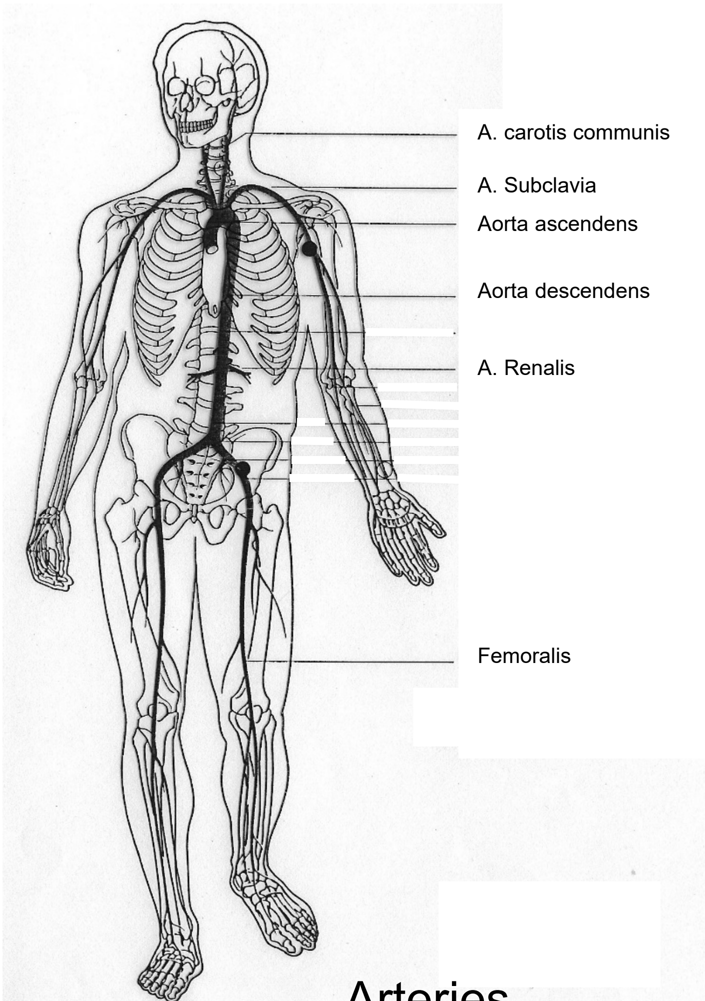
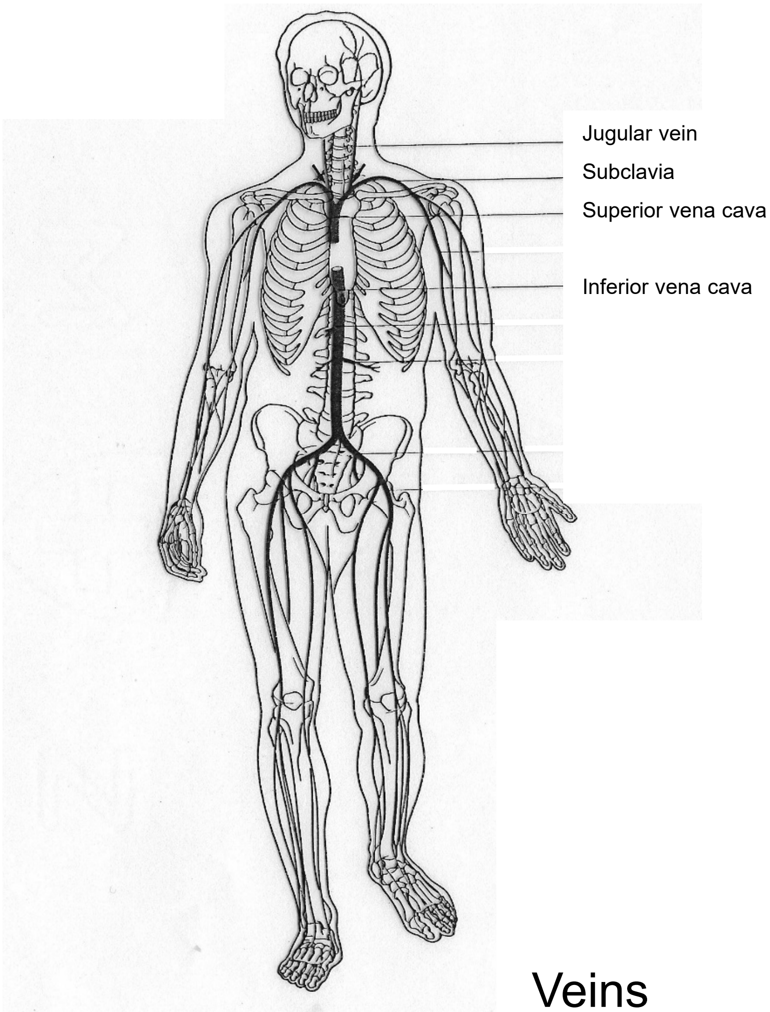
Arteries, Veins, Circulation



Arteries



Veins

Key physical quantity: blood flow

Christian Doppler

Christian Doppler (1803-1853), Austrian mathematician and physicist

Postulated the frequency shift of the light of binary stars

1845: Acoustic verification using the Amsterdam – Utrecht railway

Doppler Effect

Source

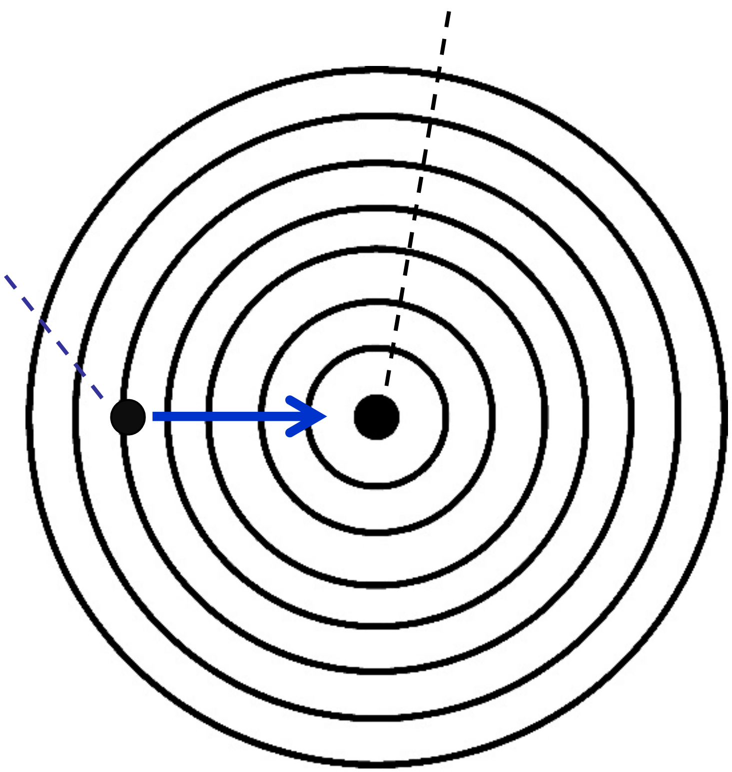
at frequency f, wavelength λ

Observer

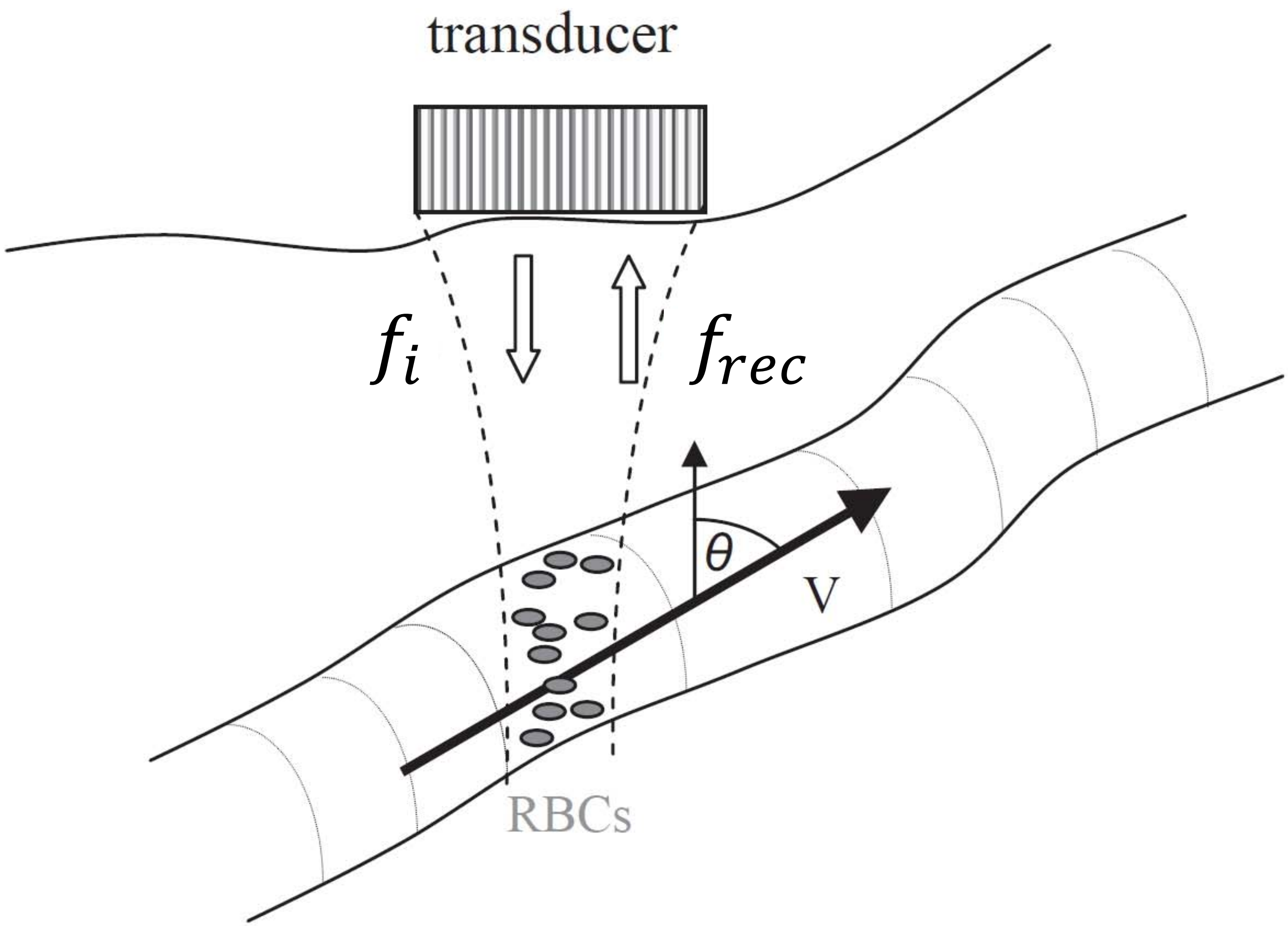
at velocity v

$$f^{eff} = \frac{c+v}{\lambda} = f\,\frac{c+v}{c}$$

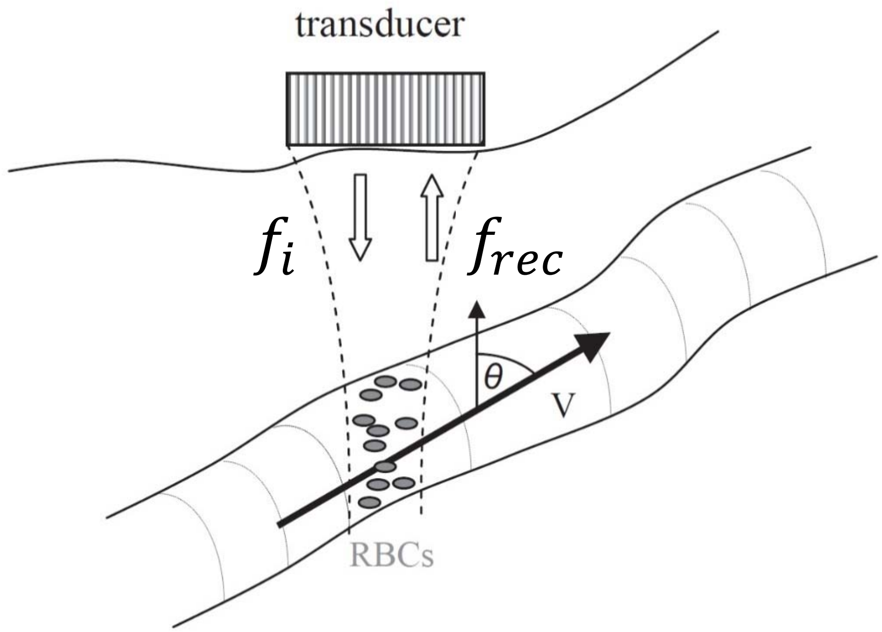
Frequency seen by observer



Doppler Effect



Doppler Effect



$$f_i^{eff} = \frac{c + v\cos\theta}{\lambda}$$

$$= \frac{f_i\,(c + v\cos\theta)}{c}$$

$$f_{rec} = \frac{f_i^{eff}(c + v\cos\theta)}{c} = \frac{f_i(c + v\cos\theta)^2}{c^2}$$

$$= f_i + \frac{2\,f_i v\cos\theta}{c} + \boxed{\frac{f_i v^2\cos^2\theta}{c^2}}$$

negligible for

$v \ll c$

$$f_D = f_i - f_{rec} \approx \frac{2\,f_i v\cos\theta}{c}$$

Doppler shift

Doppler Effect

$$f_D = \frac{2\, f_i v \cos\theta}{c} \quad \Rightarrow \quad v = \frac{c\, f_D}{2\, f_i \cos\theta}$$

blood velocity

Example:

f_i = 5 MHz, θ = 45°, v = 50 cm/s $\qquad$ f_D= 2.3 kHz (< 0.05 %)

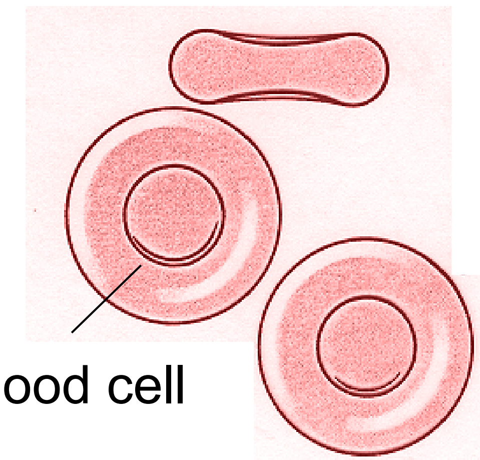
Doppler shifts are very small !

$\Rightarrow$ use high frequency, small wavelength

Must know angle θ, usually from additional B-mode scan

θ must not be too close to 90° to solve robustly for v

Scattering of Ultrasound by Red Blood Cells



Red blood cell

(Erythrocyte)

~ 7 µm

Ultrasound wavelength:

100 μm – 1 mm

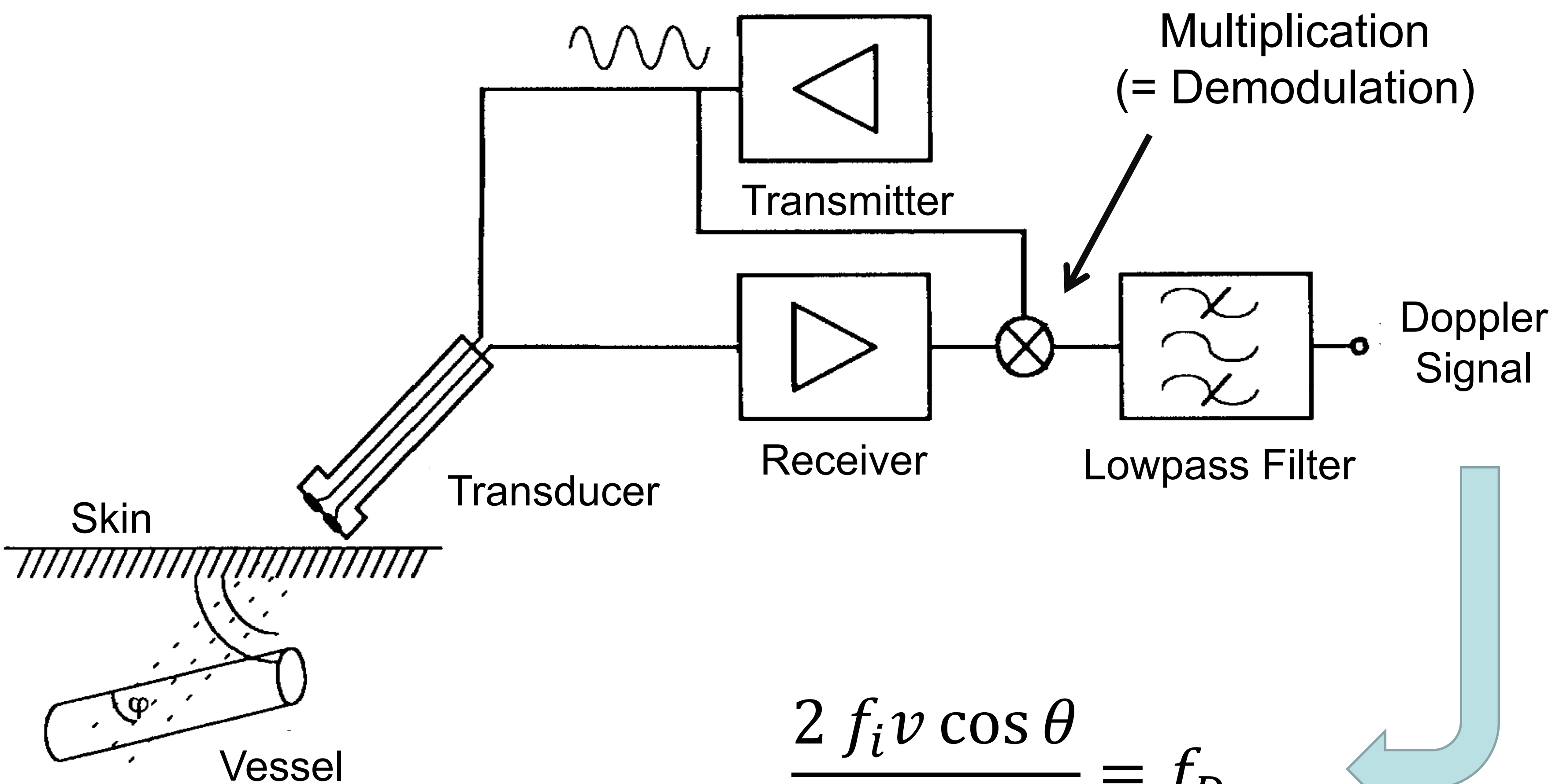
Cells much smaller than wavelength

→ Rayleigh scattering: $\sigma_s \propto \frac{1}{\lambda^4}$

→ <u>use high frequency, small λ</u>

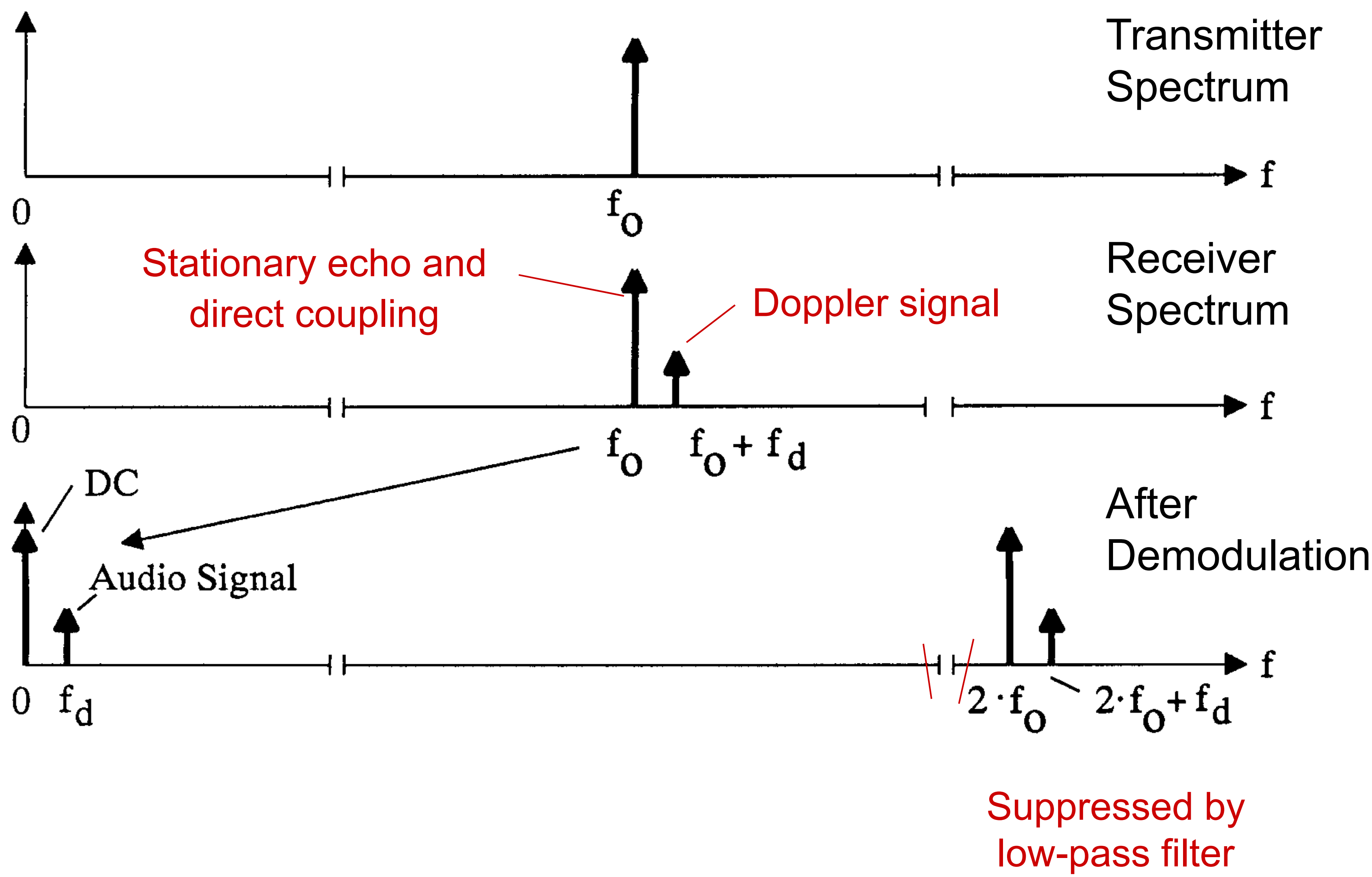
typical: 5 MHz

Continuous-wave (cw) Doppler

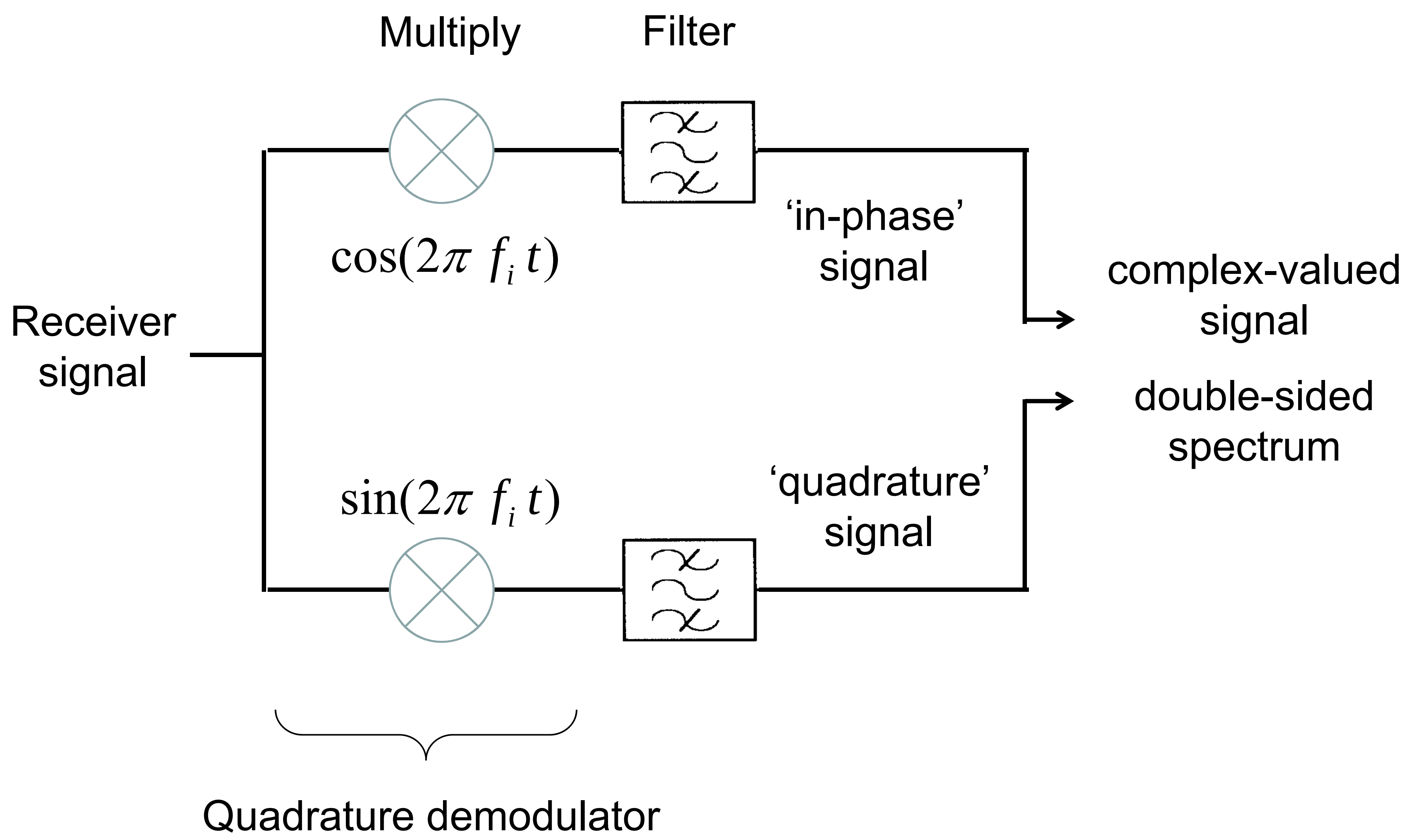


$$\frac{2\, f_i v \cos\theta}{c} = f_D$$

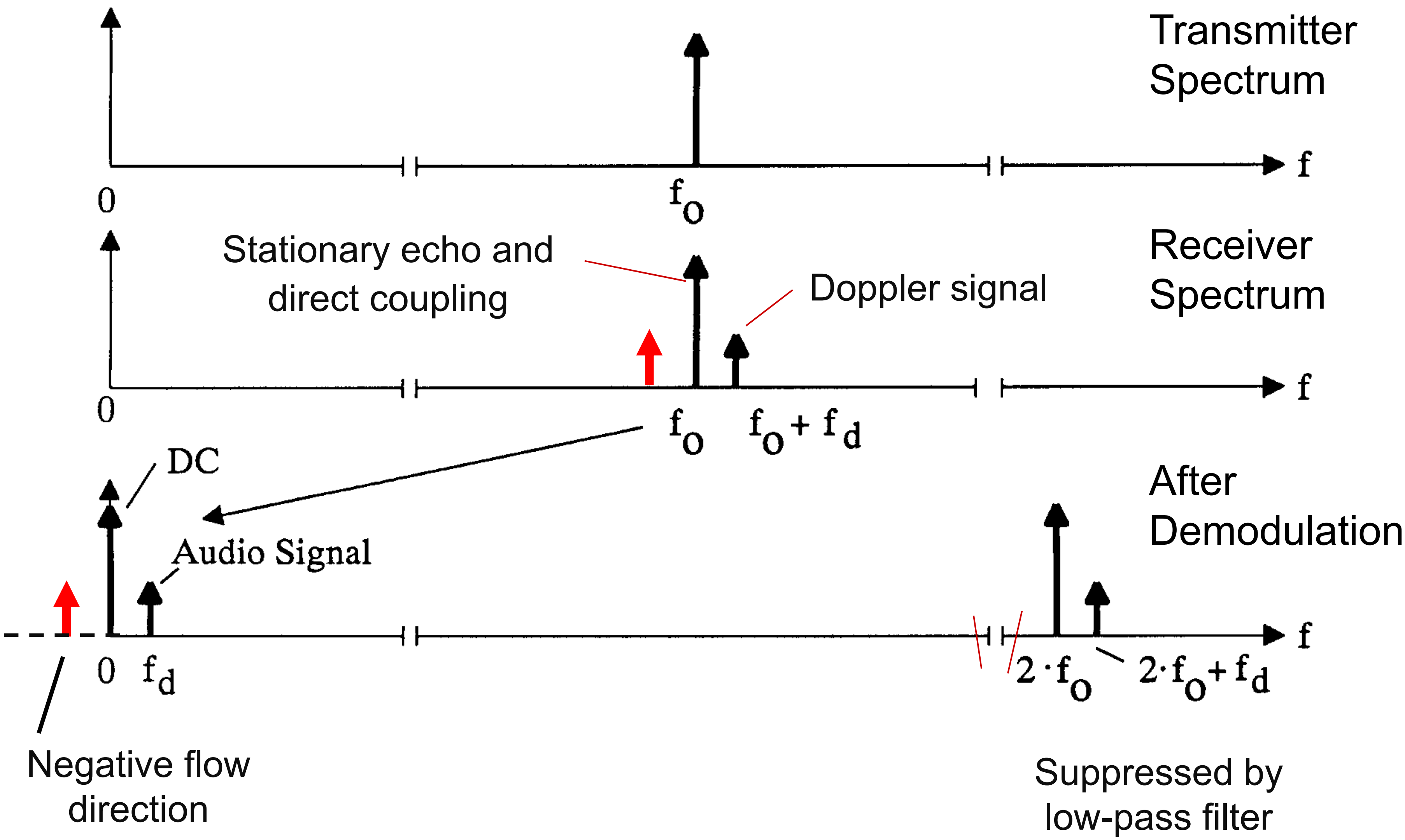
Doppler Spectrum and Demodulation



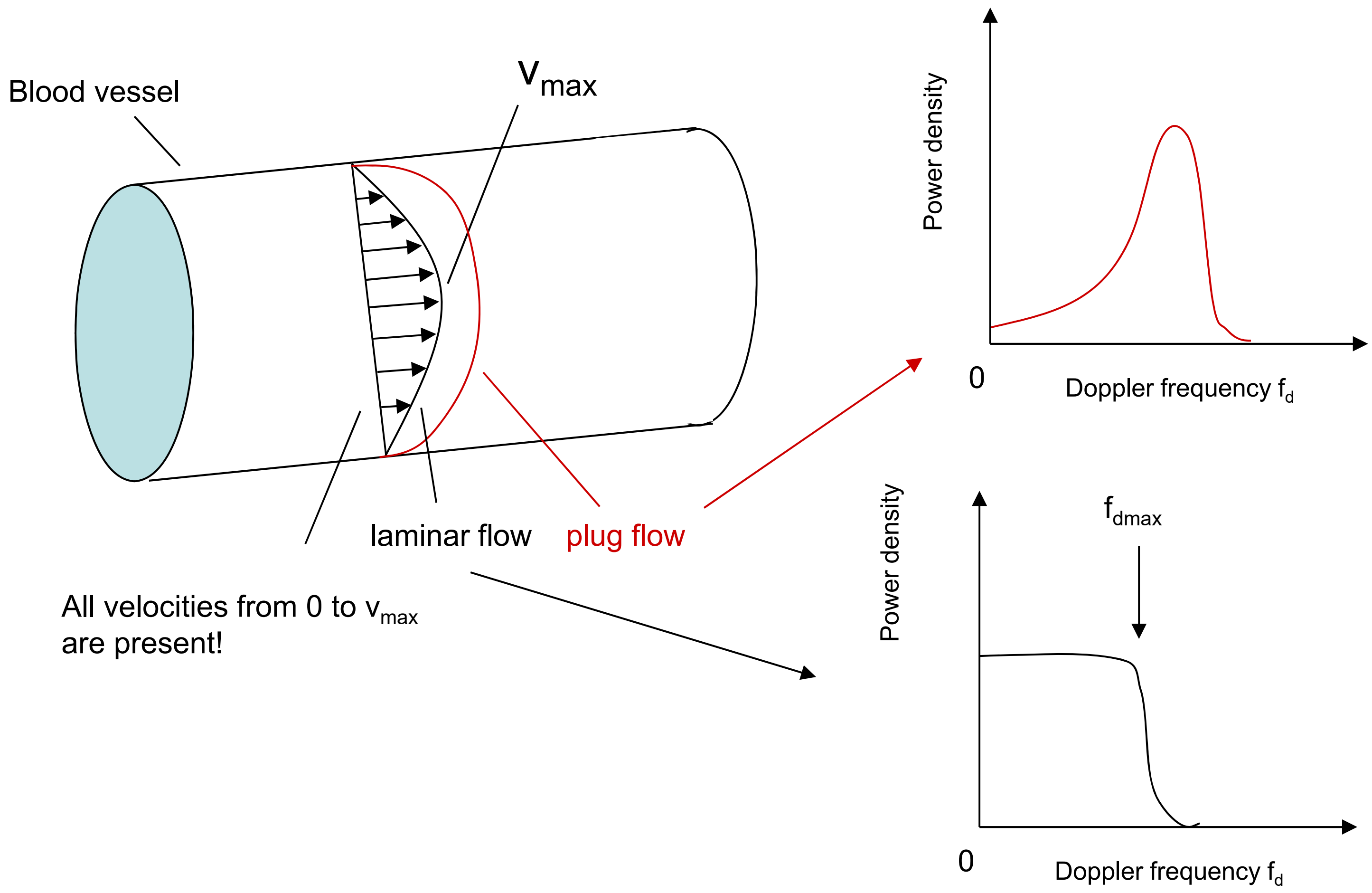
Detection of Flow Direction



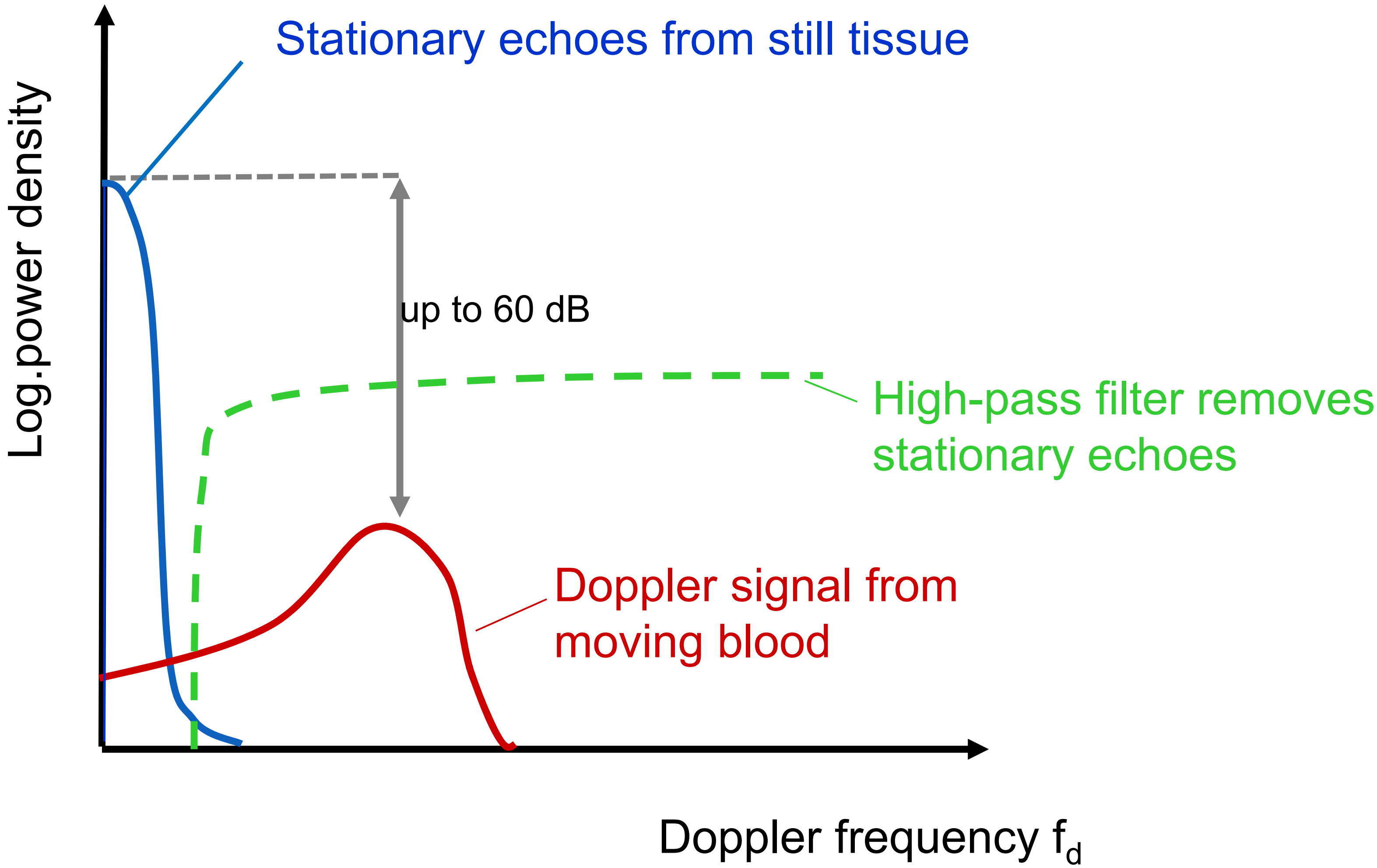
Doppler Spectrum and Demodulation



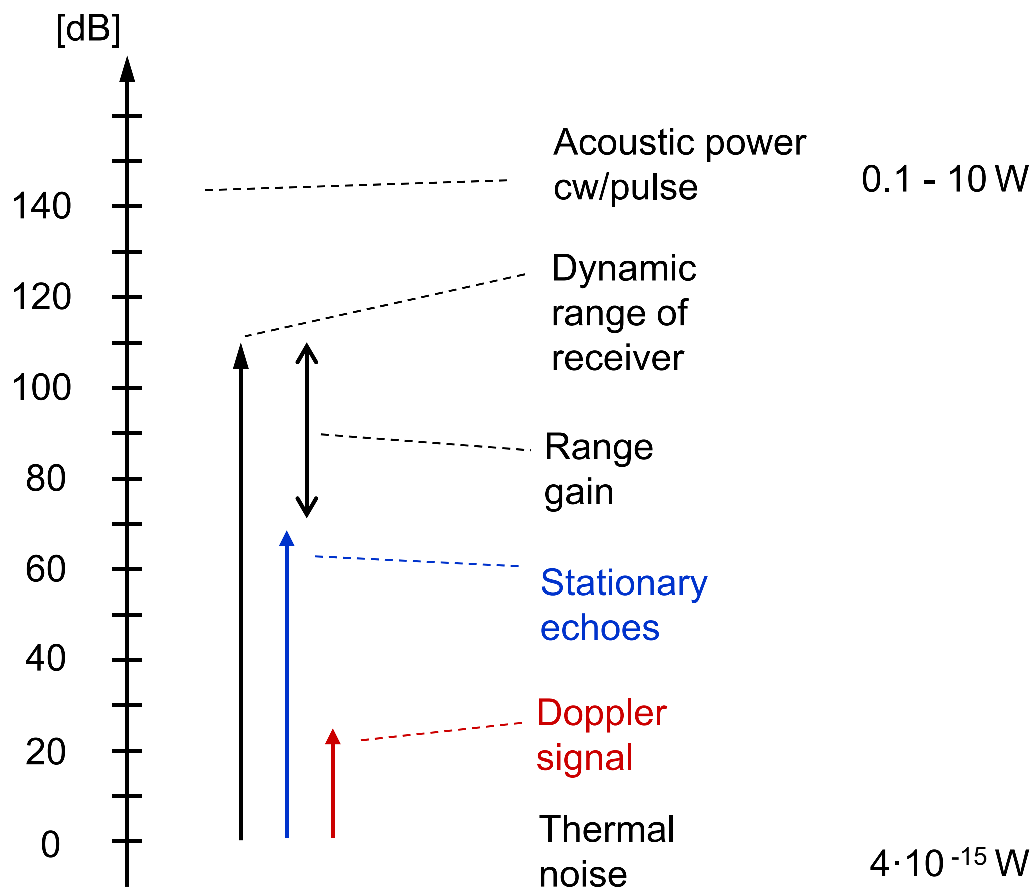
Flow Profile, Doppler Spectrum



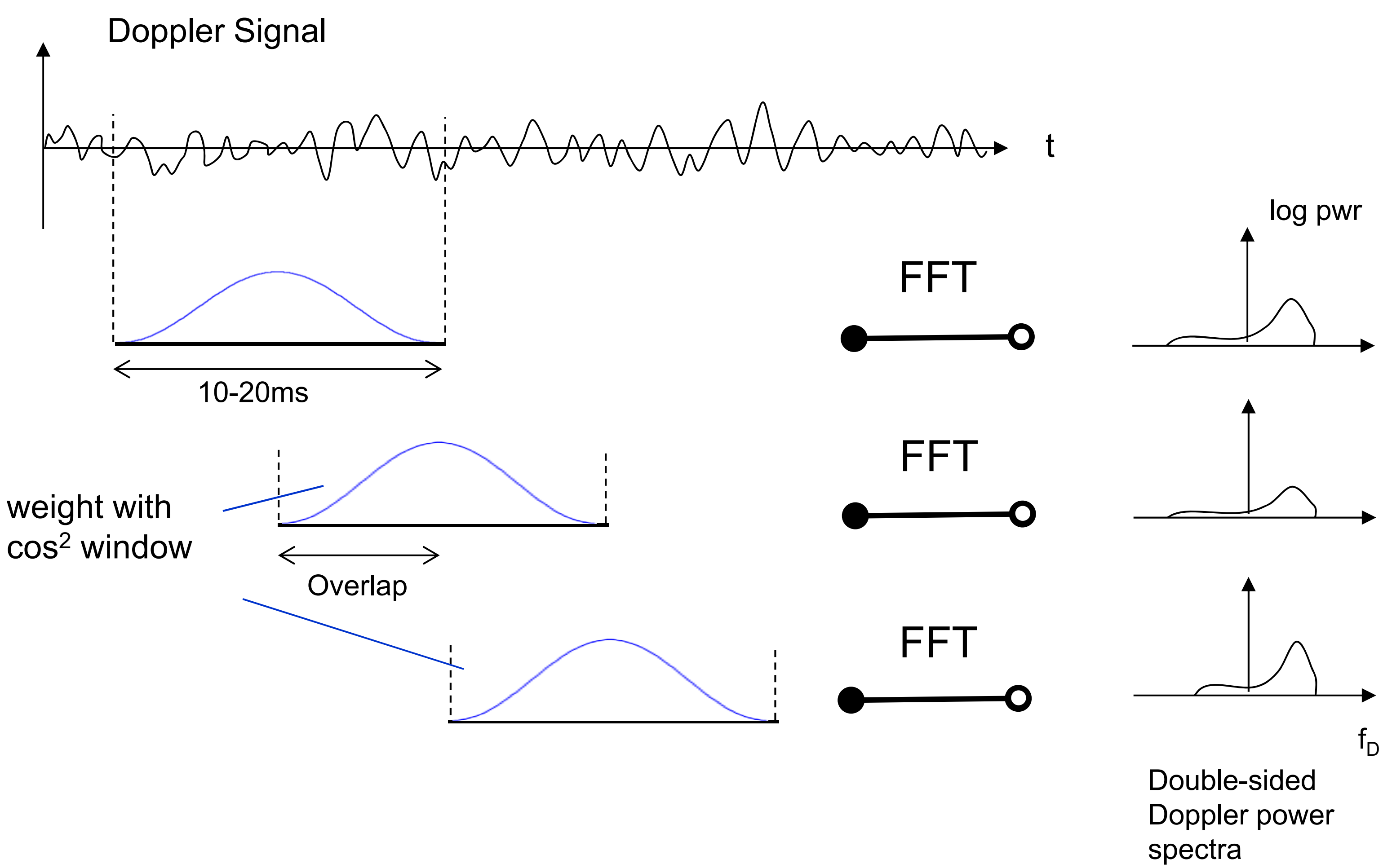
Real Doppler Spectrum with Stationary Echoes



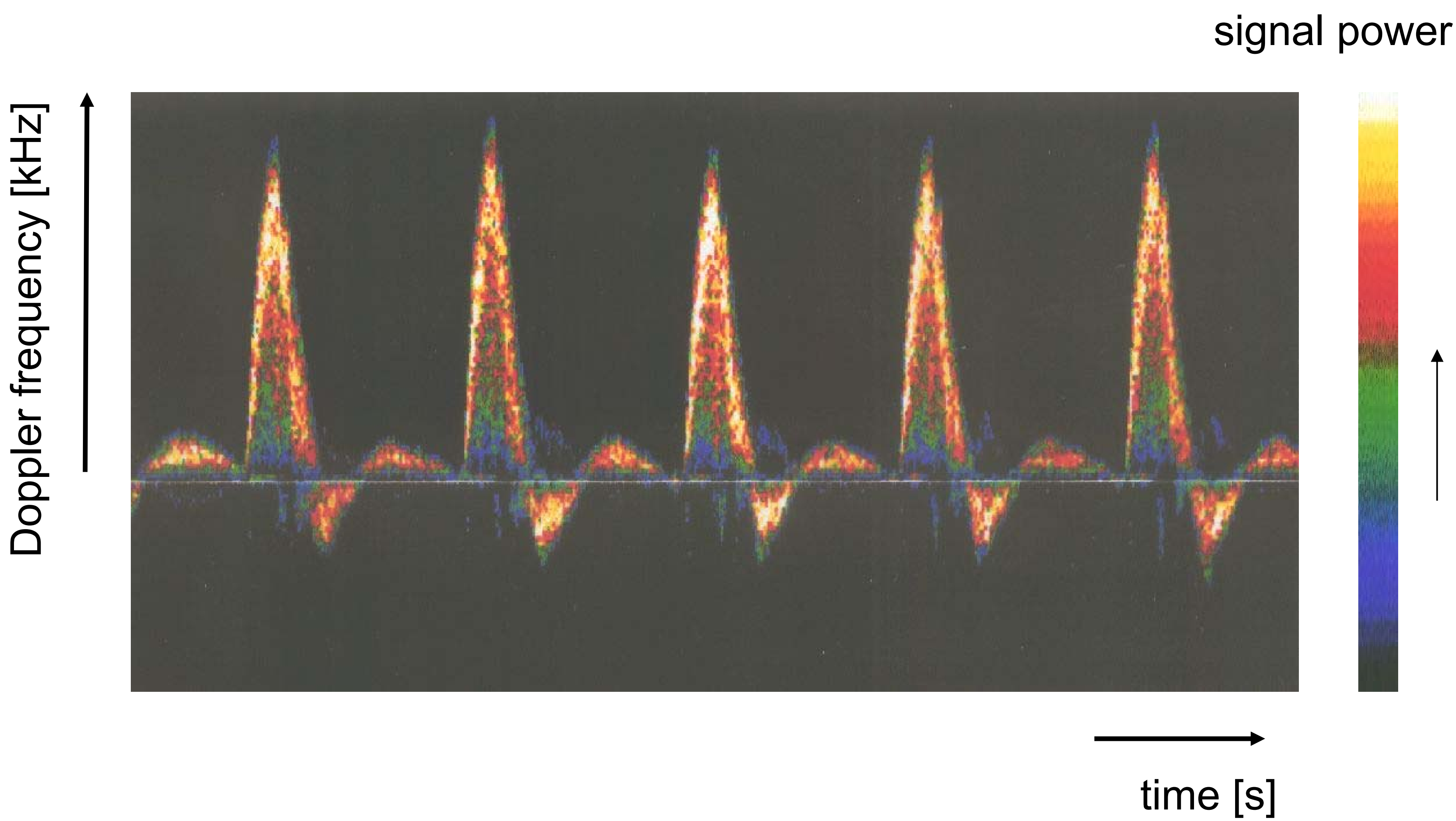
Dynamic Range



Time-Resolved Frequency Analysis

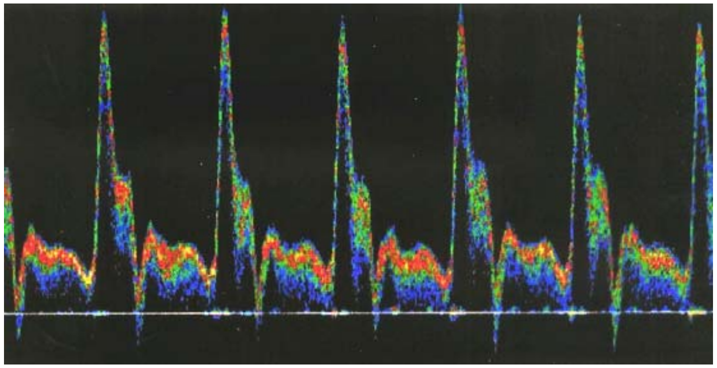


Sonogram: Arteria Femoralis

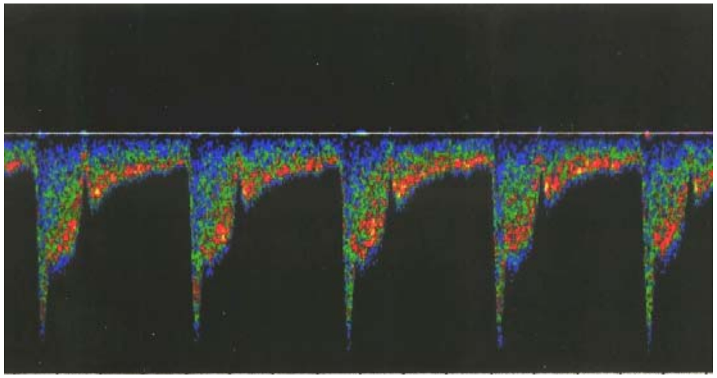


Example: Carotis Bifurcation

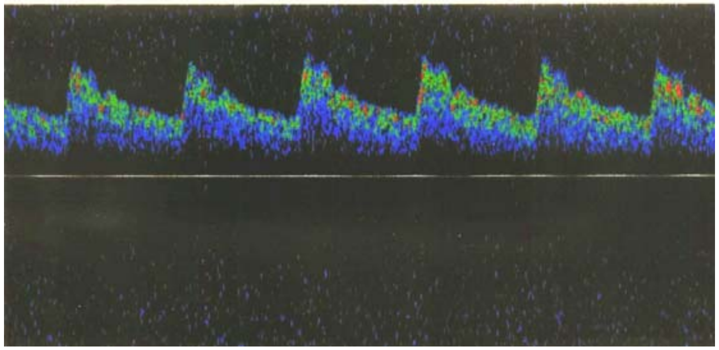
Carotis communis



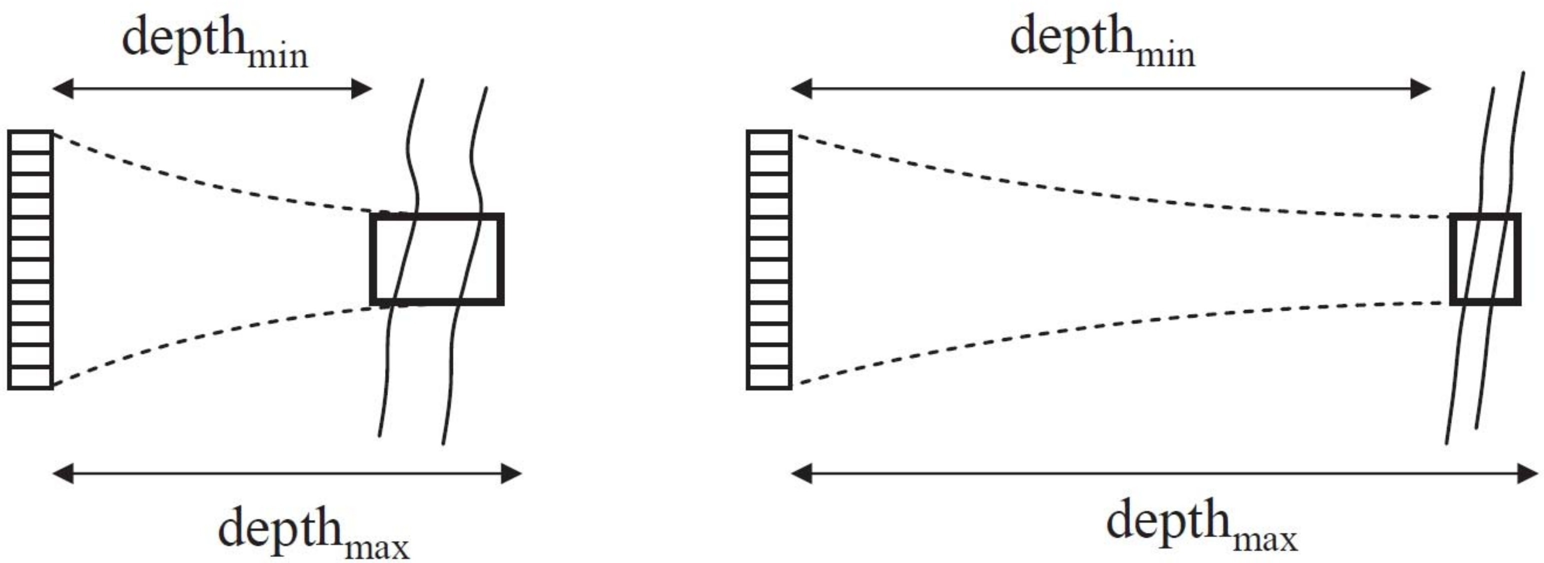
Carotis externa



Carotis interna



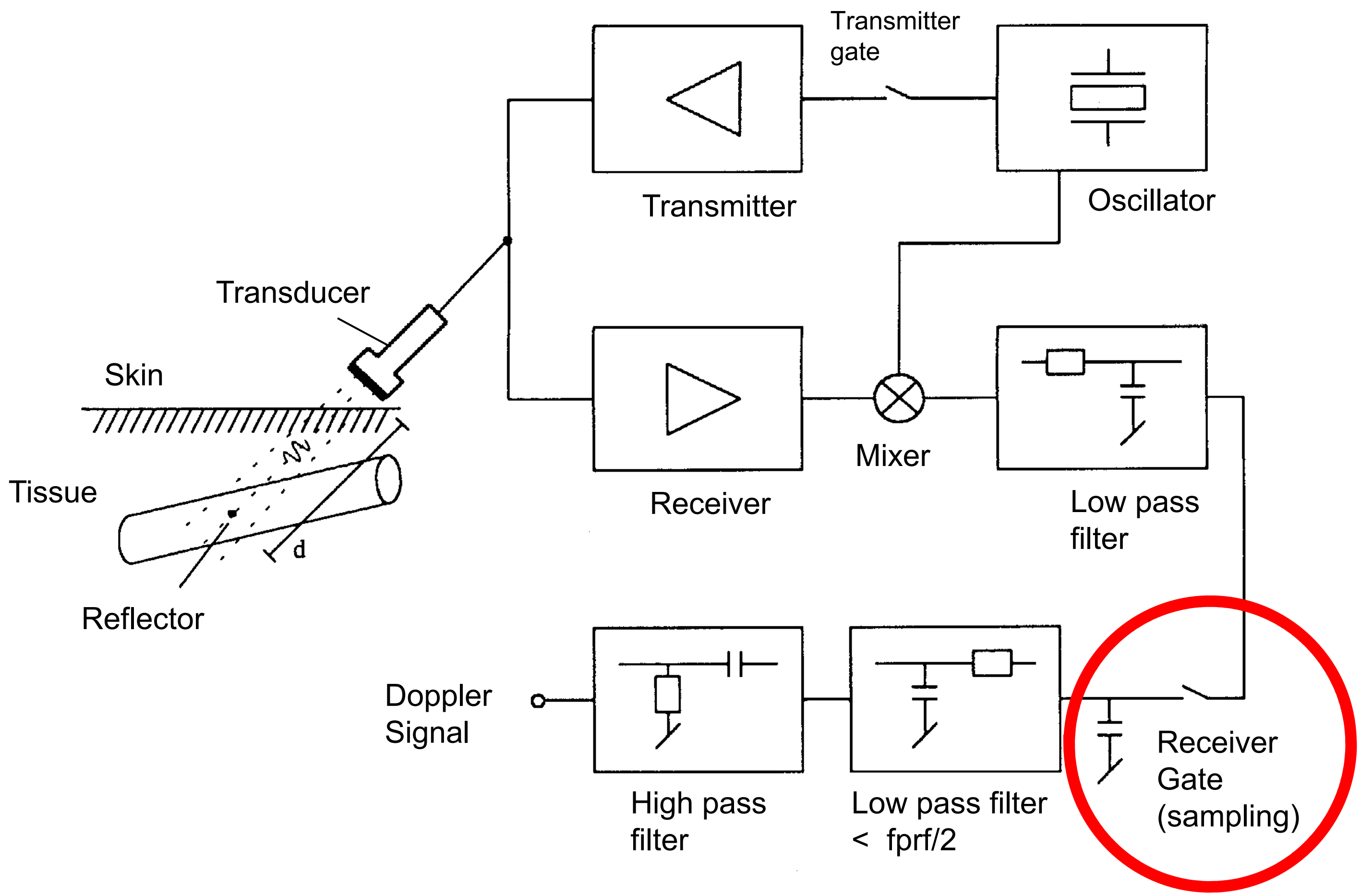
Spatial Resolution: Pulsed Doppler



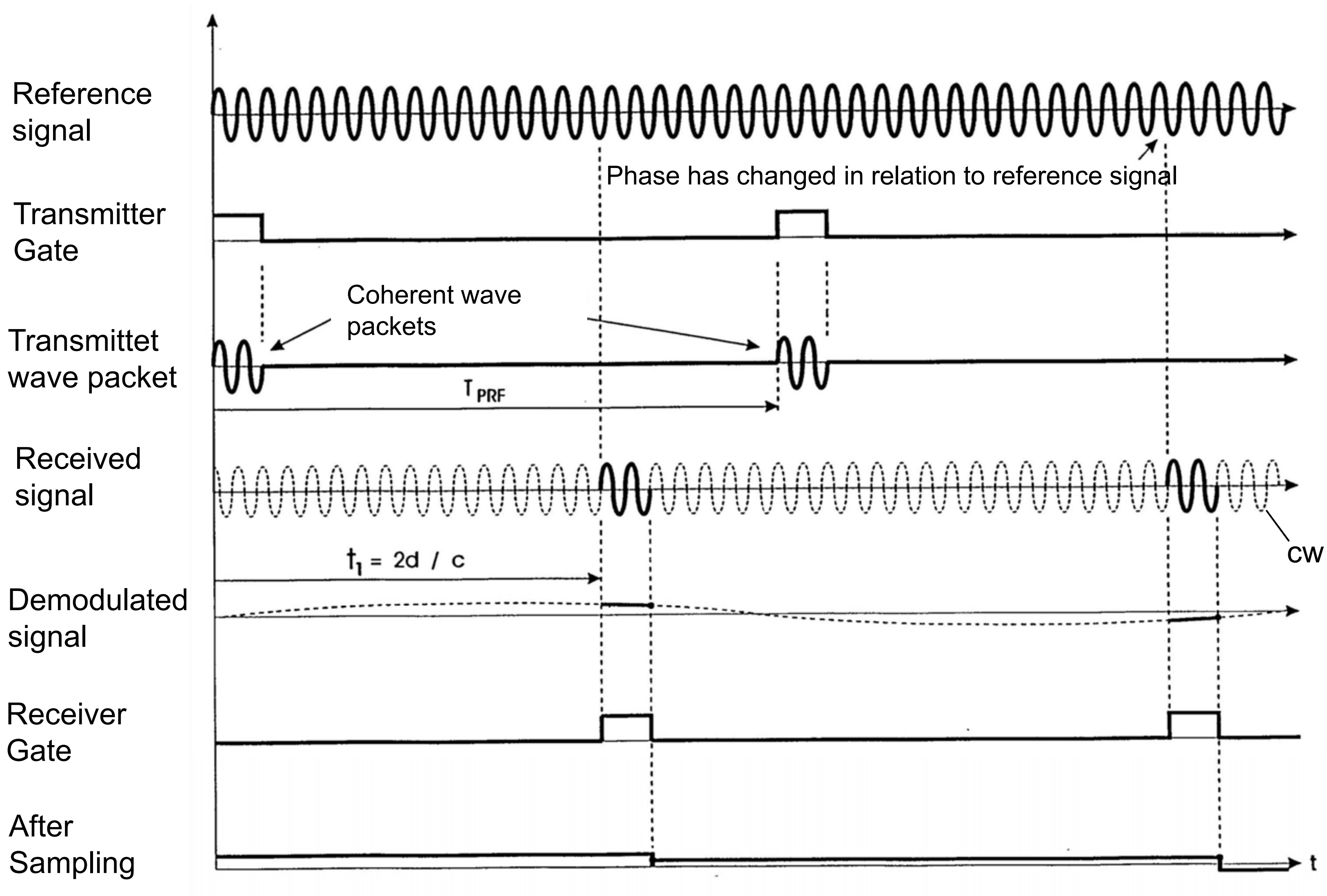
Focus beam to volume of interest

Choose gate timing for depth-selectivity

Pulsed Doppler



Time Domain



Reference signal
Phase has changed in relation to reference signal
Transmitter Gate
Coherent wave packets
Transmittet wave packet
T PRF
Received signal
cw
t1 = 2d / c
Demodulated signal
Receiver Gate
After Sampling
t

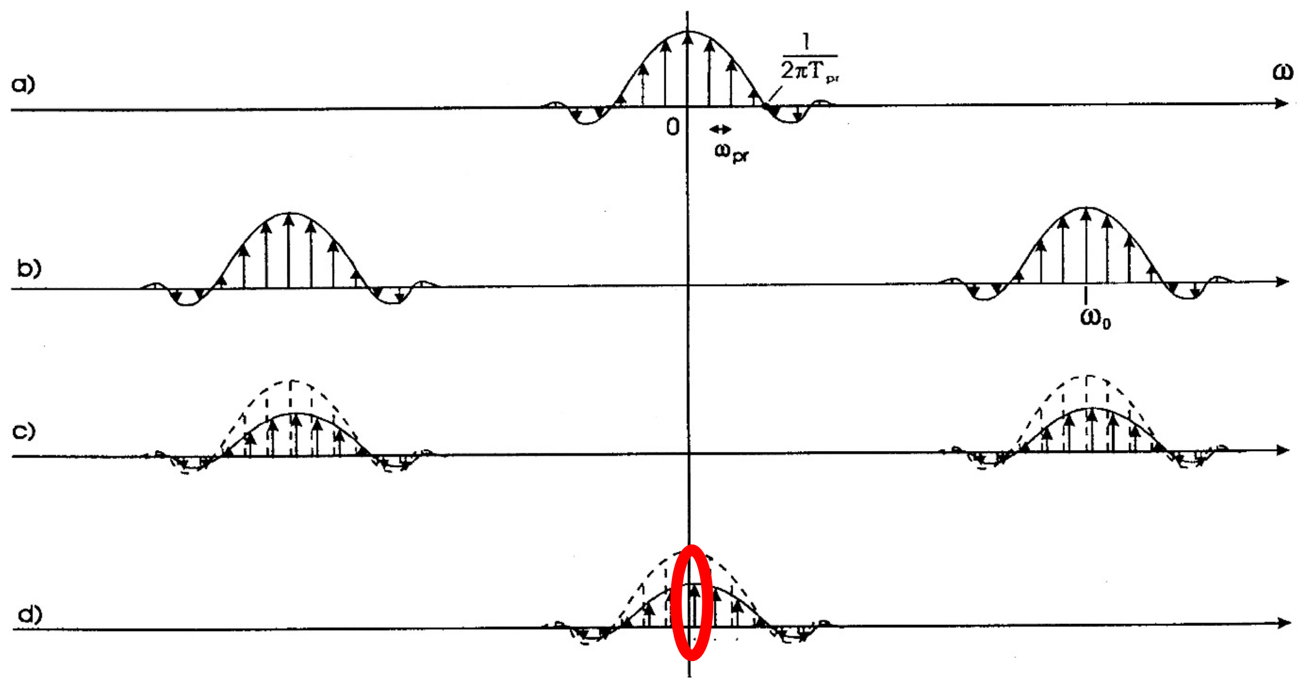
Frequency Domain

Transmitter Gate

Transmitted wave package

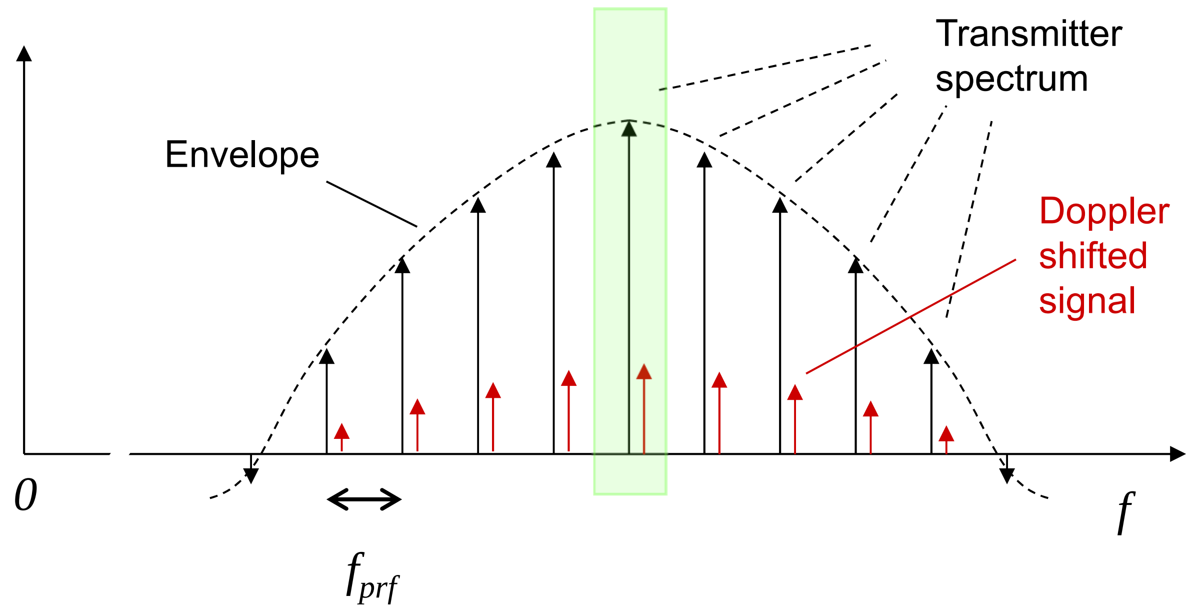
Received signal

Demodulated signal



Select main peak by low-pass filter

Nyquist Limit



Nyquist limit (sampling theorem): $-\frac{1}{2} f_{prf} < f_D < \frac{1}{2} f_{prf}$

Pulsed Doppler mode

- permits spatially selective velocity measurement
- at limited velocity range