BEN G 186B: Principles of Bioinstrumentation Design

Lecture 14

Blood Volume and Flow Measurement

References

Webster, Ch. 8 (Sec. 8.1-8.4).

BLOOD FLOW AND VOLUME

Webster Ch. 8

Direct and indirect measures of cardiac output (c.o.), the blood flow out of the aorta (volume over time, in l/s)

— Indirect measures : INDICATOR–DILUTION methods use an indicator, such as oxygen or a dye, to relate the amount of inhaled or injected indicator to a balance of its concentrations diluting in passing through the blood stream.

- Fick technique for cardiac output :

$$c.o. = \frac{dm/dt}{C_A - C_V} \quad \left(\frac{mol/s}{mol/l} = l/s \right)$$

where $\frac{dm}{dt}$: rate of oxygen consumption (mol/s)

→ measured with a spirometer (differential pressure transducer of respiratory flow of inhaled / exhaled air)

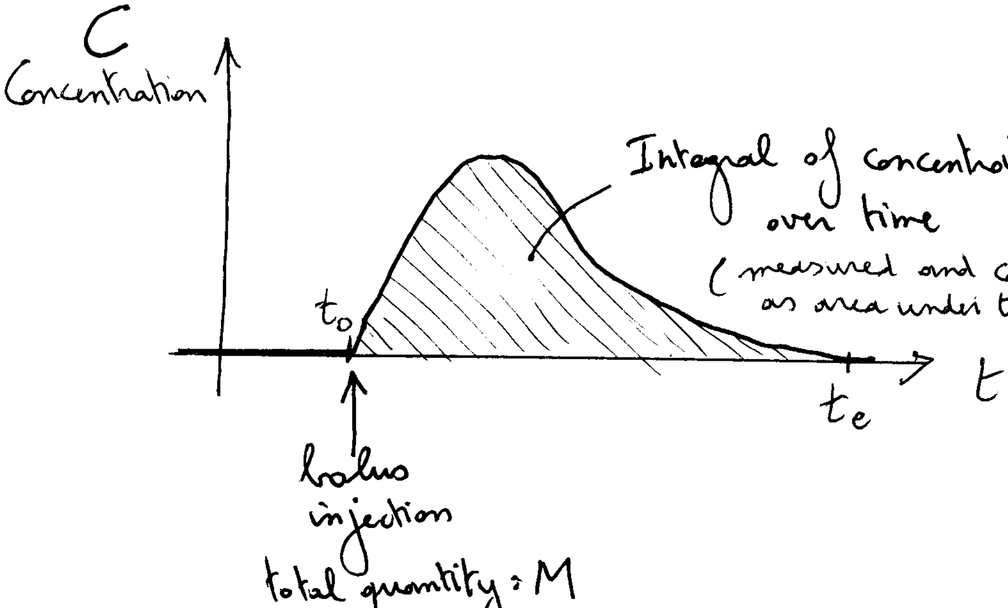
C_A, C_V : oxygen concentrations in arteries, veins (mol/l)

→ measured from blood samples taken from arteries and veins

→ typically invasive, but can be from the periphery (arms and legs)

- Rapid bolus injection :

  A fixed quantity (bolus) of the indicator is injected, all at once, into the blood stream, and the resulting concentration is measured over time :



$$C.O. = \frac{M}{\int_{t_0}^{t_e} C(t)\,dt} = \frac{\text{total quantity injected}}{\text{concentration integrated over time}} \quad \left[\frac{mol}{\frac{mol}{\ell} \cdot s} = \frac{\ell}{s} \right]$$

- Dye dilution : an optical dye, such as cardiogreen ($\lambda = 805$ nm) is used as the injected indicator, and concentration is measured by a blood oximeter (Ch. 10) (specific absorptivity at $\lambda = 805$ nm)
- Thermodilution : cold saline is injected as the indicator, and temperature is measured by a thermistor in the blood stream. Requires calibration or knowledge of specific heat and mass density of blood.

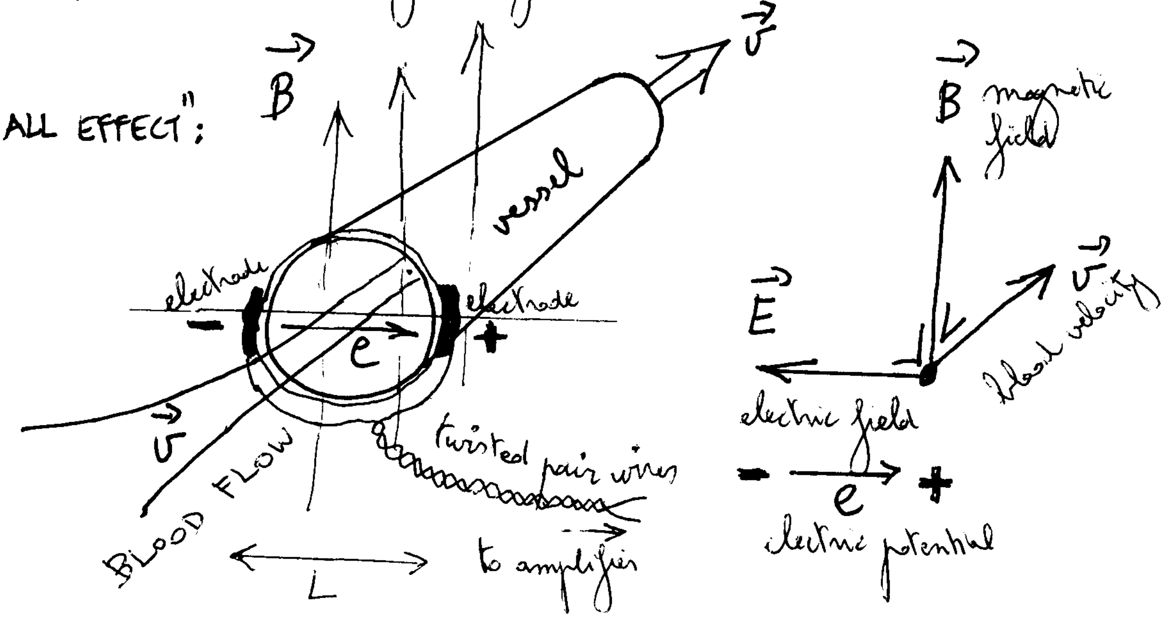
Indicator – dilution methods use simple instruments and can be minimally invasive, but only provide an average measure of blood flow and do not convey pulsative flow dynamics.

— Direct measures: invasive but faster providing pulsative flow (blood velocity, not cardiac output)

- Electromagnetic flowmeter : highly invasive!

  Measures electrical potential induced by electromagnetic force acting on conductive blood moving at a velocity $\vec{v}$ in a perpendicular magnetic field $\vec{B}$:

"HALL EFFECT":



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$ electromagnetic force on a charge q

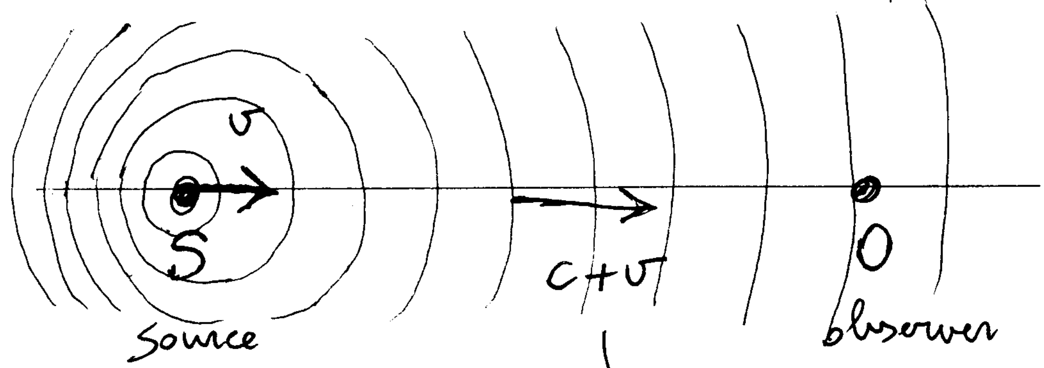
$$\Rightarrow \vec{E} = -\vec{v} \times \vec{B}$$ equilibrium electric field induced by magnetic field $\vec{B}$ in moving blood at velocity $\vec{v}$

$$\Rightarrow e = -\int_0^L \vec{E} \cdot d\vec{l} = \int_0^L (\vec{v} \times \vec{B}) \cdot d\vec{l}$$ electrostatic potential across the vessel is proportional to blood velocity

- Ultrasonic flowmeter: accurate, fast, and non-invasive! Measures velocity-sensitive Doppler frequency shift in the return from ultrasonic sound waves emitted at a given frequency.

Doppler effect:

- A single-tone source S moving at velocity v approaching an observer O sounds higher pitch to the observer than the source signal frequency f_s:



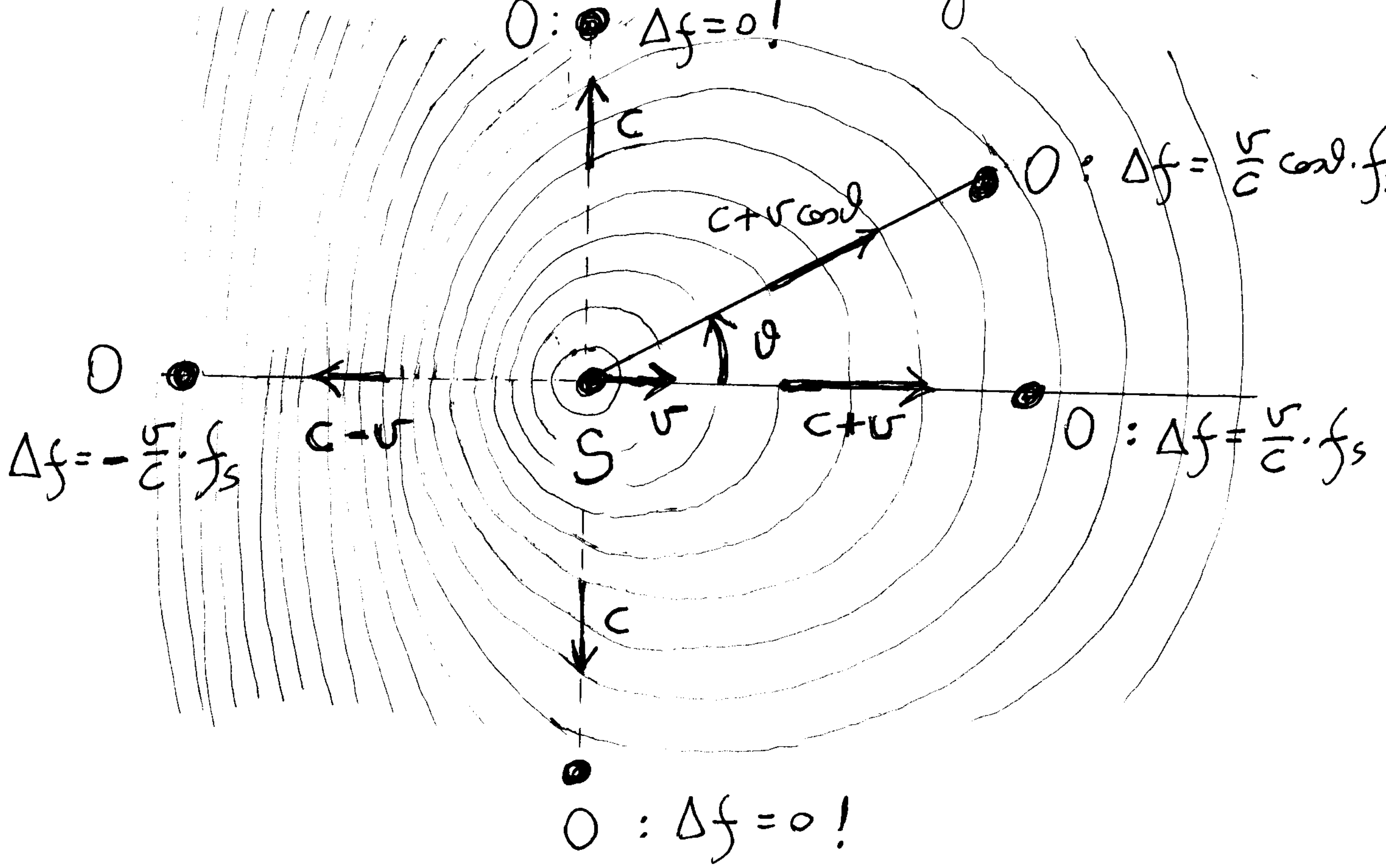
source moving towards observer with velocity v emitting sound of frequency f_s at speed of sound c

wavefront moves towards the observer FASTER than the speed of sound c by the source velocity v, making the observed frequency f_O proportionally FASTER.

$$f_O = \frac{c+v}{c} f_s$$

or $\Delta f = f_O - f_s = \frac{v}{c} \cdot f_s$ DOPPLER SHIFT

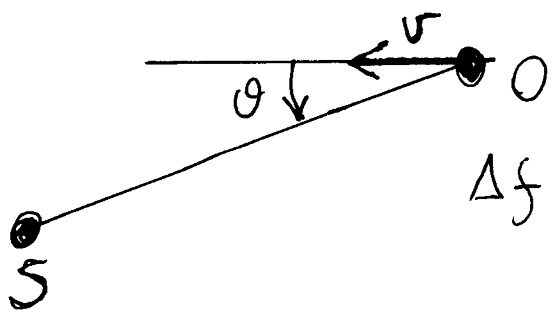
– The Doppler shift in the observed frequency depends on orientation relative to the motion of the source:



$$f_O = \frac{c + v\cos\vartheta}{c} \cdot f_s$$

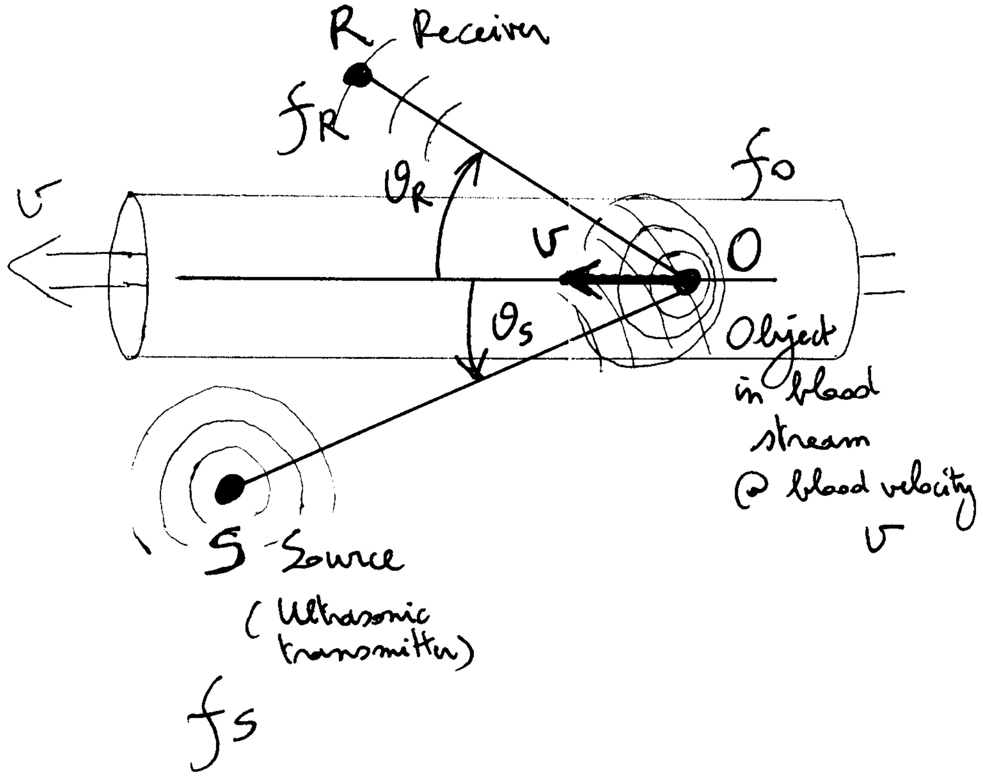
or $\Delta f = f_O - f_s = \frac{v}{c}\cos\vartheta \cdot f_s$ DOPPLER SHIFT

– It does not matter whether the source moves towards (away from) the observer, or the observer moves towards (away from) the source. What matters is the RELATIVE VELOCITY!



$\Delta f = \frac{v}{c}\cos\vartheta \cdot f_s$ (SAME)

— When an ultrasonic sound wave reaches a blood cell (or other reflecting object in the blood) O, itself becomes a "source" of sound propagation, moving with the blood velocity and emitting at the OBSERVED frequency $f_O = f_S + \frac{v}{c} \cos\vartheta_S f_S$ of the incoming wave:



$$f_R = f_O + \frac{v}{c} \cos\vartheta_R \, f_O \quad \text{received frequency}$$

$$f_O = f_S + \frac{v}{c} \cos\vartheta_S \, f_S$$

$$\Rightarrow f_R = f_S \cdot \left(1 + \frac{v}{c}\cos\vartheta_S\right) \cdot \left(1 + \frac{v}{c}\cos\vartheta_R\right)$$

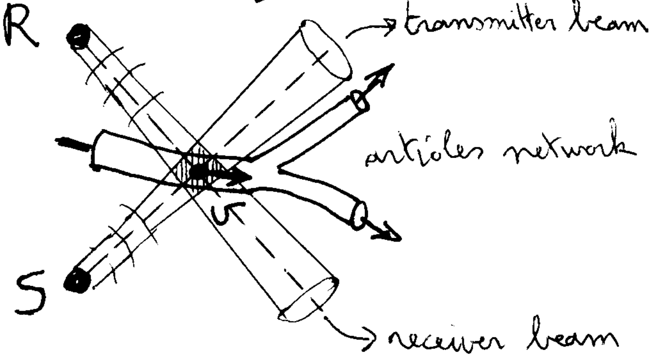
$\frac{v}{c} \ll 1$

$$\Rightarrow \Delta f = f_R - f_S \approx \frac{v}{c} \cdot (\cos\vartheta_S + \cos\vartheta_R) \cdot f_S$$

DOPPLER SHIFT between ultrasonic transmitter and receiver

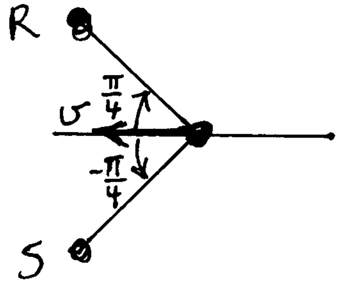
NOTES:

- Angles $\vartheta_S, \vartheta_R \neq 0$ allow to focus the transmitted and received ultrasonic beams onto a segment of a vessel for LOCAL blood velocity measurement:



e.g. $\vartheta_R = \frac{\pi}{4}$

$\vartheta_S = -\frac{\pi}{4}$

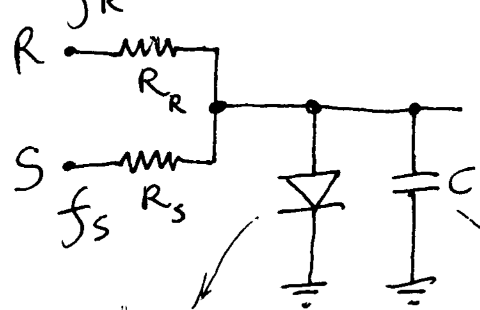


$$\Delta f \approx \frac{v}{c} \cdot \sqrt{2} f_S$$

or $$v \approx \frac{c}{\sqrt{2}} \cdot \frac{\Delta f}{f_S}$$

- Typically $v \ll c$! The small Doppler shift Δf is accurately measured by nonlinear mixing of the received and transmitted signals, and low-pass filtering

e.g.:



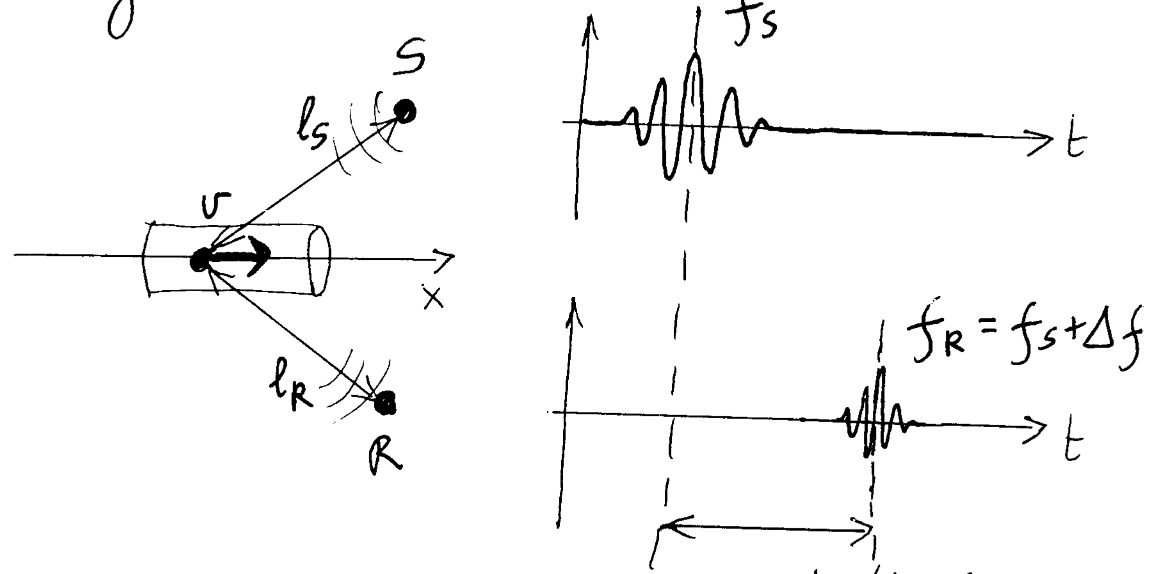
$$\pm \Delta f = \pm \frac{v}{c} \sqrt{2} f_S$$

nonlinear mixing in the diode produces intermodulation products $\pm f_R \pm f_S$

low-pass filtering removes the sum frequency components and returns the difference frequency components

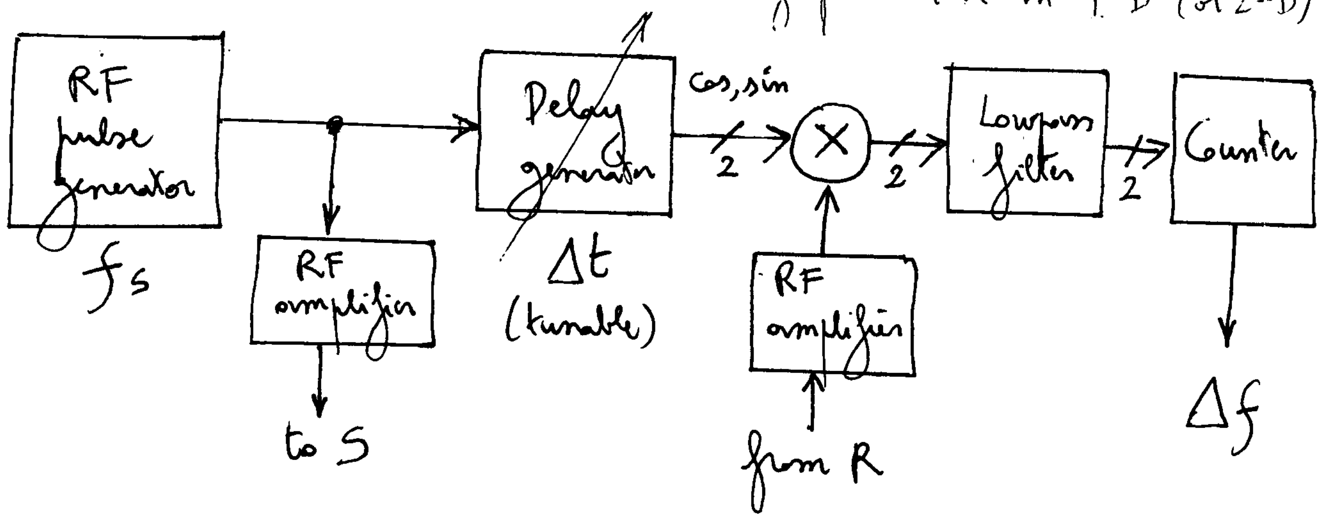
– Range-gated (or pulsed) Doppler:

1-D, 2-D or 3-D imaging of blood flow by ranging both the transmit and receive ultrasonic beams based on delay in wave propagation of the emitted and reflected pulse, e.g.:



$$\Delta t = \frac{1}{c} \cdot (l_S + l_R)$$

⟹ tuning Δt gating allows to scan along position x in 1-D (or 2-D)



Volume imaging requires several receivers R at varying delays, and lots of signal processing.

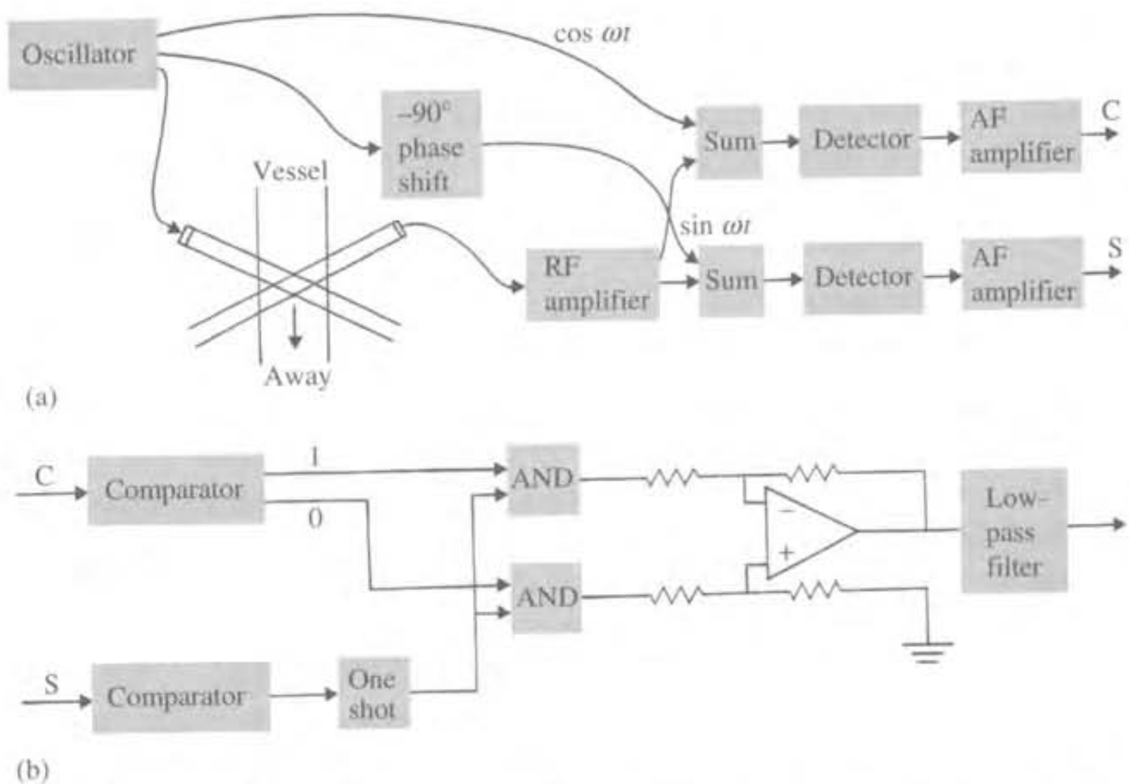


Figure 8.11 Directional Doppler block diagram (a) Quadrature-phase detector: Sine and cosine signals at the carrier frequency are summed with the RF output before detection. The output C from the cosine channel then leads (or lags) the output S from the sine channel if the flow is away from (or toward) the transducer. (b) Logic circuits route one-shot pulses through the top (or bottom) AND gate when the flow is away from (or toward) the transducer. The differential amplifier provides bidirectional output pulses that are then filtered.

Webster 4th Ed., Ch. 8, p. 358