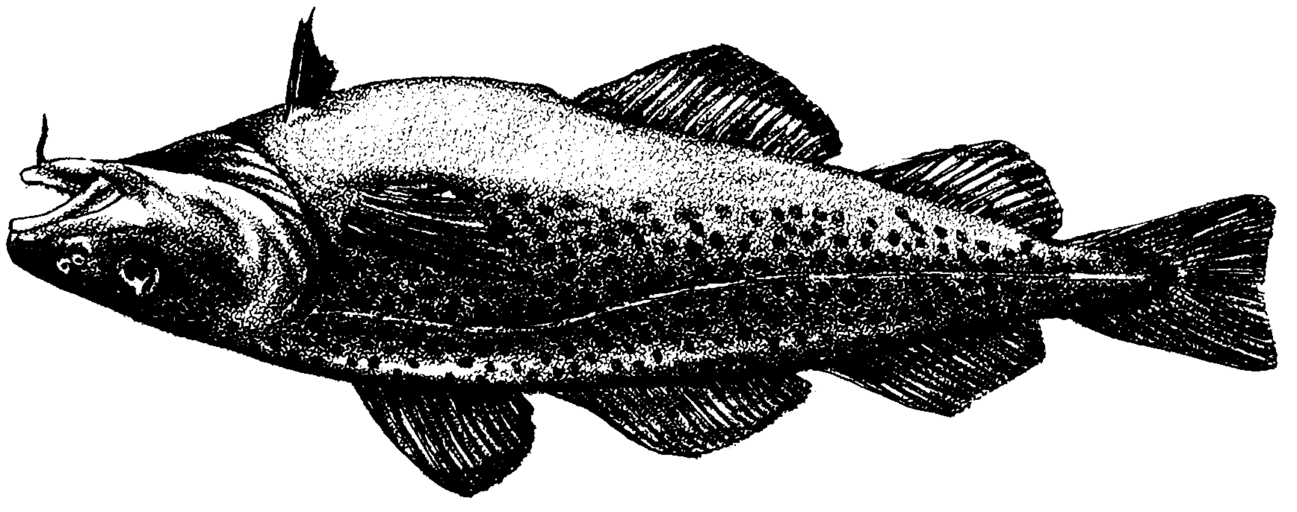
Forward & Inverse Approaches



LO: Distinguish between and apply forward and inverse approaches to estimate fish or zooplankton abundance using multifrequency acoustic data and backscatter models.

John K. Horne

Forward & Inverse Approaches

designed to use backscatter models

Forward: net catches + models ➡ predict backscatter
(then compare to empirical acoustic measures)

Inverse: empirical measures + models ➡ predict abundances
(then compare to net catches)

The Forward Problem

$$\sigma_{bs} \times \ n / \text{volume} \quad = \ s_v$$

backscatter x density of organisms = total backscatter

- used as a predictive equation
- in zooplankton acoustics to check if inverse results are reasonable (assumes net catches are representative)
- rarely matches measurements but some close results: Flagg and Smith 1989, Wiebe et al. 1997; Ressler 2002; Fielding et al. 2004

Forward Problem: Mechanics

Assume use of multiple codend net or multiple samples

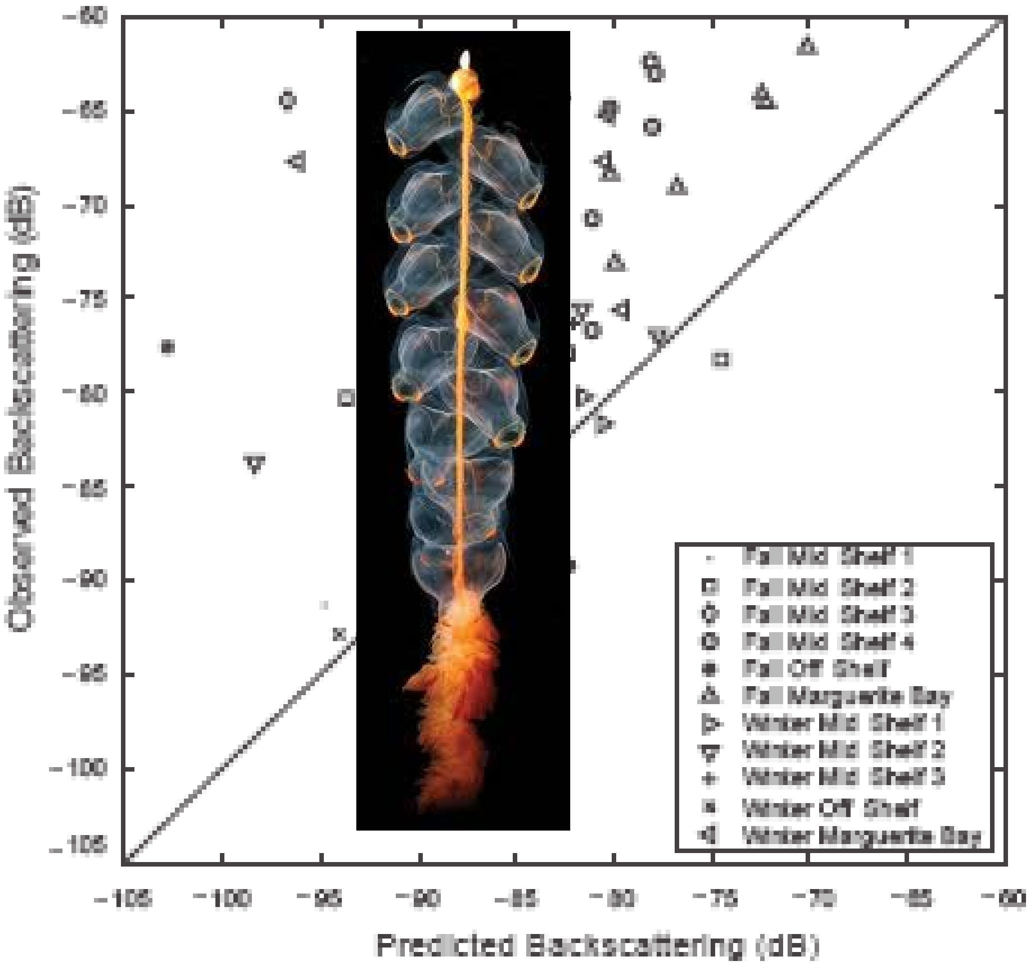
$$S_{vk} = 10\log_{10}\left[\frac{1}{V_k}\sum\sum\langle\sigma_{bs}\rangle_{ij}\right]$$

vk = volume in the kth net, of the i^{th} individual in the j^{th} taxon

use direct sampling to obtain representative samples (e.g. pumps, optics, MOCNESS, MultiNet), choose a size-dependent backscatter model for each type, and incoherently (i.e. linear) add the backscatter

Forward Problem: Example

Observed



Predicted

$n=58$, $r^2=0.43$, $p<1e^{-7}$

obs > pred

Average deviation from 1:1 = 6.8 dB

euphausiids, copepods, pteropods, siphonopohores

Why the mismatch?

Lawson et al. 2004

The ‘Simple’ Inverse Approach

$$n \quad = \quad s_v \quad \div \quad \langle \sigma_{bs} \rangle$$

number of organisms = total backscatter ÷ representative acoustic size

- empirical measurement
- fish and zooplankton acoustics (more in zoop)
- rarely compared to independent data

Inverse Algorithm Concept

If you have:

- backscatter measurements at multiple frequencies
- frequency-dependent backscatter
- size-dependent backscatter models

Then you can:

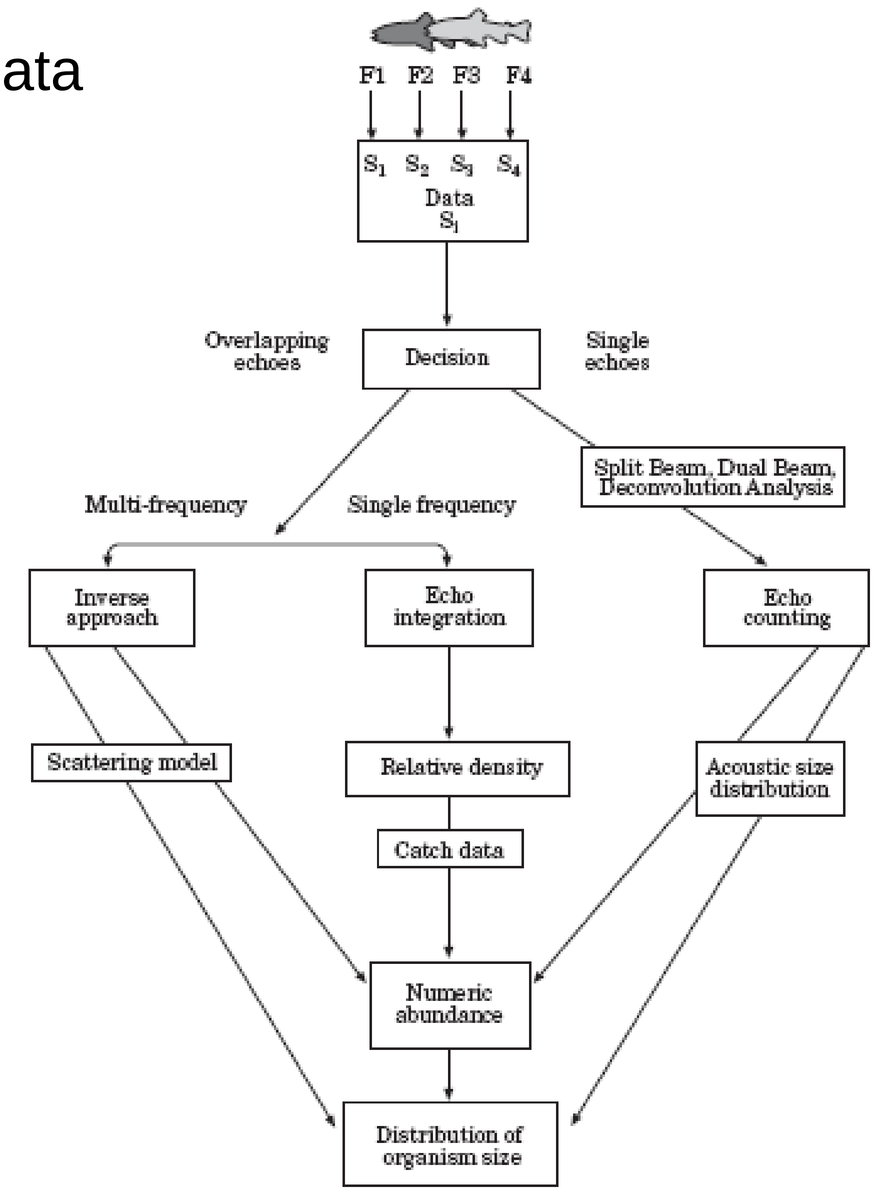
- partition total backscatter by representative acoustic sizes to get size-dependent abundance estimates

Acoustic Data Processing Options

Multifrequency Data

Inverse Approach

Backscatter Model



Horne & Jech 1998

Inverse Approach Evolution

Step Two:

Differences in echo levels at 2 frequencies could be used to estimate biomass within a size range (McNaught 1969)

Step Three:

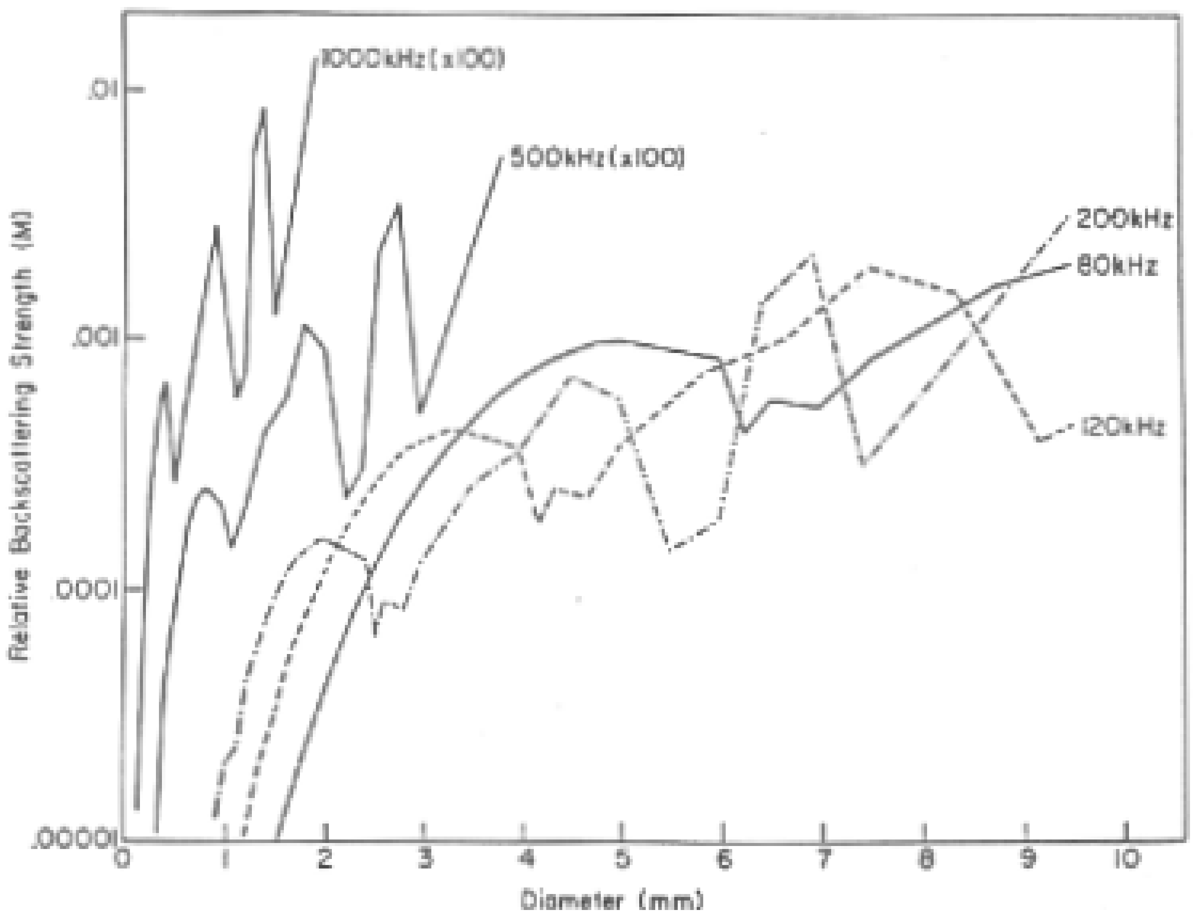
Holliday (1977) published a formal mathematical method for estimation of size-based abundance estimates

Step Four:

Improved solutions for multiple-frequencies applied to small, swimbladdered fish (Johnson 1977)

Depends on Characteristic Backscatter

maximal backscatter at different frequencies depending on diameter



F(kHz)

80

120

200

500

1000

Diameter (mm)

McNaught 1969

Inverse Approach Assumptions

1. Organisms are randomly distributed within insonified region
2. Large number of scatterers in region
3. If fish, then no multiple backscatter

Greenlaw & Johnson 1983

Additional Assumptions

1. a validated backscatter model exists
2. multiple scattering effects are negligible
3. shadowing effects are negligible
4. dependence of reflectivity on other parameters is known (e.g. temperature, salinity)
5. measurements are stationary and power can be estimated
6. frequencies must span transition from Rayleigh to geometric scattering for all organisms

Holliday & Pieper 1983

Limitations of Inverse Approach?

MUST have a validated backscatter model

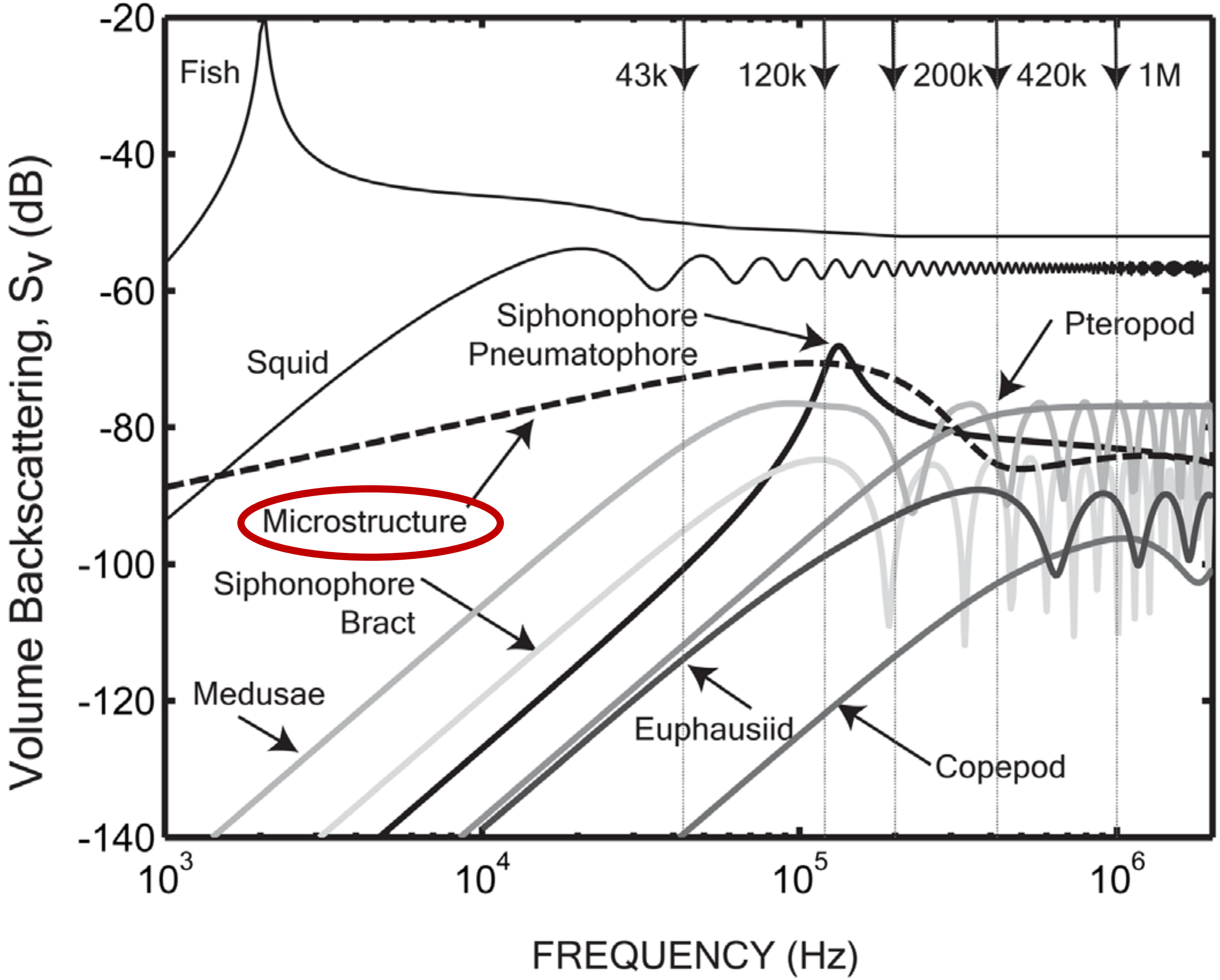
"Scattering model development constitutes the most serious technical impediment to application of multifrequency acoustical estimation at the present time."

"No model has been validated for any organism with sufficient precision to allow significant confidence in acoustically estimated abundances."

"A good deal of work in the areas of model development and model validation is called for before the estimation of scattering coefficients can be considered accurate."

Greenlaw & Johnson 1983

Current Backscatter Model Perception



frequency

Lavery et al. 2007

Taxon Scattering Models & Parameters

Taxon (*Scattering model*)	Length-to-width ratio (β_D)	Orientation (Mean, STD)	Density contrast (g)	Sound speed contrast (h)
Euphausiids and Decapod Shrimp (*DWBA uniformly-bent cylinder*)	10.5[a]	N(20,20)[b, R1]	$g=5.485L/10^4+1.002,\quad L>25$ $g=1.016,\quad L<25$[R2]	$h=5.942L/10^4+1.004,\quad L>25$ $h=1.019,\quad L<25$[R2]
Larval Crustaceans[c] (*DWBA uniformly-bent cylinder*)	2.55[d]	N(0,30)	1.058[R3]	1.058[R3]
Amphipods[c, R4] (*DWBA uniformly-bent cylinder*)	3.00[d]	N(0,30)	1.058[R3]	1.058[R3]
Ostracods[c] (*DWBA uniformly-bent cylinder*)	2.55[d]	N(0,30)	1.03[R5]	1.03[R5]
Chaetognaths and Polychaetes[c] (*DWBA uniformly-bent cylinder*)	17.15[d]	N(0,30)	1.03[R5]	1.03[R5]
Gymosome Pteropods (*Clione*)[c] (*DWBA uniformly-bent cylinder*)	1.83[d]	N(0,30)	1.03[R5]	1.03[R5]
Salps[c, R6,R7] (*DWBA uniformly-bent cylinder*)	4.0[d]	N(0,30)	1.004[R6]	1.004[R6]
Copepods (*DWBA prolate spheroid*[R10])	2.55[d]	N(90,30)[e,R8]	1.02[R5]	1.058[R9]
Medusae[R11] (*DWBA two prolate spheroidal surfaces*[R5])	NA	NA	1.02[f]	1.02[f]
Eggs (*High-pass fluid sphere*[g,R13])	NA	NA	0.979[R12]	1.017[R12]

Lavery et al. 2007

Inverse Linear Addition

At any frequency *i*

Total backscatter (s_{vi}) of a group is the sum of backscatter from individual (s_i) in length class *j* times the number of organisms (n) in length class *j* over N length classes

$$s_{v_i} = \sum_{j=1}^{N} \sigma_{ij} n_j$$

s_v is a linear function of σ_{bs}

Inverse Approach Algorithm

Measured backscatter at three frequencies (S_1, S_2, S_3) for three length classes:

$$s_1 = \sigma_{11} n_1 + \sigma_{12} n_2 + \sigma_{13} n_3$$

$$s_2 = \sigma_{21} n_1 + \sigma_{22} n_2 + \sigma_{23} n_3$$

$$s_3 = \sigma_{31} n_1 + \sigma_{32} n_2 + \sigma_{33} n_3$$

Solving equations for vector *n* provides abundance estimates in each length class

under, even, over determined problems

Inverse Approach Algorithm

Criterion for 'solving' N equations:

Minimize the sum of the squared deviations between calculated s_v and measured backscatter s_v for M frequencies

$$\frac{\partial}{\partial n_j}\left[\sum_{i=1}^{M}\left(\left\langle s_{v_i}\right\rangle - s_{v_i}\right)^2\right] = 0$$

NNLS Non-negative least-squares (Lawson and Hanson 1974)
constraint: no negative abundances in any length class j

Inverse Algorithm Alternatives

1. Least Squares
2. Regularization Methods: similar to least squares but smoothed result, multiple solutions possible
3. Backus-Gilbert Inversion: similar to regularization but parameter is bounded

Potential Measurement Error Sources

1. Random Error – assumes stationarity, minimize variance (70 pings for 1 dB of uncertainty $\approx$ 12%)
2. Bias Error – noise, signal to noise ratio (min. 12 dB will increase variance by 25%)
3. Validity Error – adequate sample numbers for model averages (defines resolution of the data)

Greenlaw & Johnson 1983

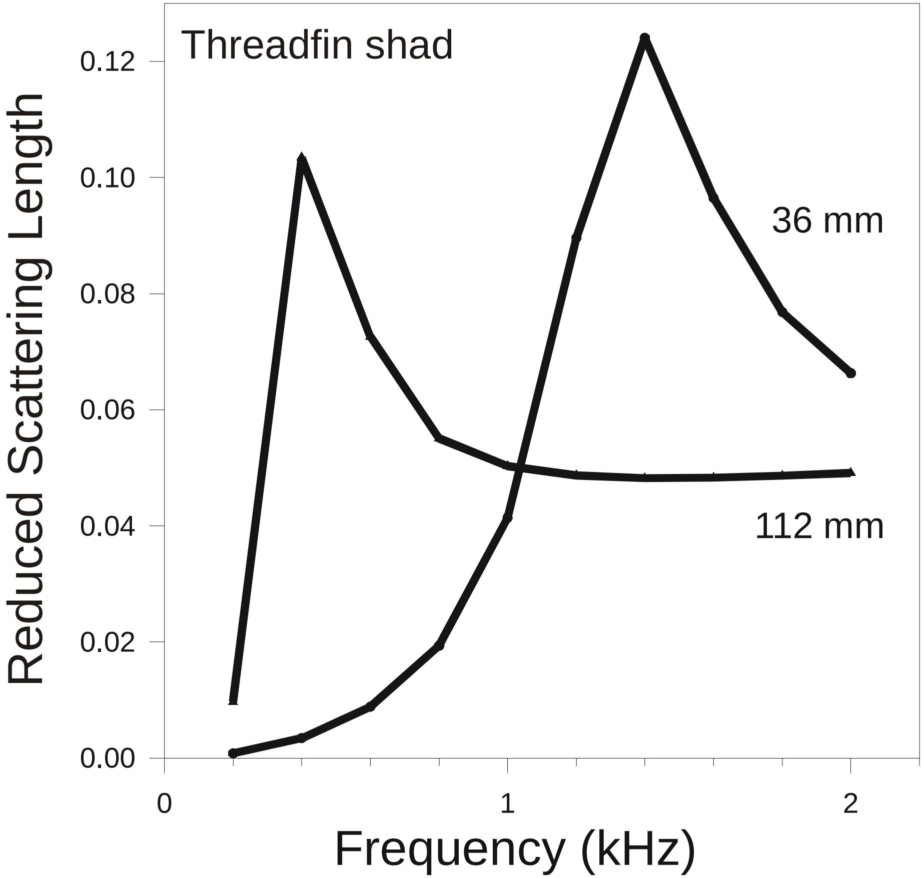
User Decisions

1. Measurement frequencies
2. Size classes
3. Spatial Coverage and Resolution of Samples (beamwidth and directivity)
4. Analytic algorithm
5. Backscatter Model

Decisions based on assumed sizes and distribution of targeted population

Inverse Approach Application

Threadfin shad (*Dorosoma petenense*)



- use ‘acoustic volume reverberation’ (i.e. resonant backscatter)
- must span Rayleigh to geometric scattering (Holliday& Pieper 1995)

Can technique be used with geometric scattering frequencies?

How to Validate Technique?

Can’t:

- demonstrate mathematical accuracy of acoustic abundance estimates on wild populations

Can:

- use simulated populations with known backscatter characteristics to quantify accuracy of abundance estimates

Inverse Simulations

How do acoustic carrier frequency and length class choices influence accuracy of length-based abundance estimates?

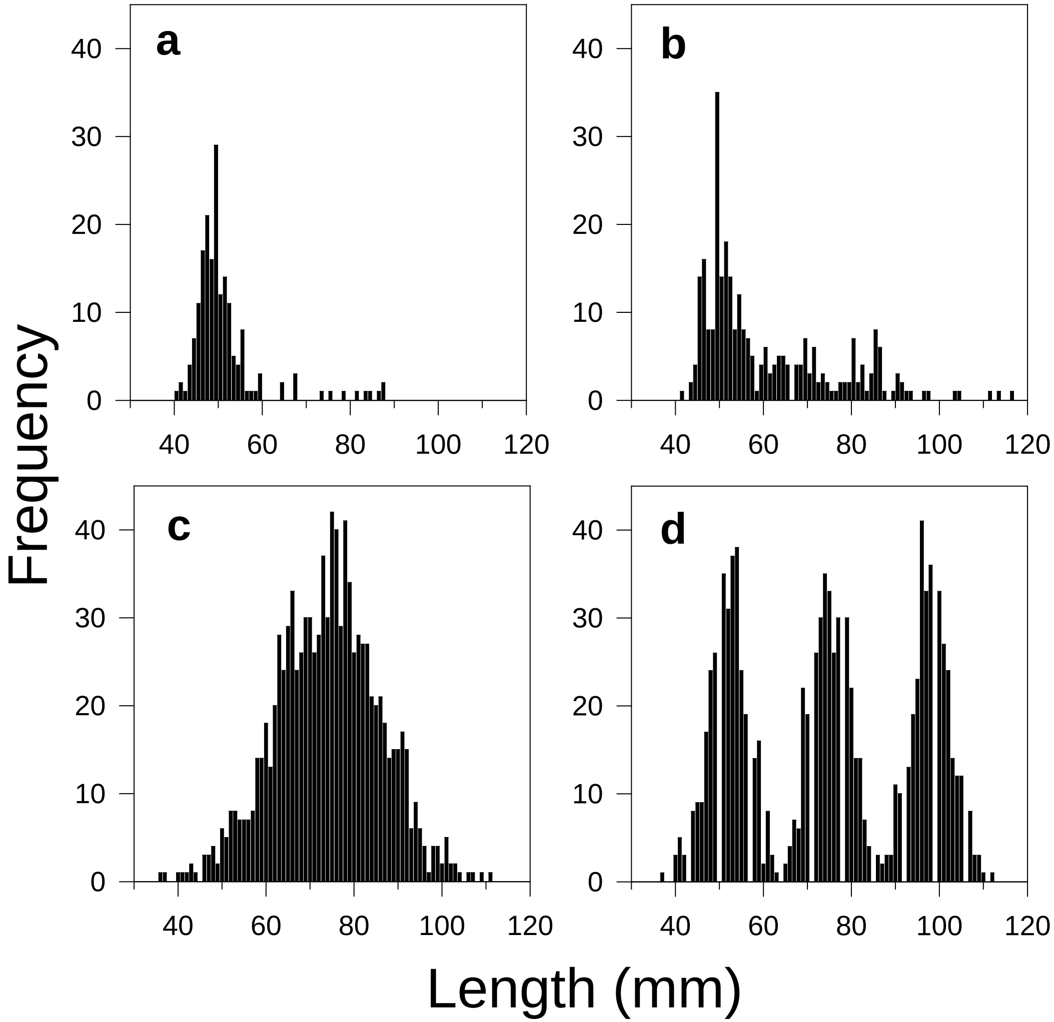
Tools available:

- 5 geometric backscattering frequencies 38, 70, 120, 200, 420 kHz
- representative length frequency distributions from net hauls
- KRM backscatter model

Threadfin Shad Populations

Purse Seine Catches

Simulated



Per Capita Deviance Measures

Population Estimate Index

$$\Delta_{total} = \left| \frac{\hat{n} - n}{n} \right|$$

Within Length-class Index

$$\Delta_{within} = \sum_{j=1}^{N} \left| \frac{\hat{n}_j - n_j}{n_j} \right|$$

If ‘perfect’ estimate then index values = 0

Simulation Results: Abundance

Total Abundance:

- matched uni and tri modal population abundances
- mean index value 0.078 $\pm$ 0.082 s.d. n=68

Within Length-Class:

- inconsistent among frequency combinations and across length-class criteria
- mean index values 8.32 $\pm$ 13.6 s.d. n=68
- values ranged 65 fold in even-determined simulations

Simulation Results: Frequency

Total Abundance:

- ‘best’ estimates all contained 70, 200 kHz
- equal interval centered on mean(s)

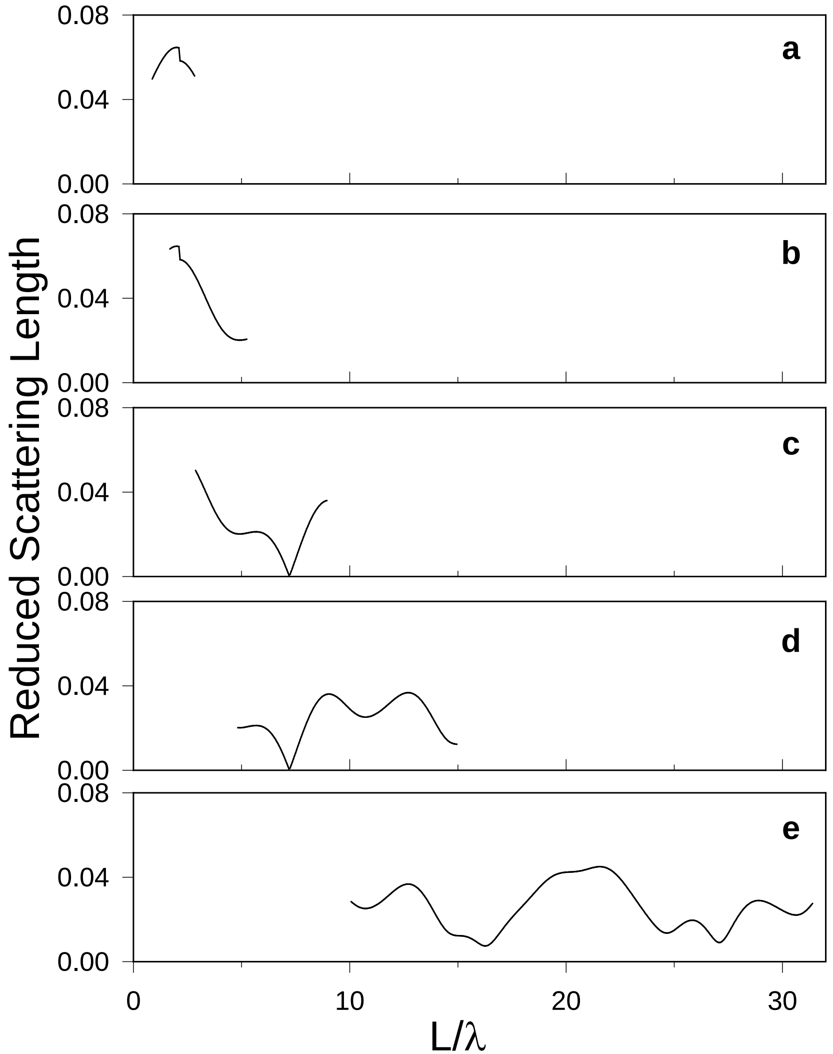
Within Length-Class:

- ‘best’ estimates all contained 38, 70, 120 kHz
- ‘best’ size class criterion was equal interval across range (compared to means, node and null values)

Frequency & Length Dependent Backscatter

Length Range

36 – 112 mm



Frequency (kHz)

38

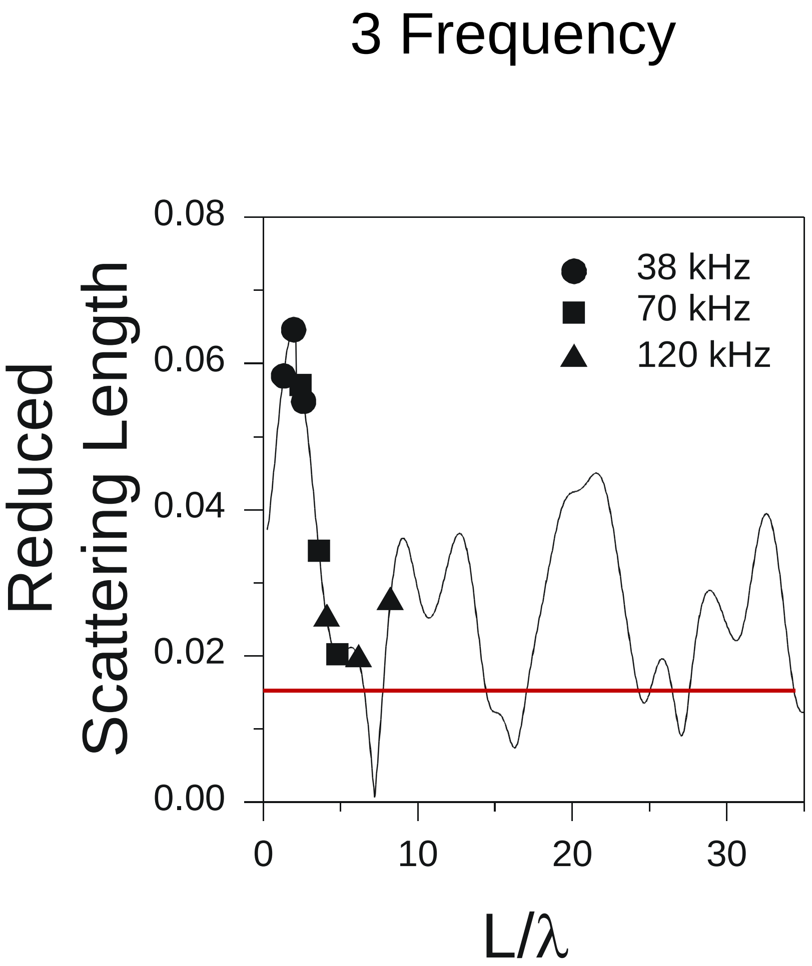
70

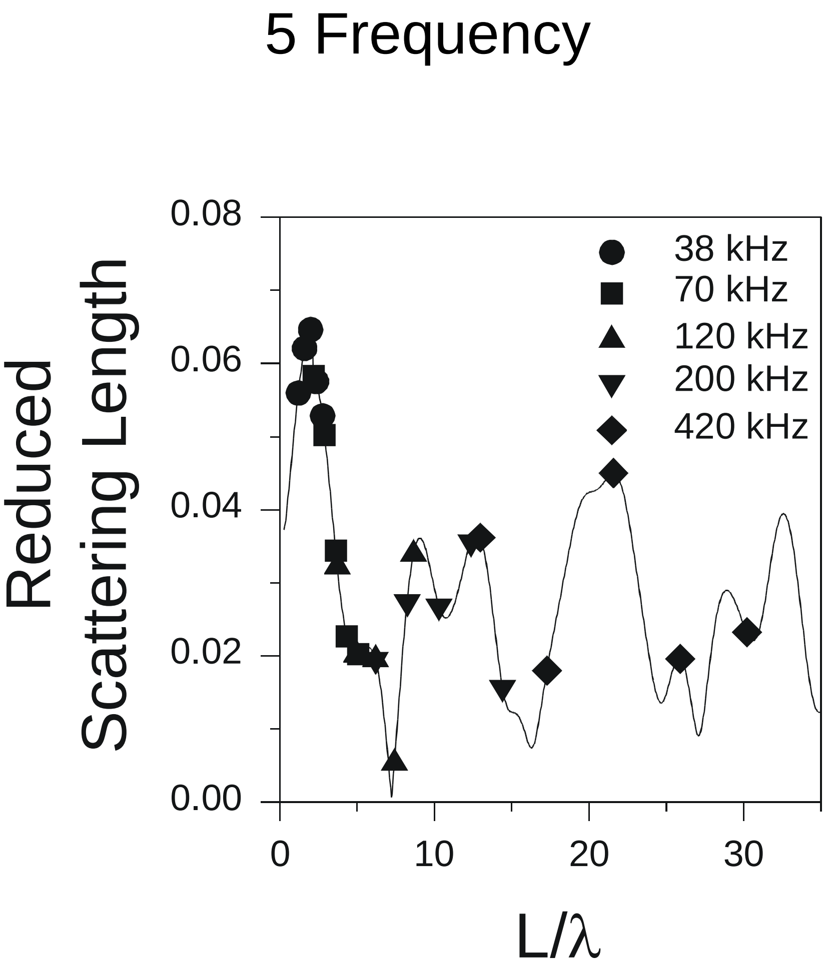
120

200

420

Multiple Frequency Choice





non-unique amplitude – L/λ combinations

Reference Backscatter Values

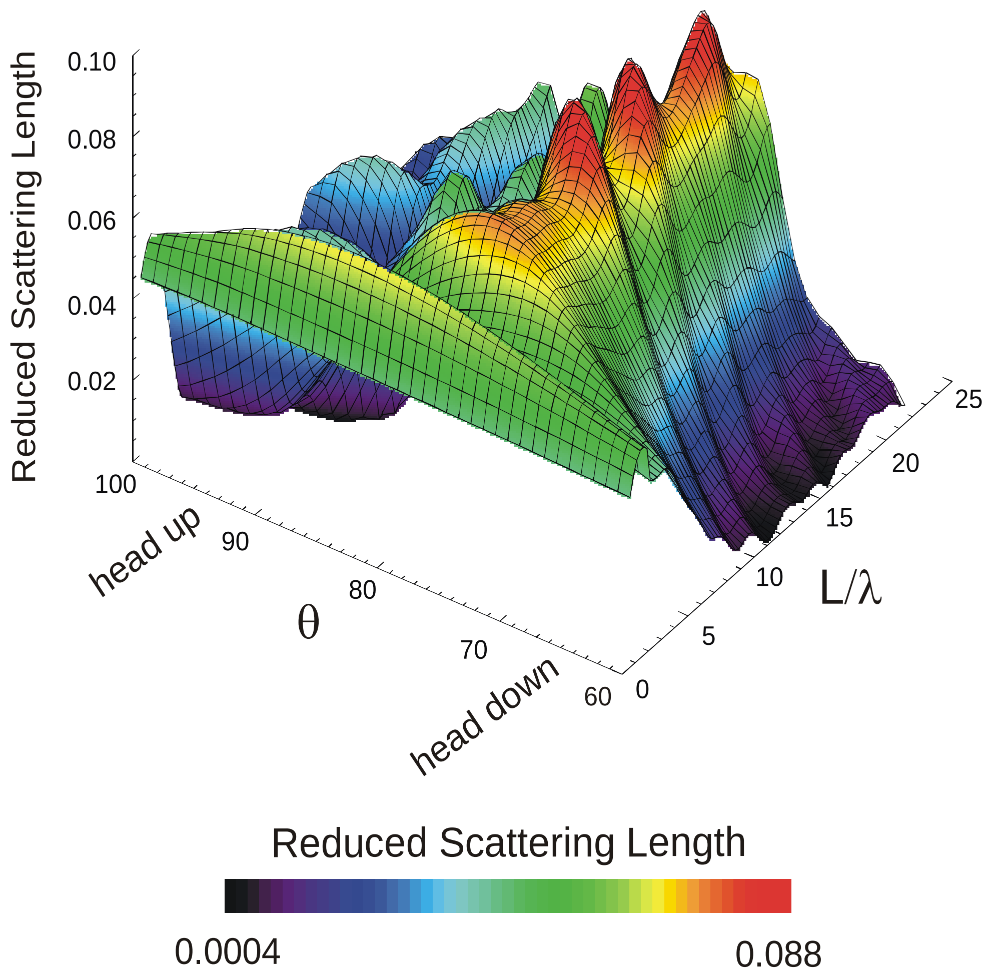
- ‘best’ results occurred when L/λ values encompassed full amplitude range, minimized overlap among reference scattering points, and maximized number of features defined

Feature = peak or valley on the backscatter curve

- three points are needed to define a feature

Threadfin Shad Backscatter Response

modeled length
75 mm



What about
behavioral
effects?