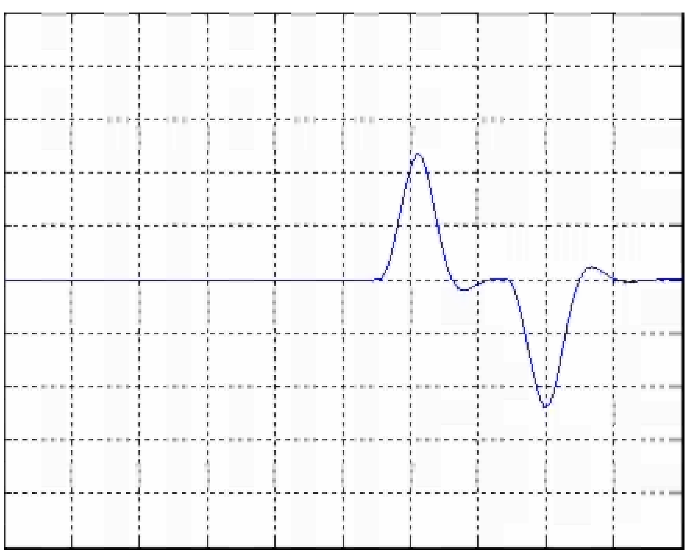
The number of cycles received during the pulse period at each range depends on the Doppler frequency and the pulsewidth



Doppler Outputs for I/Q Detection



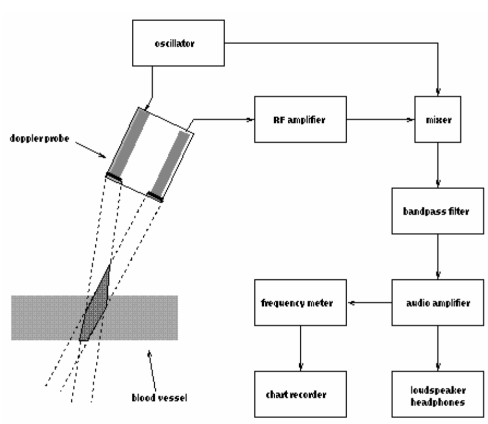
Doppler Outputs: Phase Detector



Doppler Sensors

- Many sensors using both ultrasound and electromagnetic waves make use of the Doppler principle to measure target motion effects
- Sensors can either use continuous wave (CW) or pulsed waveforms
- CW sources generally determine velocity only
- Pulsed sources can discriminate range and velocity

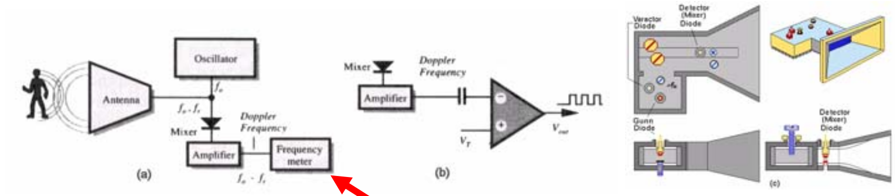
Continuous Wave Ultrasound Example



Schematic of Monitor

Doppler Flow and Heartbeat Monitor

Continuous Wave Radar Examples

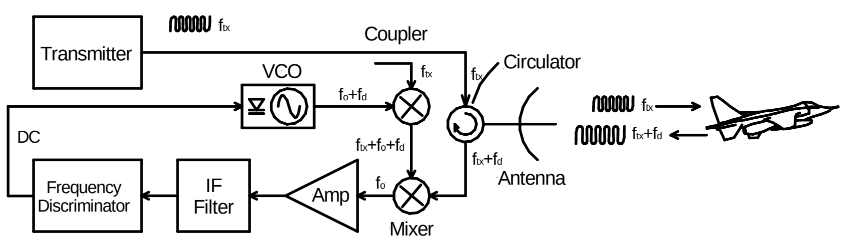


- X-Band (8-12GHz) intruder alarm
- Iris coupled Gunn Oscillator Based
- Output power 1-10mW
- Integral horn antenna

K-band (24.15GHz) sports radar
Gunn oscillator
Output power 40-100mW
Lens antenna
Accuracy +/-1km/h (typical)

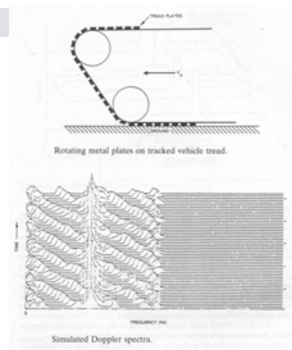
Doppler Missile Tracker

- A narrow band fixed frequency tracking filter at f_o in the IF chain rejects noise and crosstalk from the transmitter
- The filter is followed by a discriminator that produces a DC voltage proportional to the frequency error
- This drives a voltage controlled oscillator (VCO) that produces a signal f_o+f_d that is mixed with the transmit signal to produce the local oscillator
- This automatic frequency control ensures that the received signal f_t+/-f_d is always down converted to a constant frequency f_o irrespective of the target speed

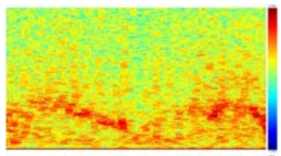


Doppler Target Identification

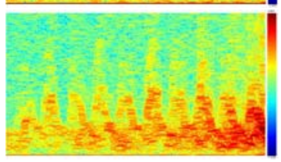
- Moving targets, or moving components of targets can be used to identify them
  - In military applications this includes helicopter blade spectra and tank track signatures
  - In security applications, Doppler spectra can discriminate between human and animal intruders



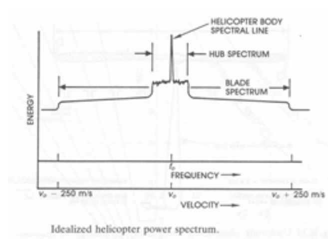
Tank tread spectra



Doppler spectrogram of a large white dog



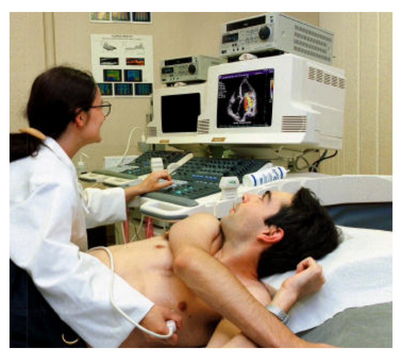
Doppler spectrogram of a small mousy human target



Helicopter spectrum

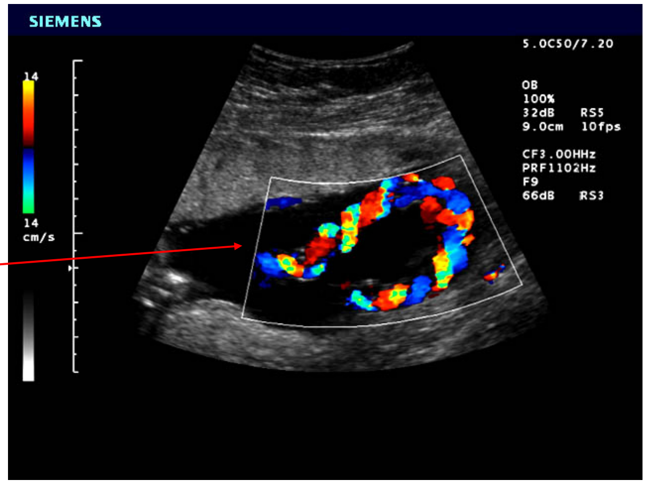
Pulsed Doppler Ultrasound

- Pulsed Doppler ultrasound systems can produce 2D images encoded for movements
- Because the transmit and receive signals are separated in time, a single transducer can be used
- Pulsed Doppler is often incorporated into conventional pulsed echo ultrasound systems (duplex scanning)
- Very short pulses are used, typically only a few cycles long, to obtain the best possible resolution
- Typically a “sampling volume” that is smaller than the whole image is processed for Doppler



Pulsed Doppler Ultrasound Image

Sampling volume for Doppler processing



Pulsed Doppler Weather Radar