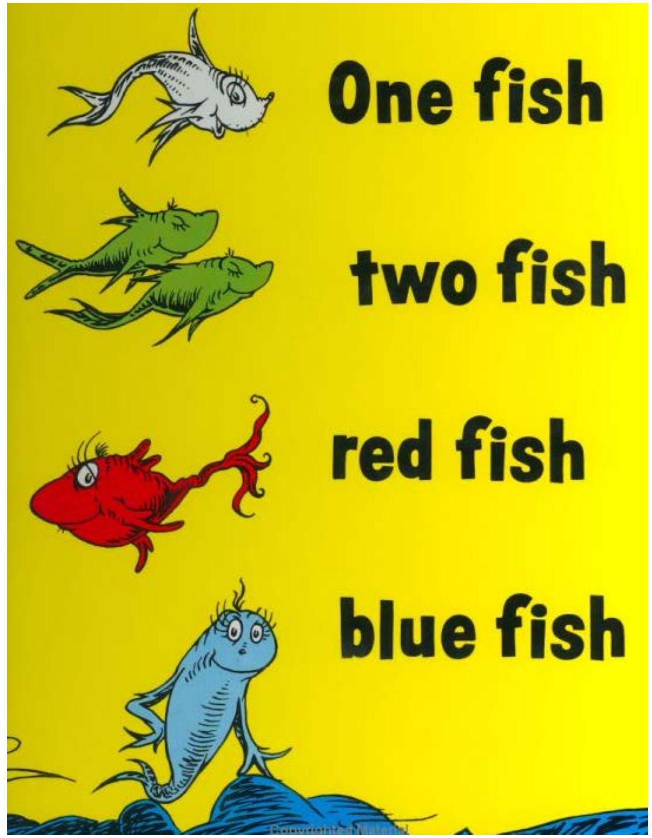
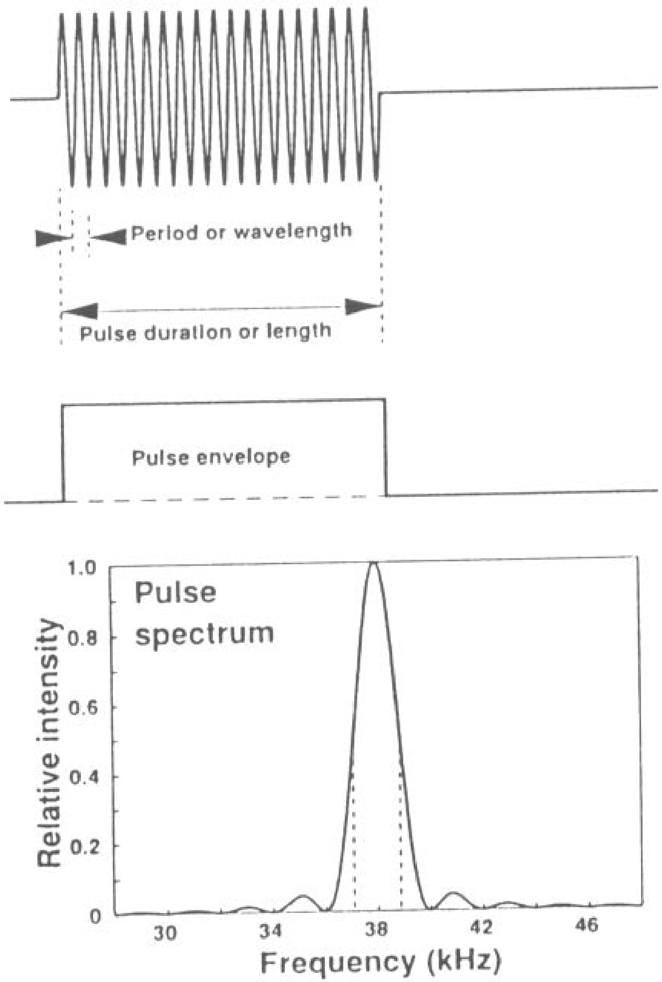
Acoustic Signal Processing



LO: Apply acoustic signal processing techniques to estimate abundances of pelagic fish species.

John K. Horne

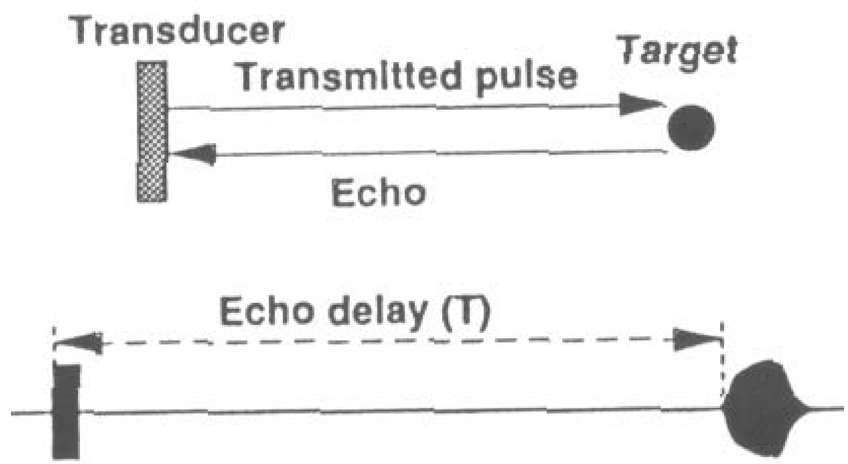
Echo Envelope



- time dependent amplitude of returned echo

- elapsed time T for an echo to return

$T = 2\ r/c \qquad r = cT/2$



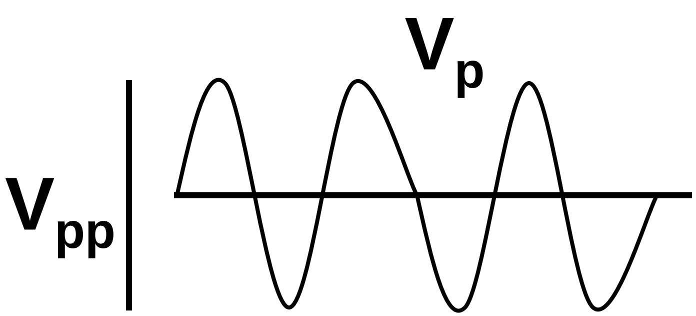
Measuring Voltage

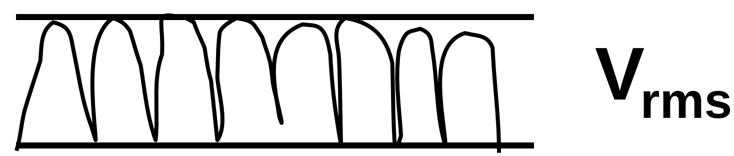
Volts peak V_p = peak value

Volts peak to peak $V_{pp} = 2\ V_p$

Volts root mean squared $V_{rms} = V_{pp}/2\sqrt{2}$

Volts detected = just positive

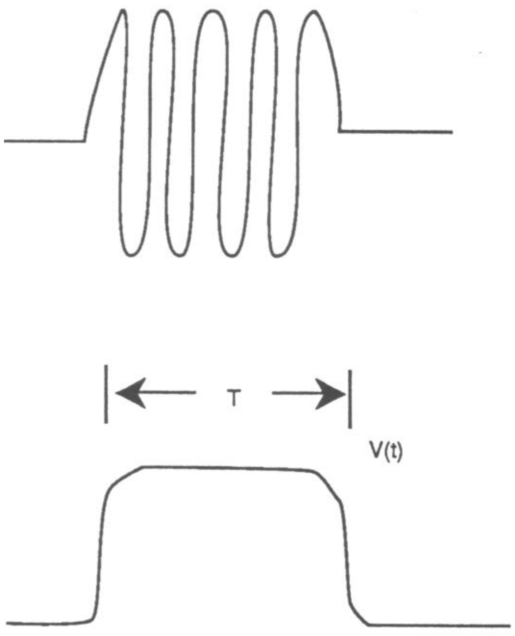




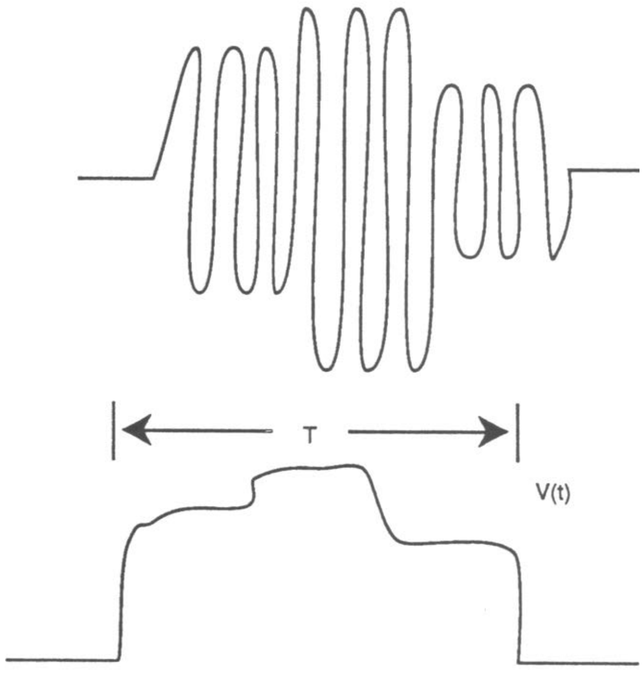
$20\log(V_{rms})$ = dBv || 1 V_{rms}

Echo Shapes

Single



Overlapping



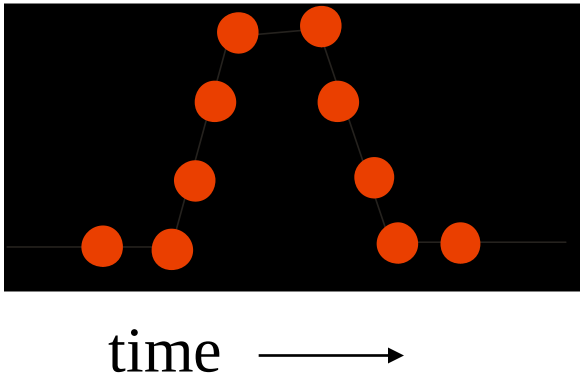
Digitizing Echoes

Traditional Approach:

- echosounder ‘samples’ received echo at a fixed rate (e.g. 25 kHz)

Example: if pulse width is 0.4 ms then how many samples?

25,000 samples/s x 0.0004 s = 10 samples



Digitizing Echoes II

Sampling Theory Approach:

- sample rate dependent on Nyquist sampling criterion of pulse length

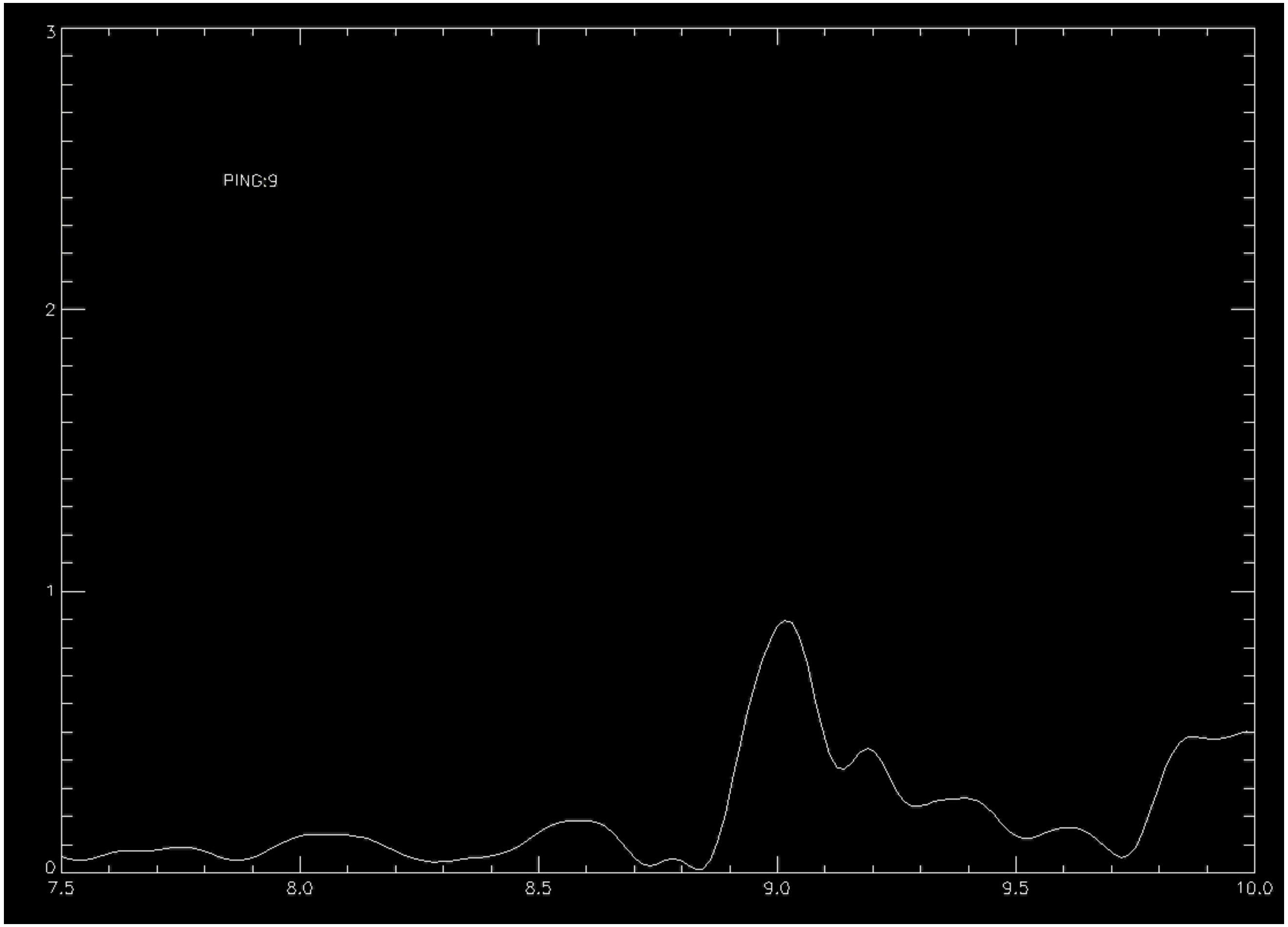
Nyquist-Shannon sampling theorem frequency:

"If a function $x(t)$ contains no frequencies higher than B Hz, it is completely determined by giving its ordinates at a series of points spaced $1/(2B)$ seconds apart."

=> You can recreate the signal by sampling it at ½ τ

EK and ES 60 samples at $\tau/4$

What is an Echo?



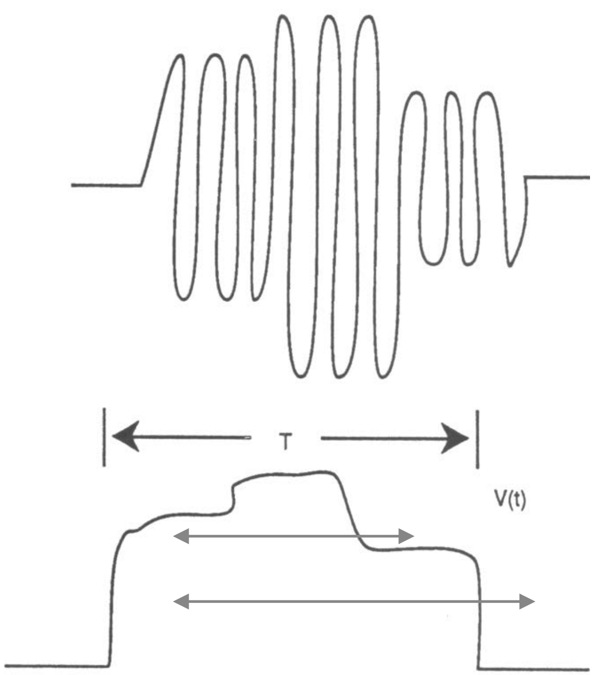
Single Target Criteria

- metrics of echo envelope: width, correlation, phase

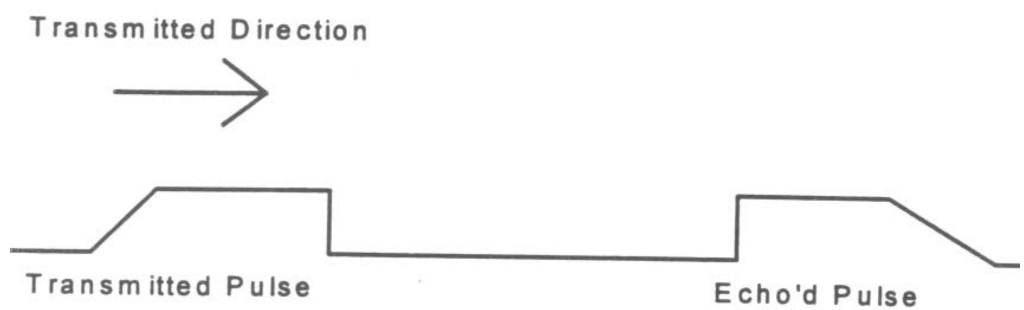
Echo envelope width: 1/2, 1/4, 1/8 maximum echo amplitude

Echo correlation: returned echo with incident pulse

Envelope width



Envelope correlation



$$\text{Correlation} = \frac{\Sigma(real\_echo(*ideal\_echo))}{\sqrt{(\Sigma(real\_echo^2)*\Sigma(ideal\_echo^2))}}$$

Single Target Criteria: Phase

Phase Metric Criteria

Reject as single echo if…

average phase deviation: average deviation in samples within single echo exceeds a preset limit

standard phase deviation: standard deviation of phase measurements athwart or along exceeds a preset limit

phase comparison: phase difference between adjacent elements in each pair exceeds a preset limit within 6 dB of peak amplitude

see Soule et al. 1996

Estimating Denstiy

Depending on density you have 2 choices:

Echo Counting – count individual echoes (if densities < 1 animal / sample volume)

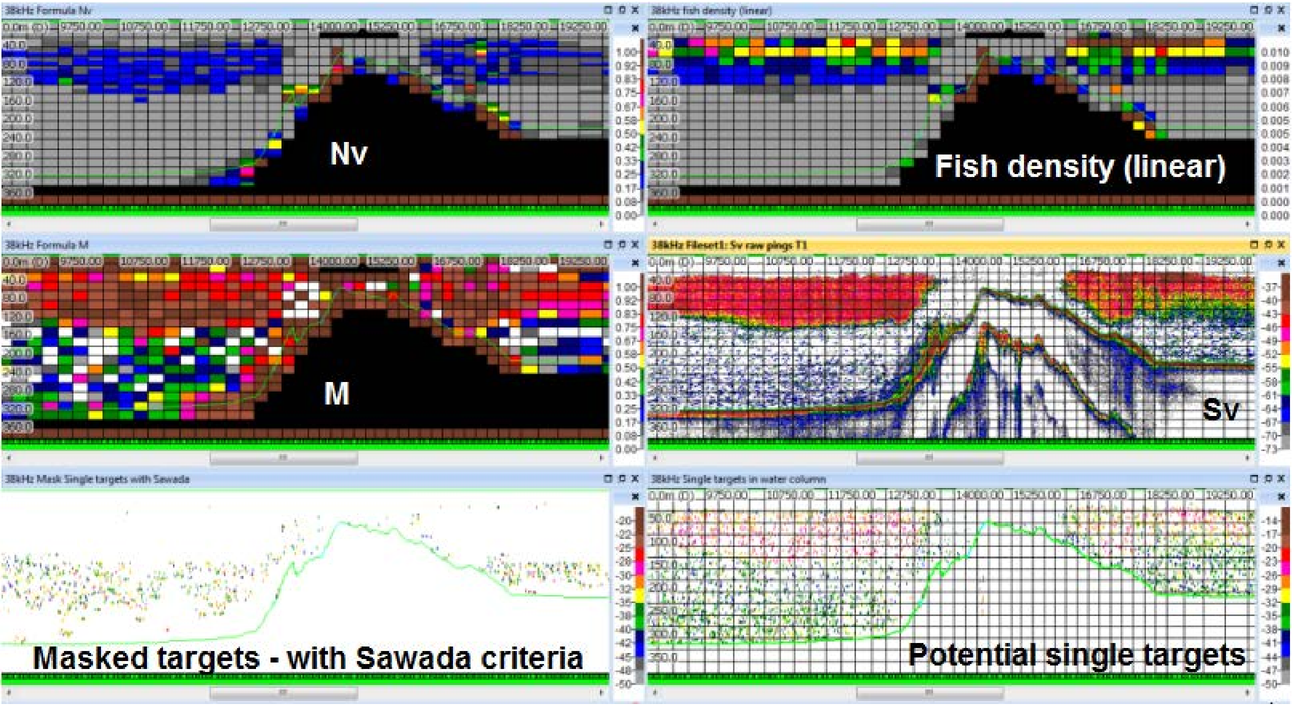
Echo Integration – sum total energy and divide by energy from representative individual

Critical Density

$\rho_c = 1/V_c$ critical density α 1/volume

Value should be less than $1/m^3$, ideal less than $0.2\ /m^3$

Sawada et al. (1993); Ona and Barange (1999)



M = ratio of multiple to single echoes

Nv = fish density

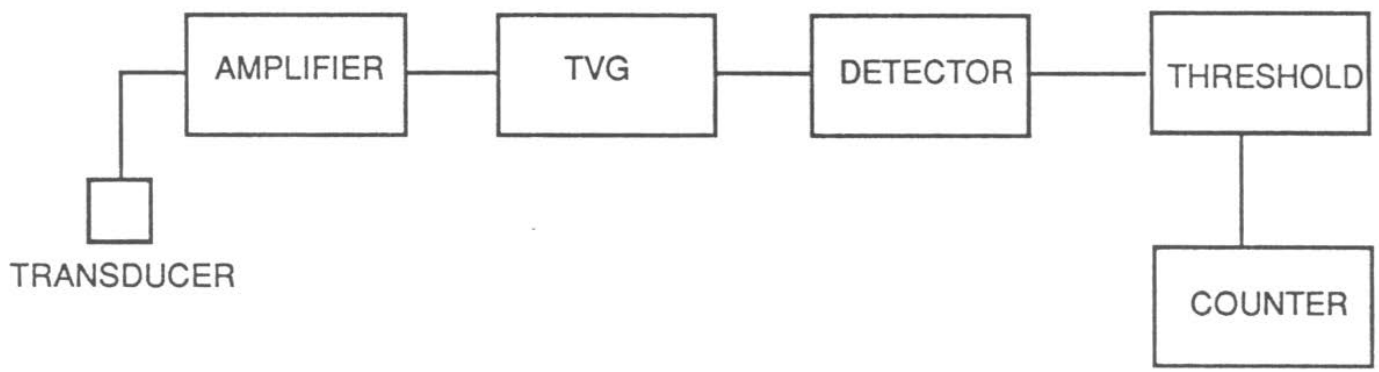
$Nv < 0.04$

$M < 0.7$

Target Counting

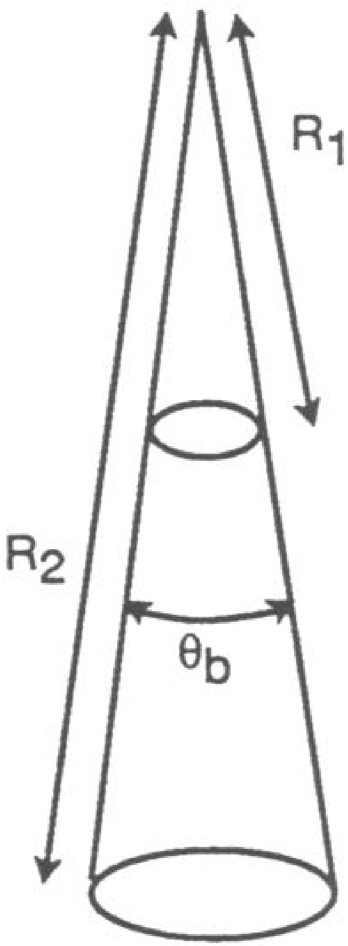
- first observed by Trout (1952)
- first attempted by Midttun and Saetersdal (1957)
- number of target echoes above threshold standardized to volume insonified
- threshold is used to screen noise and to reject targets smaller than those of interest (i.e. size matters)

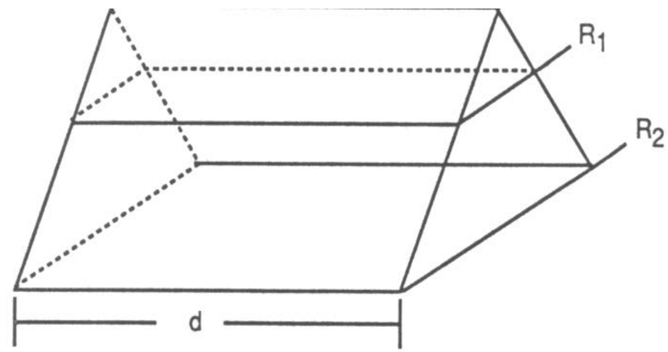
Echosounder Target Counting



$$Density = \frac{\sum counts}{(\# \, pings)(volume/ping)}$$

Target Counting Volume





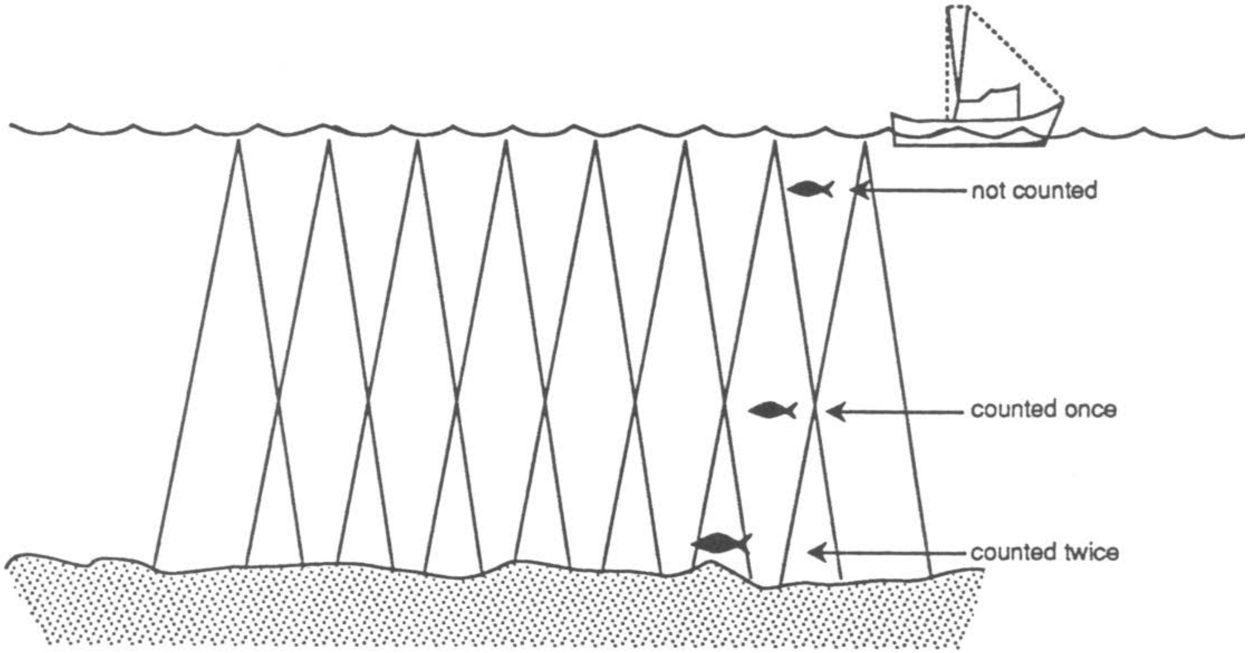
$$Volume = (area of\ end)*(d)$$

$$Volume = \frac{1}{3}\left(R_2^{\,3} - R_1^{\,3}\right)\ \sin^2\left(\frac{\theta_b}{2}\right)$$

$$Density = \frac{\#echoes}{volume\ insonified}$$

Target Counting Volume

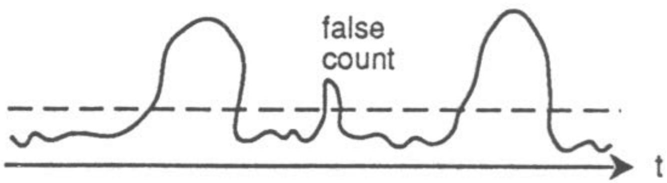
- dependent on beamwidth, pulse length, and target range (i.e. resolution and range)



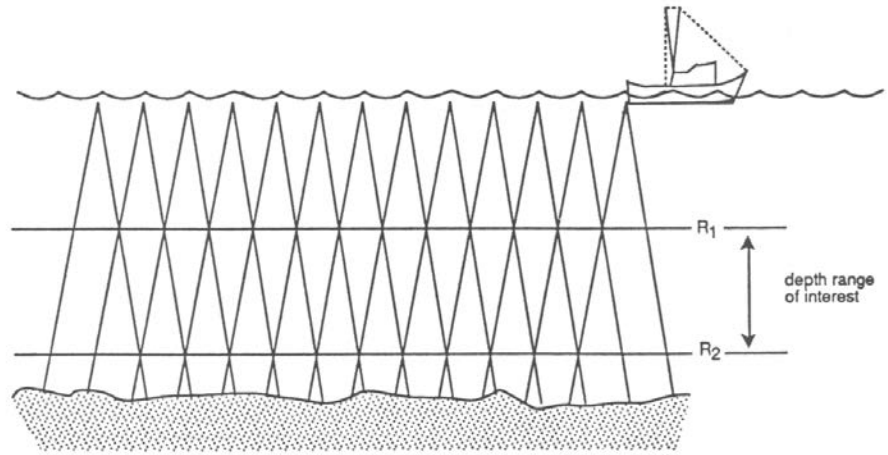
Pulse overlap: beamwidth, boat speed, and target or depth range

Target Counting Potential Problems

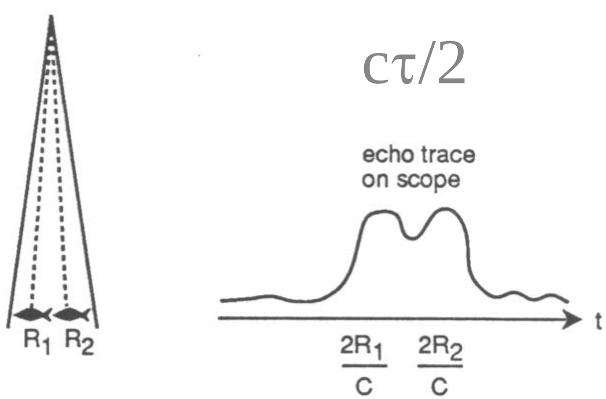
False Targets (threshold)



Pulse Overlap

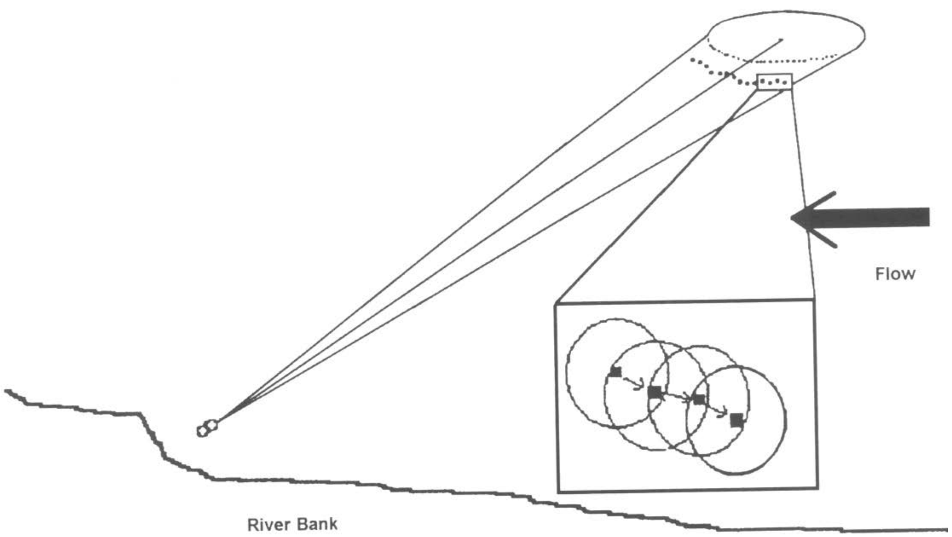


Target Overlap (multiple targets)



Target Tracking

- single or split beam data that contain range, time, angles of single targets
- set limits for the time, speed, and distance between echoes from a ‘tracked’ target
- establishes a sphere volume in each successive echo predicting position of next echo
- used to determine count, velocity, aspect, and mean target strength



Applications: rivers, hydropower intakes, fish bypass, tidal turbine monitoring

see Blackman 1986

Echo Integration

- first proposed by Dragesund and Olsen (1965)

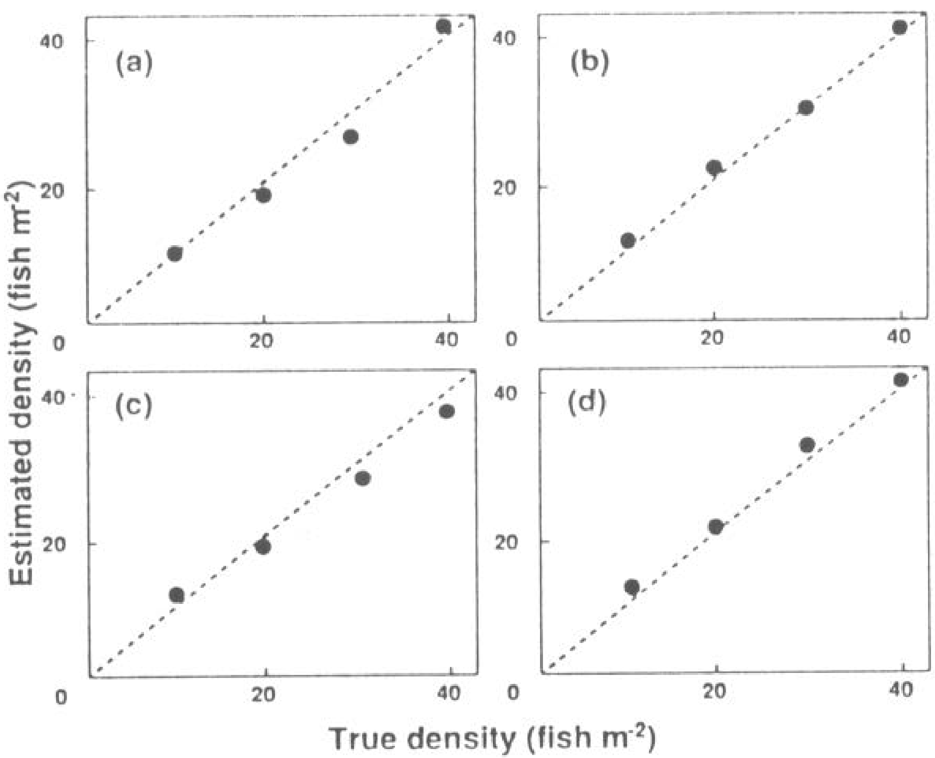
- average acoustic energy (i.e. intensity) in specified range bins

$$\bar{I} \propto N\overline{\sigma}_{bs}$$

where $\bar{I}$ is average intensity, N is number of fish, and $\overline{\sigma}_{bs}$ is the average backscatter from representative fish

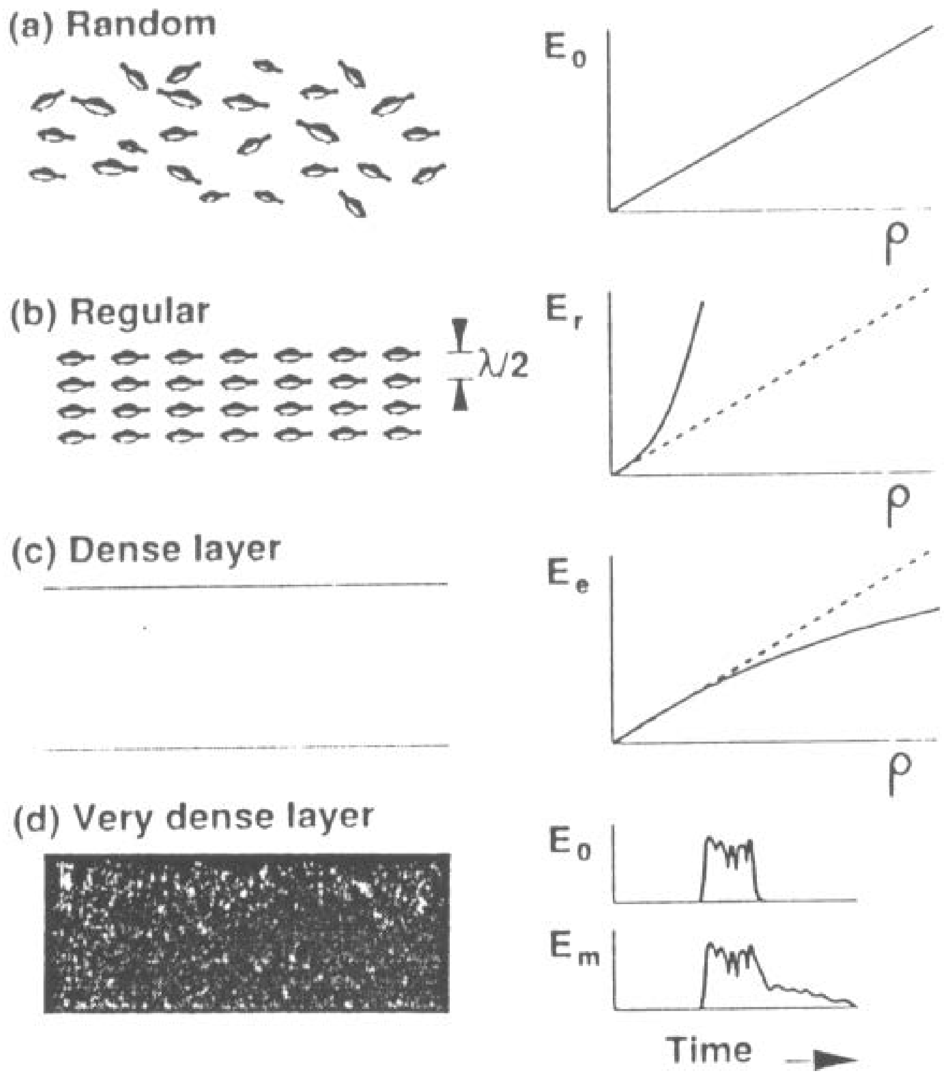
Linearity Principle

- assumes density is proportional to energy
- assumes acoustic extinction (i.e. shadowing) and multiple scattering are negligible
- definitive experimental evidence by Foote (1983)



- used caged, free-swimming herring and pollack
- frequency range 38 kHz - 120 kHz
- densities up to 57 fish m^{-3}

Deviations from Linearity



linear increase

exponential increase (n^2),

due to coherent scattering

decay due to shadowing

multiple scattering, shadowing

Echo Integration Terms: Linear

3 components:

acoustic size, number of scatterers, volume insonified

Definitions:

s_v = volume backscattering coefficient = $\sum \frac{\sigma_{bs}}{V} = \frac{n\sigma_{bs}}{V}$

s_a = area backscattering coefficient = $\int_{z1}^{z2} s_v \, dz$

s_A = nautical area backscattering coefficient = $4\pi(1852)^2 s_a$

Echo Integration Terms: Log

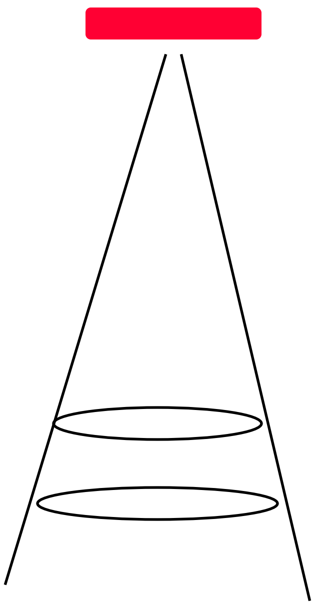
S_v = (mean) volume backscattering strength = $10\log_{10}(s_v)$

S_a = area backscattering strength = $10\log_{10}(s_a)$

S_A = nautical area backscattering strength = $10\log_{10}(s_A)$

cf. Table 1, MacLennan et al. 2002

Integration volume



assume beam is ideal with solid angle of ψ steradians

$$V = \frac{c\tau}{2}\psi r^2$$

for a circular xducer:

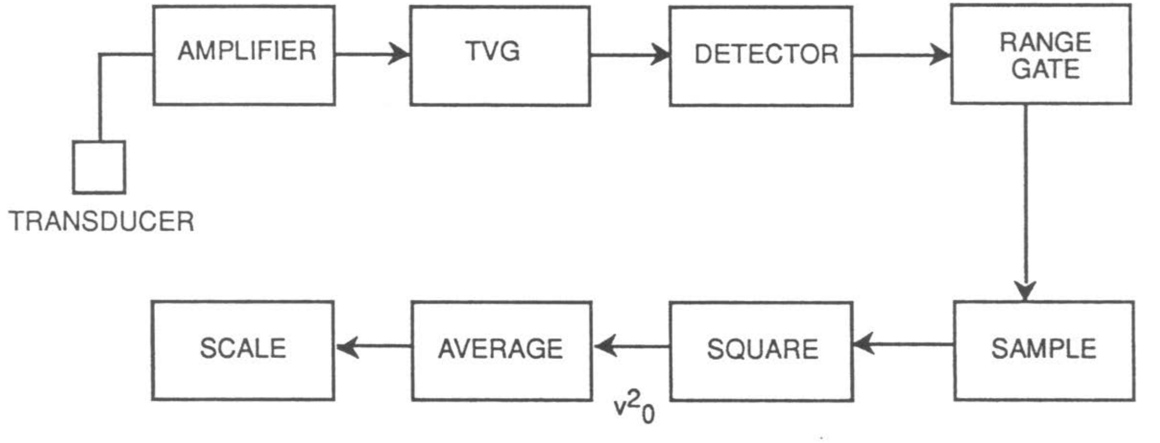
$$\psi = \left(\frac{4.853}{kD}\right)^2$$

k = wave number rad/m
= 2π/λ = 2πf/c
D = diameter of xducer

Echosounder Integration

$$E_i = \int_{t1}^{t2} \left| v(t) \right|^2 dt$$

where E_i is the echo integral and v(t) is the voltage at time *t* after the pulse



Echosounder Integration

Remember:

$$\left|P_{scat}\right|^2 = \left(p_0 r_0\right)^2 \left(\frac{1}{r_{target}}\right)^2 \left(\frac{1}{r_{source}}\right)^2 \sigma_{bs}$$

linear sonar equation for single targets

$EL = SL - TL_{target} - TL_{source} + TS$ log form for single targets

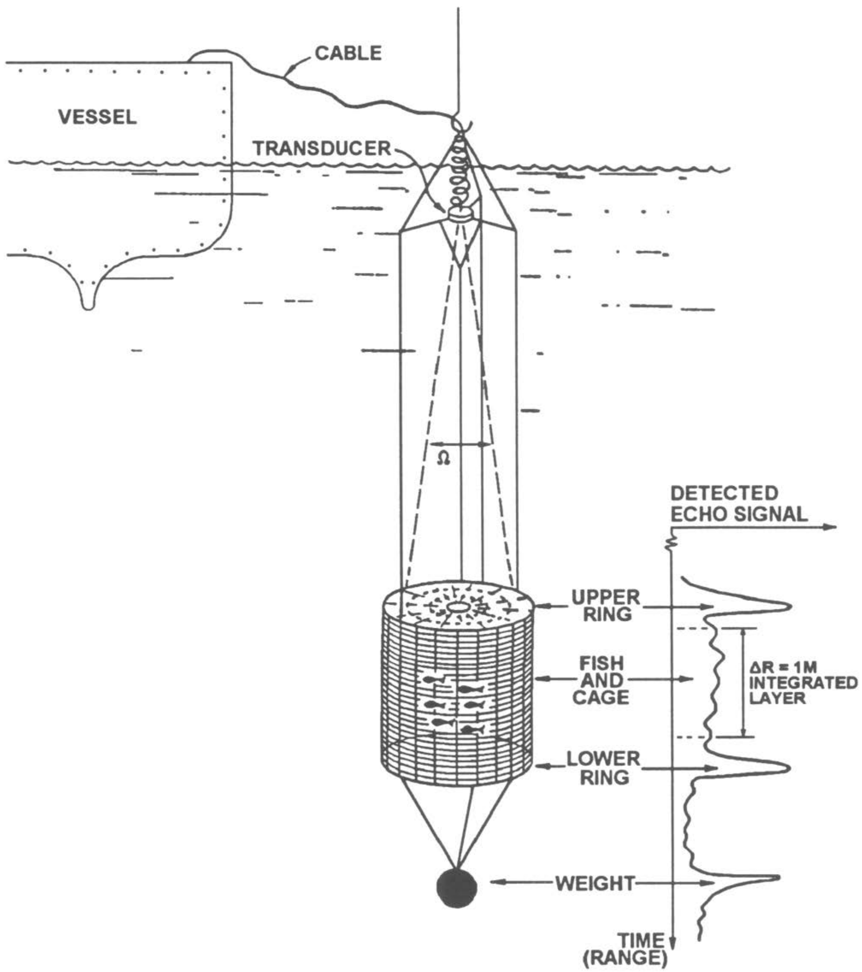
For groups, energy comes from volume

$RL = SL - 2TL + S_v + \mathbf{10\ log\ V}$ log form for aggregations

$S_v = N\sigma_{bs}$

Where does volume term come from?

Echo Integration Measurement



- group of fish in cage
- gate layer to time (i.e. range) within cage
- integrate echo returns from gated layer

Burczynski 1979

Echo Integration Limitations

dead zones: near-surface, near-bottom

non-linear effects: shadowing, multiple scattering

no acoustic species identification: rely on other methods

must know backscattering properties of target for numeric density estimates

Single Target Backscatter

Pressure of Backscattered Sound

$$p_{scat} = D_t D_r \frac{[p_o r_o]}{r^2} l_{bs}$$

where: D_t =directivity of transmit, D_r = directivity of receiver, p_o = reference pressure, r = range, l_{bs} = scattering length of target (units m)

$$l_{bs} = \frac{p_{scat} r^2}{D_t D_r [p_o r_o]}$$

Reduced backscatter quantities (non-dimensional):

Reduced Scattering Length (RSL) = l_{bs}/L_o

where L_o is a reference length, 1 m

Relationship Among Terms

Square of the absolute scattering length is backscattering cross section σ_{bs}

$$\sigma_{bs} = |l_{bs}|^2 \qquad \text{(units m}^2\text{)}$$

Log transform of σ_{bs} is Target Strength TS

$$TS = 10\log(\sigma_{bs}) \qquad \sigma_{bs} = 10^{(TS/10)}$$

Reduced Target Strength

$$TS = 10\log\left(\sigma_{bs}/L_o^2\right) = 20\log\left(|l_{bs}|/L_o\right)$$

where L_o is a reference length, 1 m

The 4π Factor

Principles and Applications of Underwater Sound (NRDC 1946)

define target area (σ) as:

$\sigma = \pi a^2$ where a = radius of a sphere acoustic cross section

Isotropic scattering by a single particle

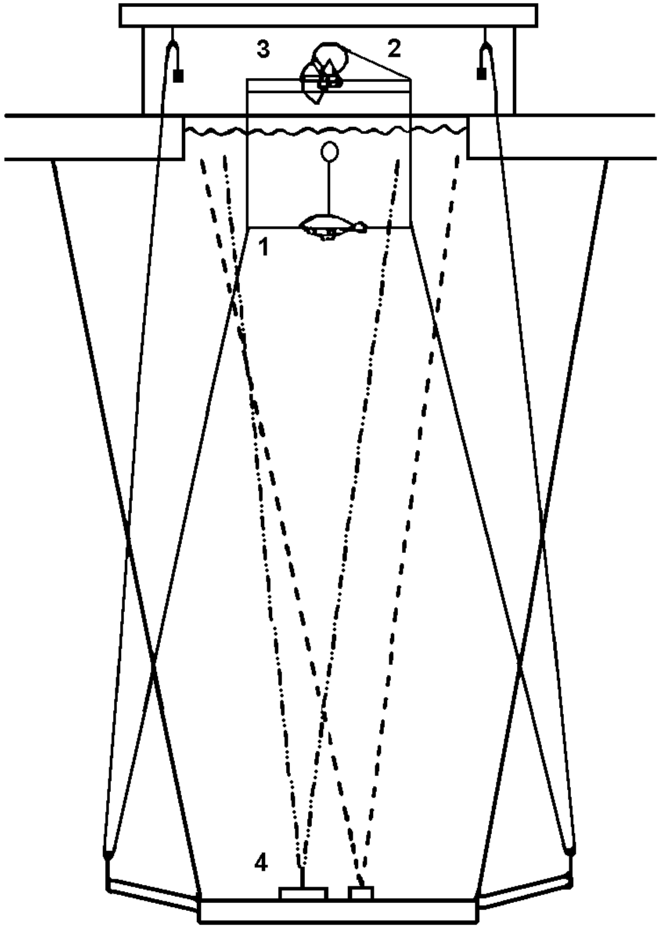
$I_s = I_i \, \sigma / 4\pi r^2$ where I_s = scattered intensity, I_i = incident intensity

and $TS = 10\log(\sigma/4\pi)$

But for backscatter (i.e. non-isotropic):

$TS = 10\log(\sigma_{bs})$ backscattering cross section

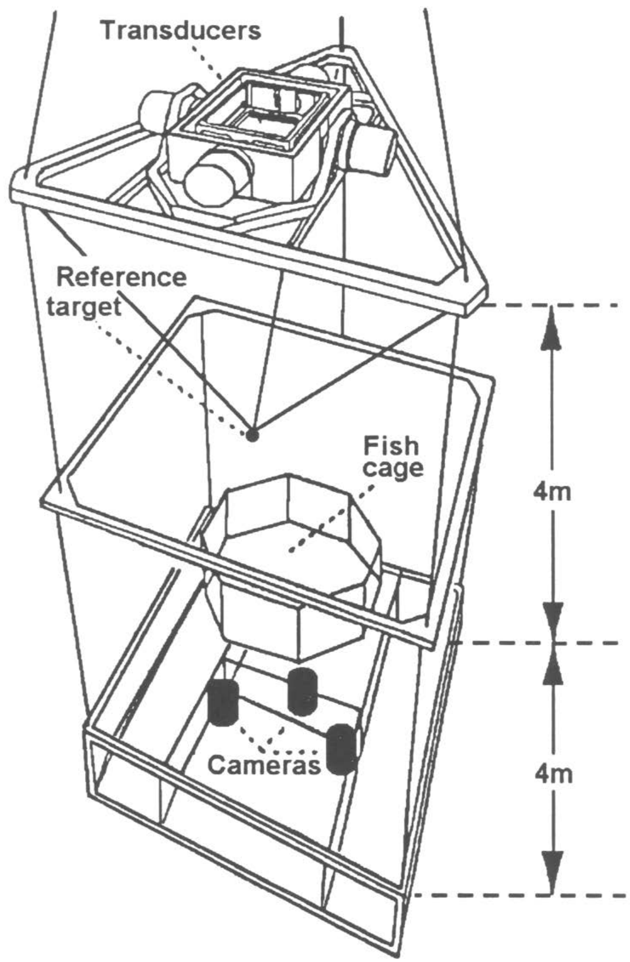
Target Strength Measurement



- individual tethered fish
- frequency-dependent measurements at known tilt angles
- *but* dead fish

Nakken and Olsen 1977

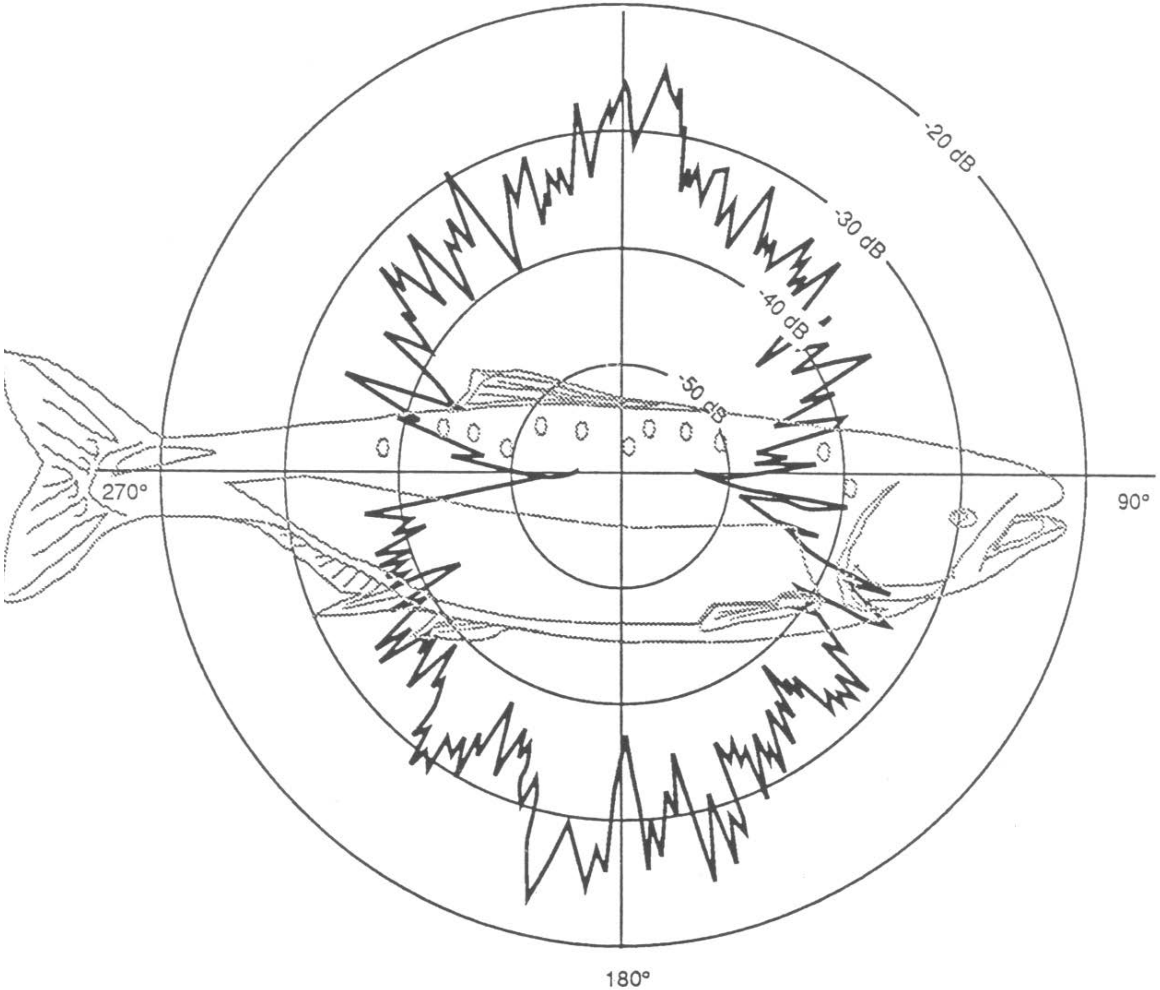
Target Strength Measurement



- measurements of fish in a cage
- use optics to verify tilt angles
- use a reference target to ensure consistent system performance

Edwards and Armstrong 1984

Why is aspect important?



Fish are directional scatterers

Acker 1977

Target Strength and Fish Length

- relationship exists between organism size, measured by length or mass, and amount of scattered sound

Assumptions:

- sampled targets are within the size range used to determine statistical relationship between organism and amplitude of echo
- statistical relationship between organism and echo amplitude is independent of frequency (with the exception of Love)
- statistical relationship is independent of behavior or can be averaged across behaviors (with the exception of Middtun)

Target Strength and Fish Length

Method:

- empirically measure target strengths of individual, known-sized organisms: *in situ* and using nets

- regression relation between target strength and fish length (exponential or log-linear)

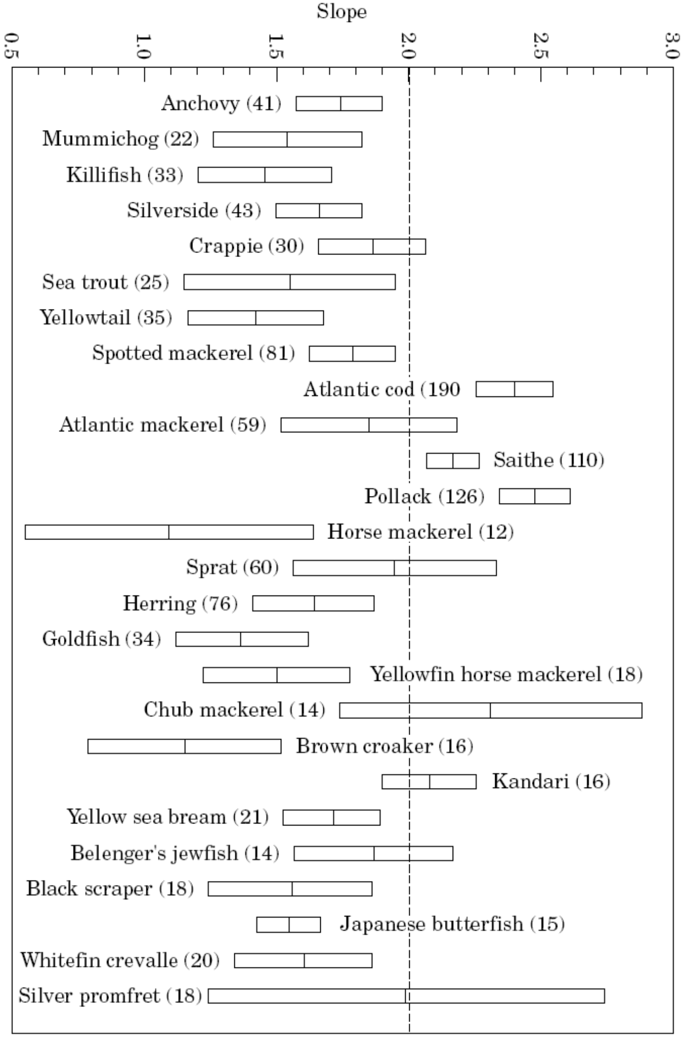
$$TS = a \log(L_{cm}) + b$$

Foote (1987) if $TS \propto L^2$ $TS = 20 \log(L_{cm}) + b$

where TS is target strength (dB), L is total length (cm)

Target Strength and Fish Length

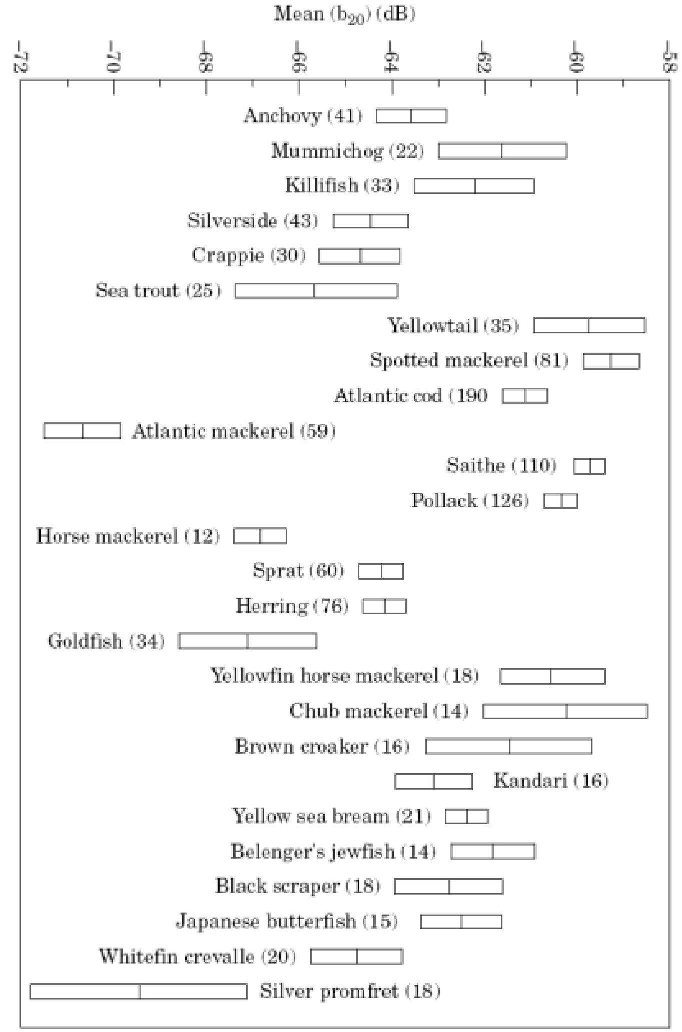
a values



If TS α L^2 then predict a = 2

*slopes and intercepts not transferable across species

b_{20} values



McClatchie *et al*. 1996