Modeling Acoustic Backscatter: Gradual or Punctuated Evolution?

FHL 2008

LO: Evaluate basis and assumptions underlying historical and current acoustic backscatter models for fish and zooplankton.

John Horne

What is a ‘Model’?

Parsimonious representation of the truth

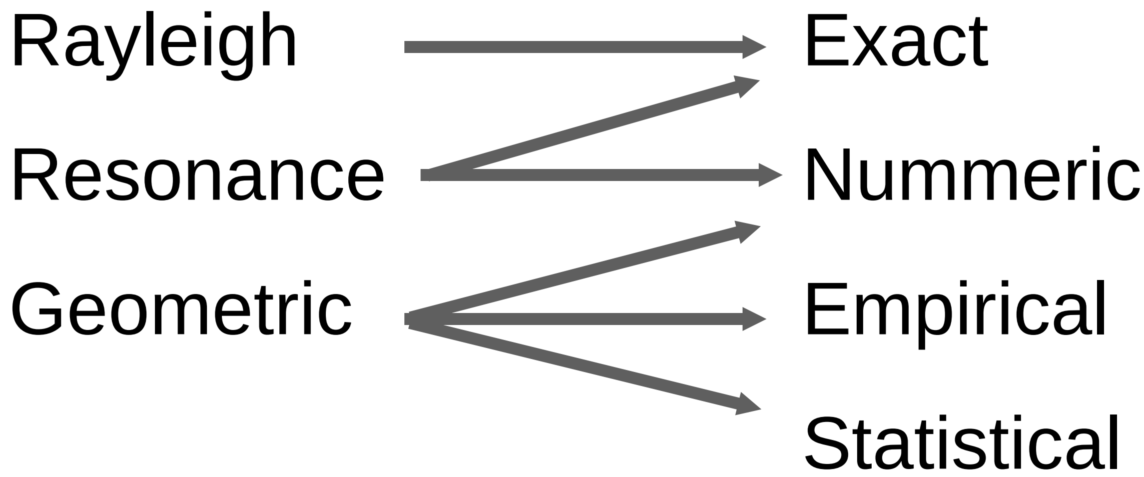
If life was simple:

rigid body – 1 wave equation, analytic solution for 11 shapes

But

Elastic – 3 coupled scale equations, solution limited to 3 shapes: sphere, infinite cylinder, infinite rectangular slab

Model Categories & Analytic Methods



Organism or Structure:

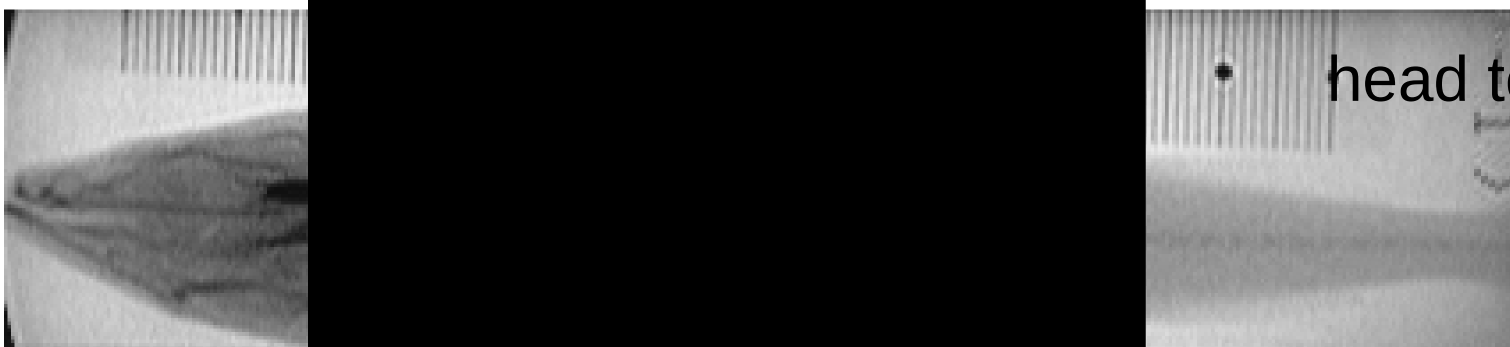
Zooplankton, Fish, Body, Fish Swimbladder, Whole Fish

Imaging Evolution

Walle[redacted]*ammus*)

CAT scans:

head to tail



"… models b[redacted]apes, …, are inadequa[redacted]pes are symmetrical [redacted]or transverse p[redacted]ladder is not." (Foote 1985)

"…fish an[redacted]cribed by simple the[redacted]oustically-superfluou[redacted] (… Clay 1998)

Walleye Pollock

Limitation of Geometric Forms

"… models based on simple geometric shapes, …, are inadequate, if only because such shapes are symmetrical with respect to the horizontal or transverse plane, while the general swimbladder is not."

"The consequence of asymmetry in swimbladder form is often observed in the significant asymmetry of dorsal and ventral aspect target strength functions of the same fish."

Foote 1985

Geometric Form Exception

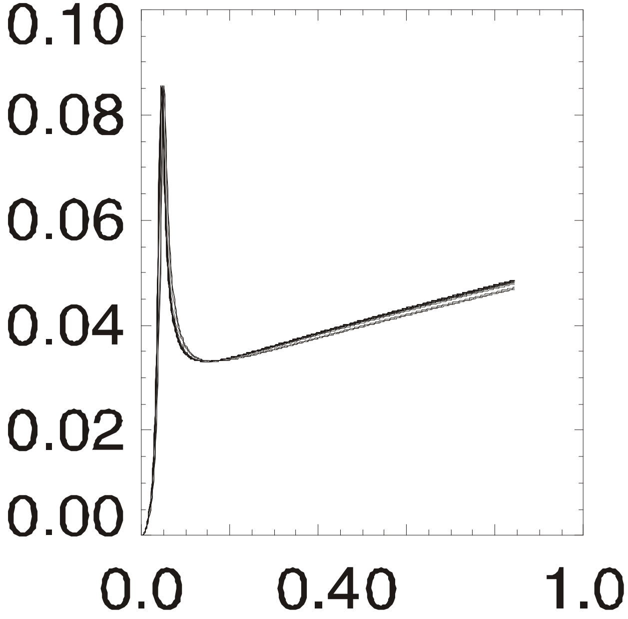
geometric shapes are viable representations when modeling resonant or Rayleigh scattering

Why?

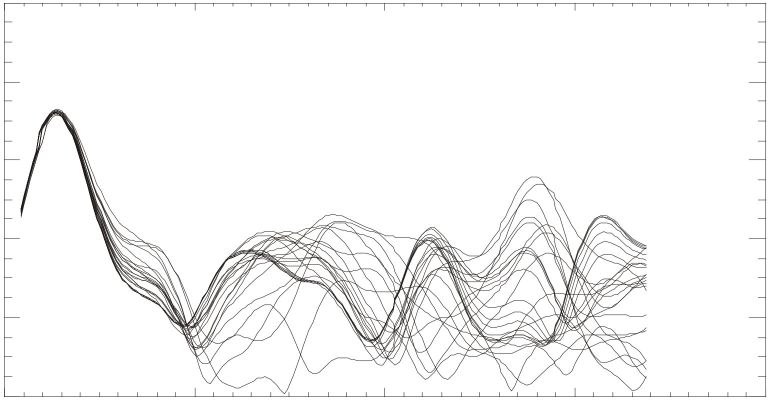
orientation doesn’t matter, targets are point scatterers

Affect of Image Resolution

What level of detail is acoustically appropriate?



KRM Model Predictions



Jech and Horne 1998

Backscatter Model Alphabet Soup

BEM - Boundary Element Method

DCM - Deformed Cylinder Model

DWBA - Distorted Wave Born Approximation

PT-DWBA - Phase-tracking DWBA

SDWBA – Stochastic DWBA

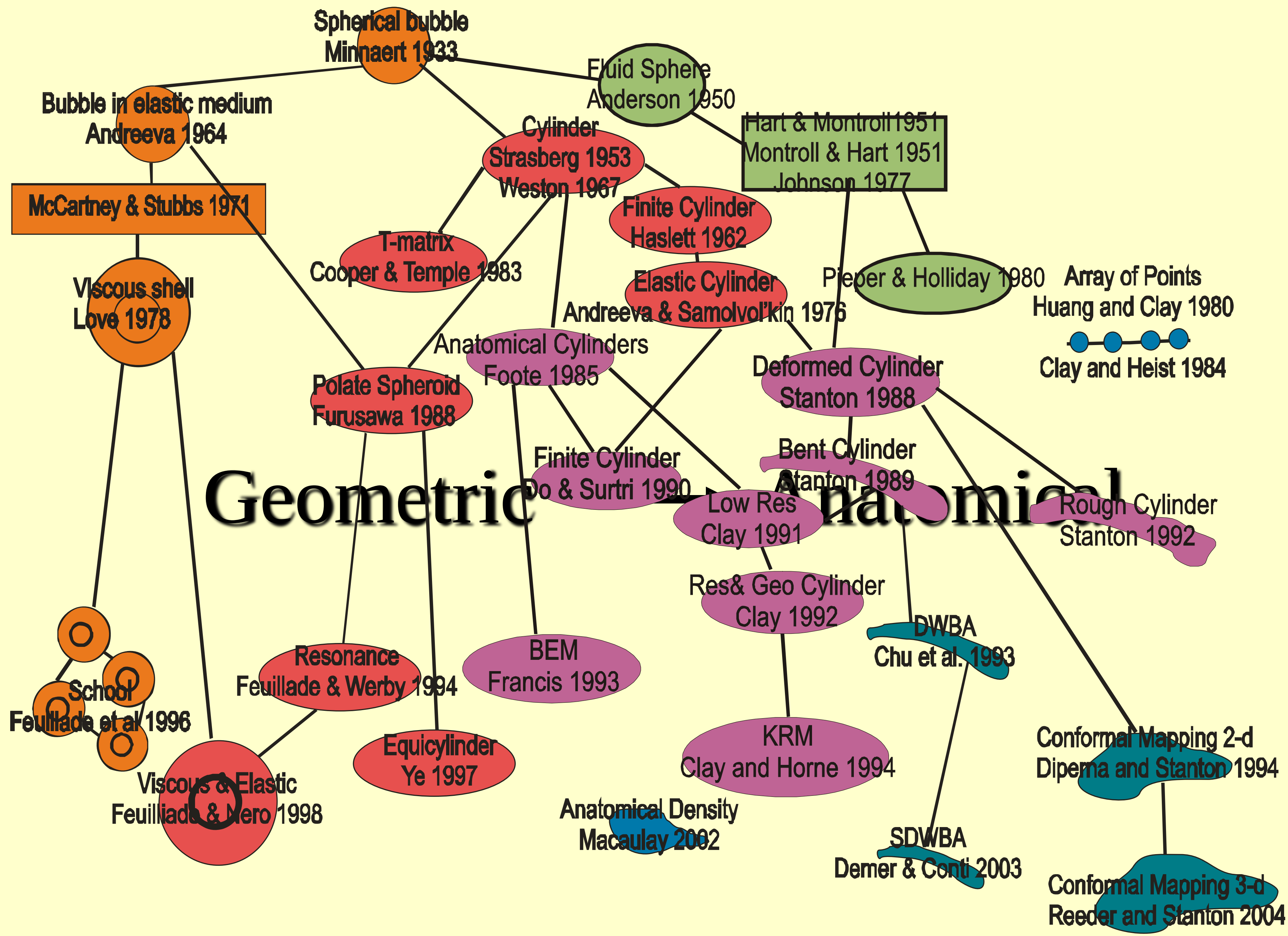
FEM - Finite Element Method

FMM - Fourier Matching Method

KA - Kirchhoff Approximation

KRM - Kirchhoff-ray Mode

MSS - Modal Series Solution



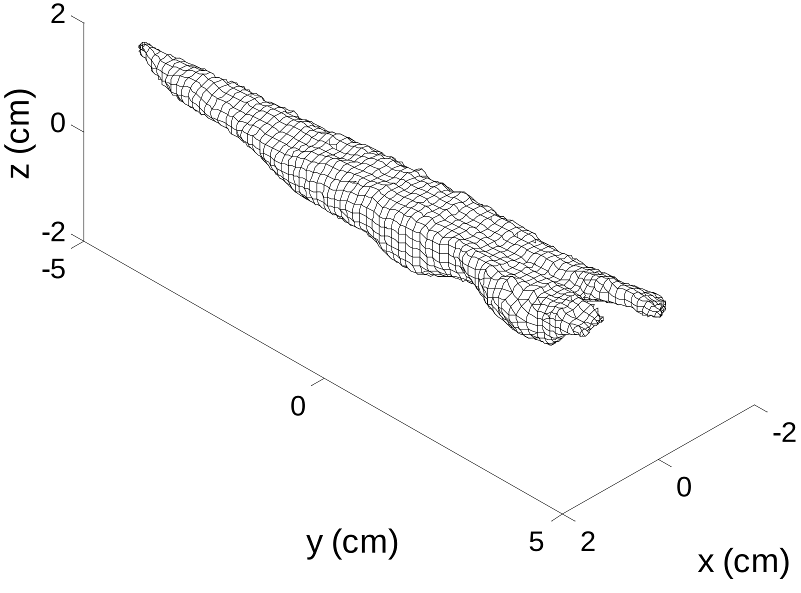
Spherical bubble
Minnaert 1933
Fluid Sphere
Anderson 1950
Bubble in elastic medium
Andreeva 1964
Cylinder
Strasberg 1953
Weston 1967
Hart & Montroll1951
Montroll & Hart 1951
Johnson 1977
McCartney & Stubbs 1971
Finite Cylinder
Haslett 1962
T-matrix
Cooper & Temple 1983
Elastic Cylinder
Andreeva & Samolvol'kin 1976
Pieper & Holliday 1980
Array of Points
Huang and Clay 1980
Clay and Heist 1984
Viscous shell
Love 1978
Anatomical Cylinders
Foote 1985
Deformed Cylinder
Stanton 1988
Polate Spheroid
Furusawa 1988
Bent Cylinder
Stanton 1989
Finite Cylinder
Do & Surtri 1990
Geometric → Anatomical
Low Res
Clay 1991
Rough Cylinder
Stanton 1992
Res& Geo Cylinder
Clay 1992
DWBA
Chu et al. 1993
School
Feuillade et al 1996
Resonance
Feuillade & Werby 1994
BEM
Francis 1993
Equicylinder
Ye 1997
KRM
Clay and Horne 1994
Conformal Mapping 2-d
Dipema and Stanton 1994
Viscous & Elastic
Feuilliade & Nero 1998
Anatomical Density
Macaulay 2002
SDWBA
Demer & Conti 2003
Conformal Mapping 3-d
Reeder and Stanton 2004

Boundary Element Method

Calculated using Hemholtz intergral for amplitude and displacement from any point on discretized surface (where *l*<1/3λ)

Capabilities: valid at all frequencies, accuracy depends on quality of discretization, includes diffraction

Limitations: computationally intensive

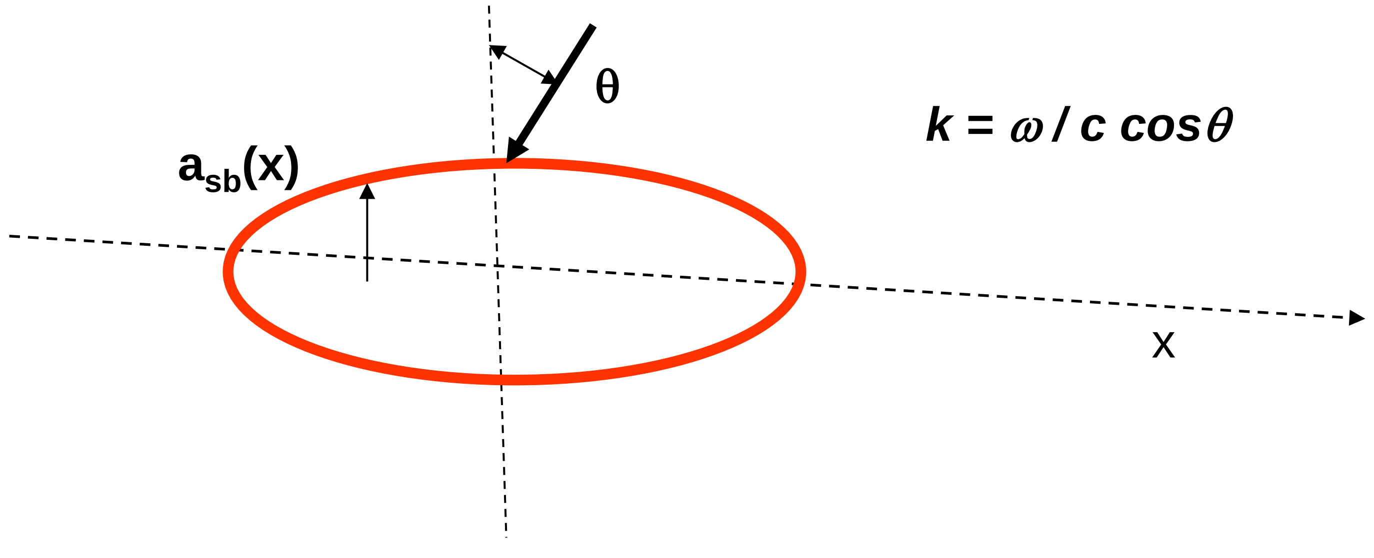


Deformed Cylinder Model

Exact modal series solution for infinite cylinder (used for prolate spheroid swimbladder)

Capabilities: variety of material properties

Limitations: restricted angle range, arbitrary shape

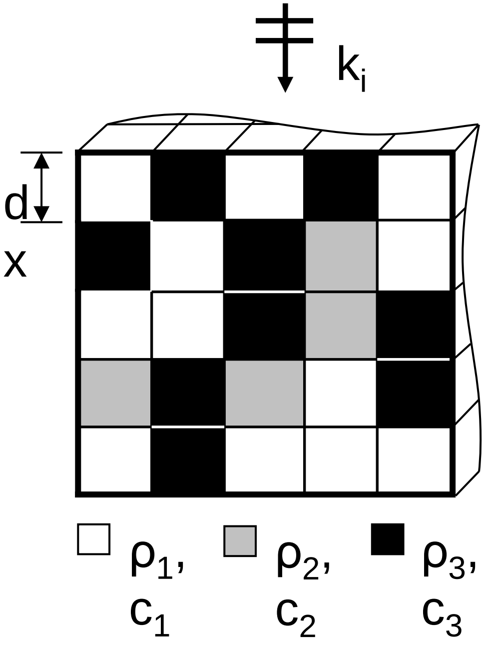


Distorted Wave Born Approximation

Designed for weak scattering objects, density differences, can integrate pieces to accommodate phase differences

Capabilities: valid for all frequencies, at all angles, for any arbitrarily shaped object with small contrast in sound speed and density (body)

Limitations: weakly scattering objects (g, h near unity), inhomogenous mediums

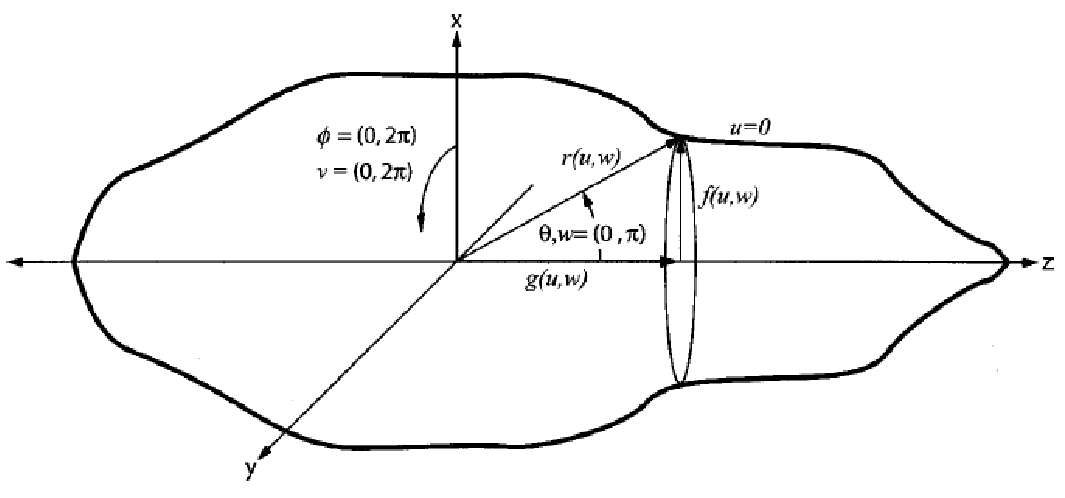


Fourier Mode Matching

Exact anatomical representation, exact solution for finite-length objects

Capabilities:, all frequencies, all orientation angles, all scattering geometries (back, forward, and bistatic), all boundary conditions

Limitations: far-field scattering, axisymmetric shape, numerical implementation, frequency and/or shape irregularity, conformal mapping (single-valued radius and “needle points”)

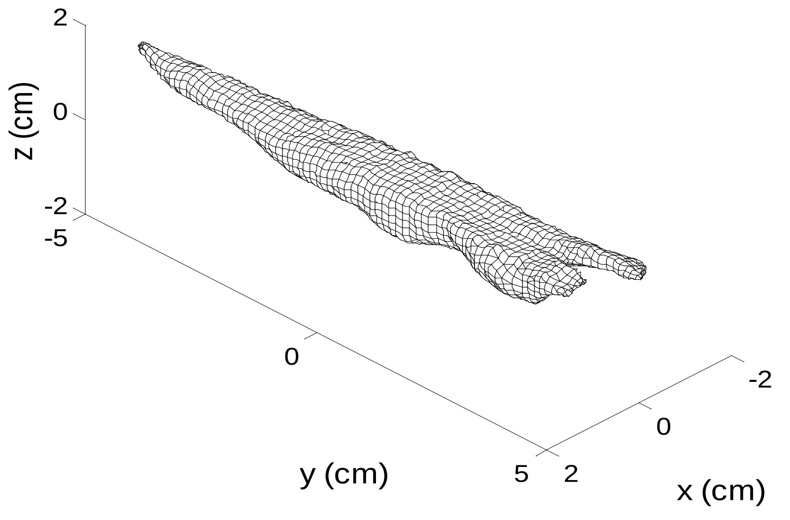


Kirchhoff Approximation

Surface backscatter using Kirchhoff integral

Capabilities: valid for geometric frequencies, for any shape, high or low resolution morphometry

Limitations: typically applied to swimbladder only, restricted angle range

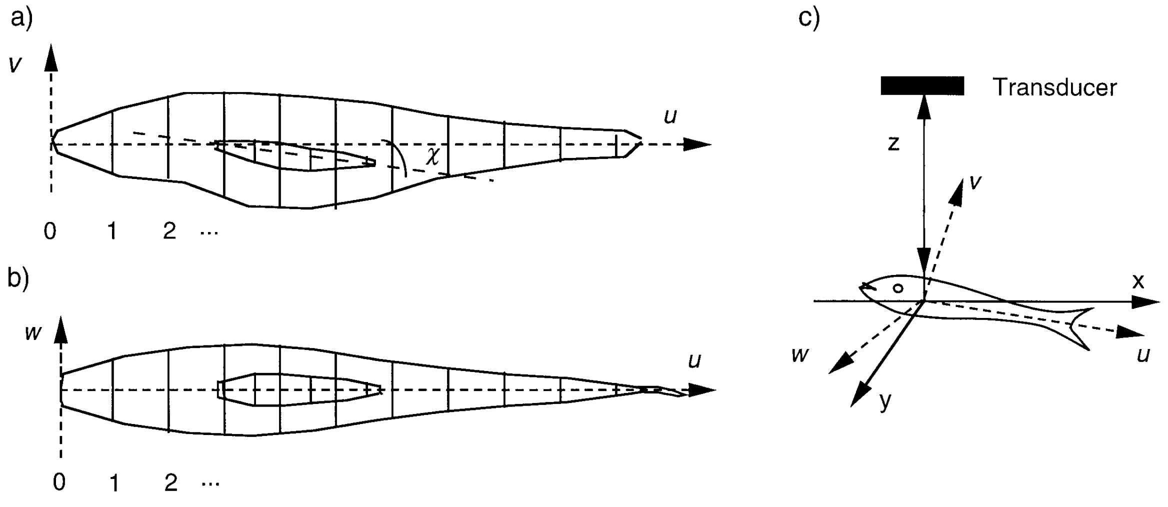


Kirchhoff-ray Mode

Breathing mode at or below resonance (ka <0.15), surface backscatter using Kirchhoff integral, cylindrical anatomical representation

Capabilities: any shape, unlimited inclusions, backscatter from all interfaces

Limitations: forced symmetry, restricted angle range, no diffraction

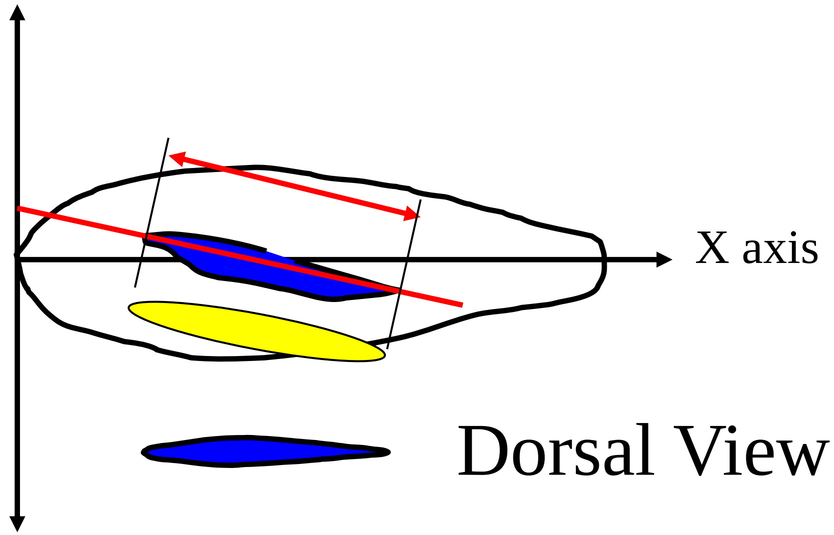


Prolate Spheroidal Mode

Scalar wave equation, spheroidal coordinates, spheroidal wave function (angle, radial function)

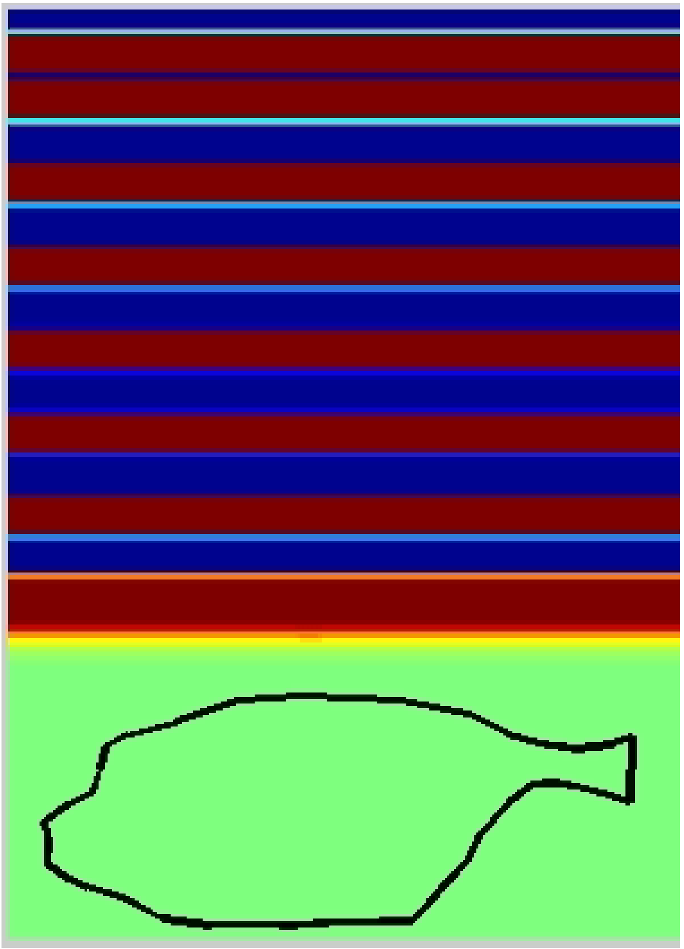
Capabilities: theoretically valid for all frequencies, at all angles

Limitations: geometric representation, strong scattering objects (?)



Finite difference, time domain

Black oreo *(Allocyttus niger)*



plane wave, c=1491 m/s,

τ = 0.32 ms, f = 38 kHz

G. Macaulay

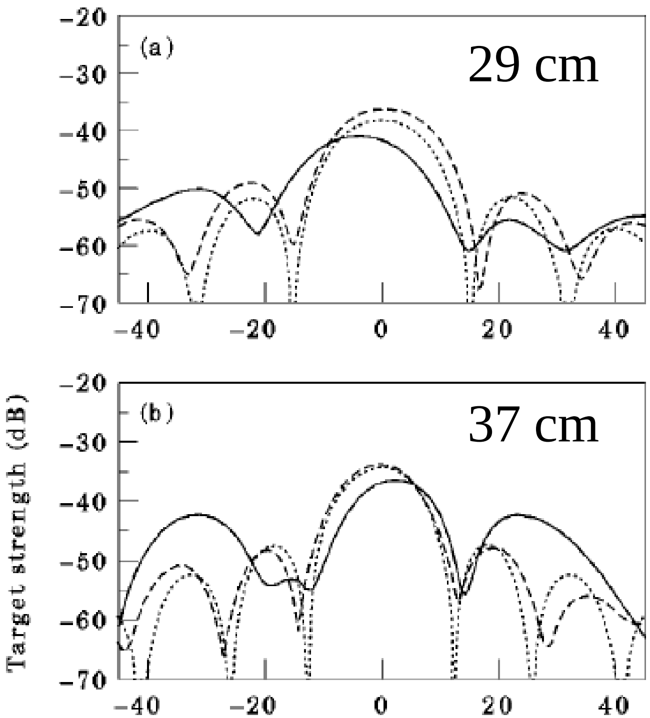
Summary Model Comparison

Model	Organism Representation	Analytic Method
BEM	Anatomical, triangular mesh	Hemholtz equation
Conformal Mapping	anatomical shape	Hemholtz equation
DWBA	deformed anatomical cylinders	line integral
KRM	anatomical cylinders	breathing mode + Kirchhoff
Finite Difference	actual shape, density	finite difference, time domain

Backscatter Model Comparisons

mapping, deformed cylinder, equicylinder

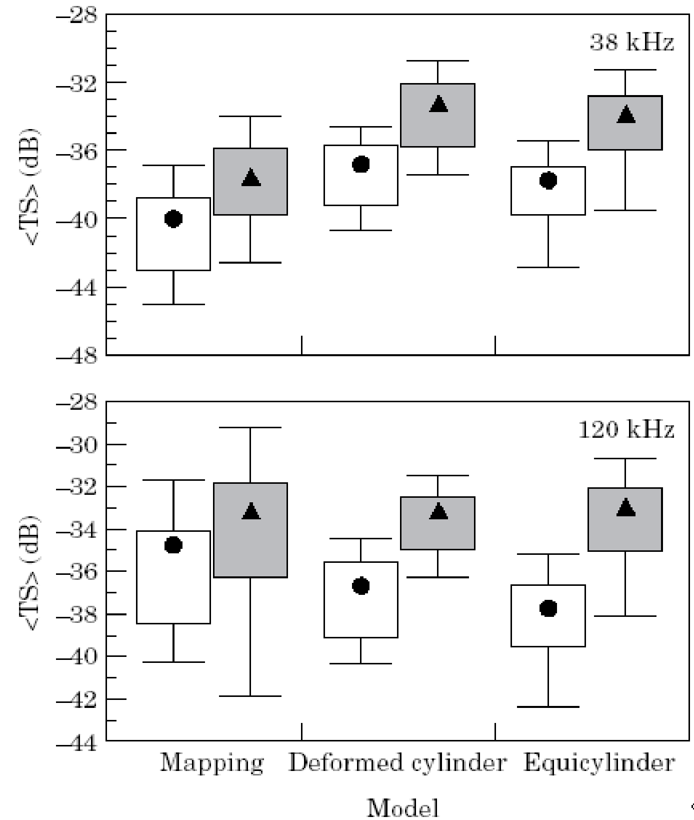
Blue Whiting (*Micromesistius australis*)



McClatchie et al. 1996

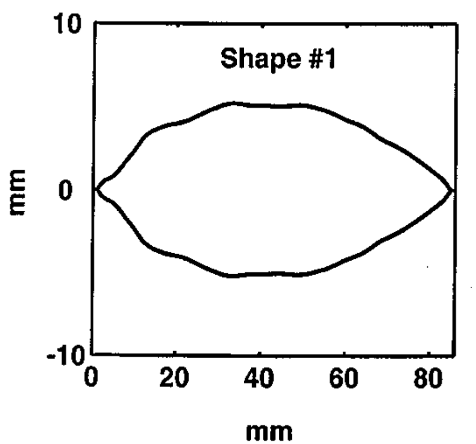
Tilt averaged

5º, 15º

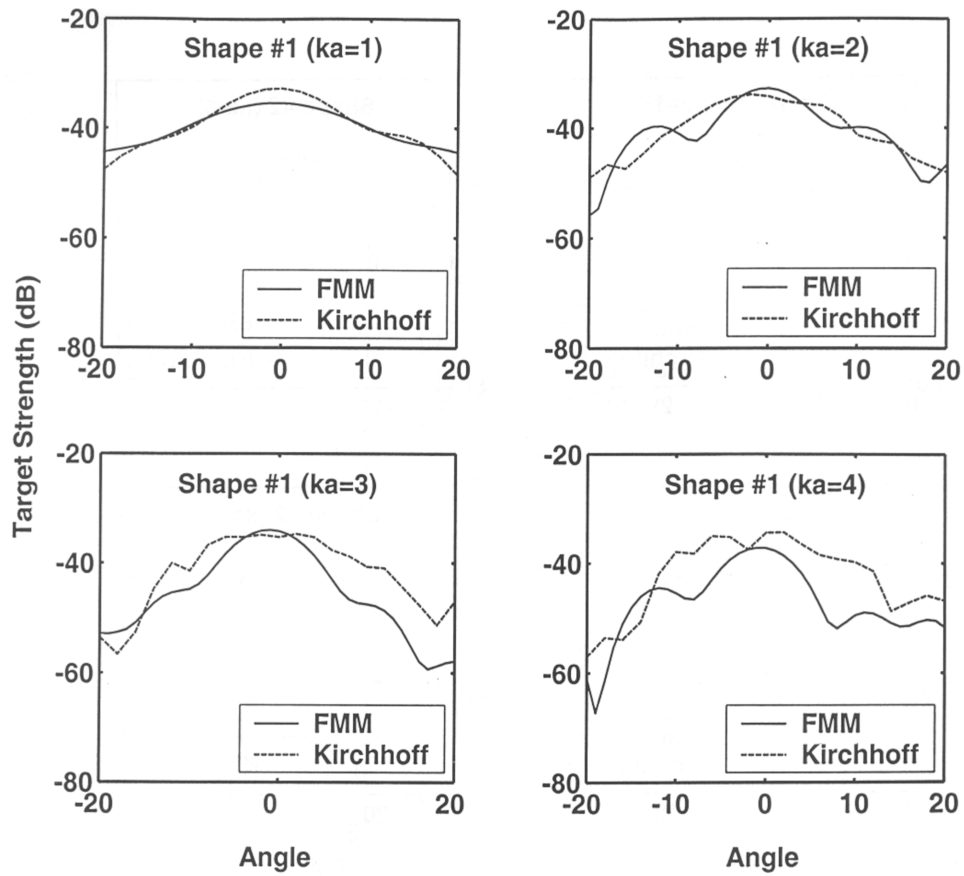


Expanded Model Comparisons

Fourier Matching Method (FMM) (aka Conformal Mapping) vs Anderson sphere, deformed cylinder, t-matrix, BEM, exact prolate spheroid, Kirchhoff approximation



Swimbladder cross-section



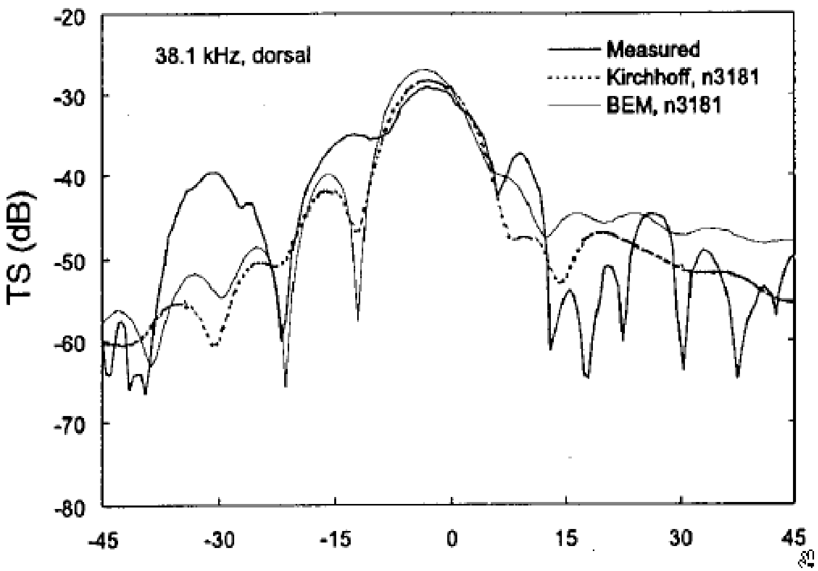
Reeder & Stanton 2004

Model Comparison to Empirical Measures

Finite Boundary Element (BEM) Model and Kirchhoff approximation

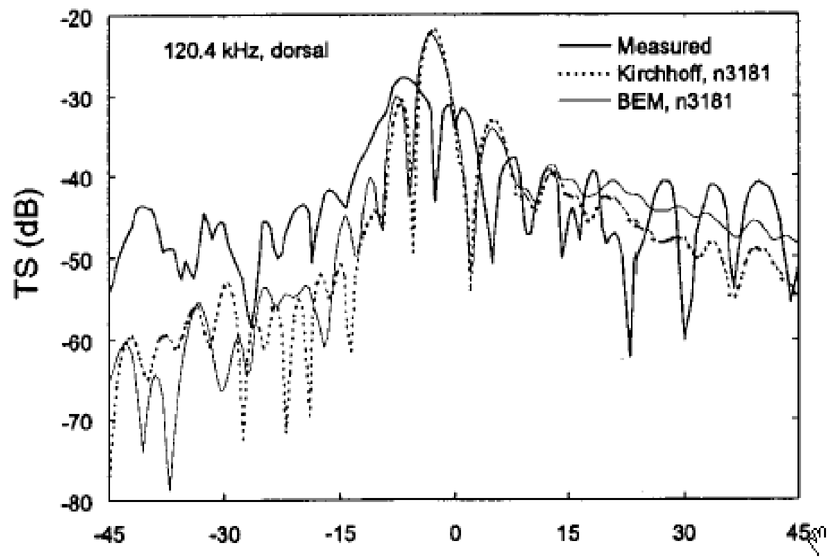
Pollack (*Pollachius pollachius*)

38 kHz



Tilt angle (deg)

120 kHz

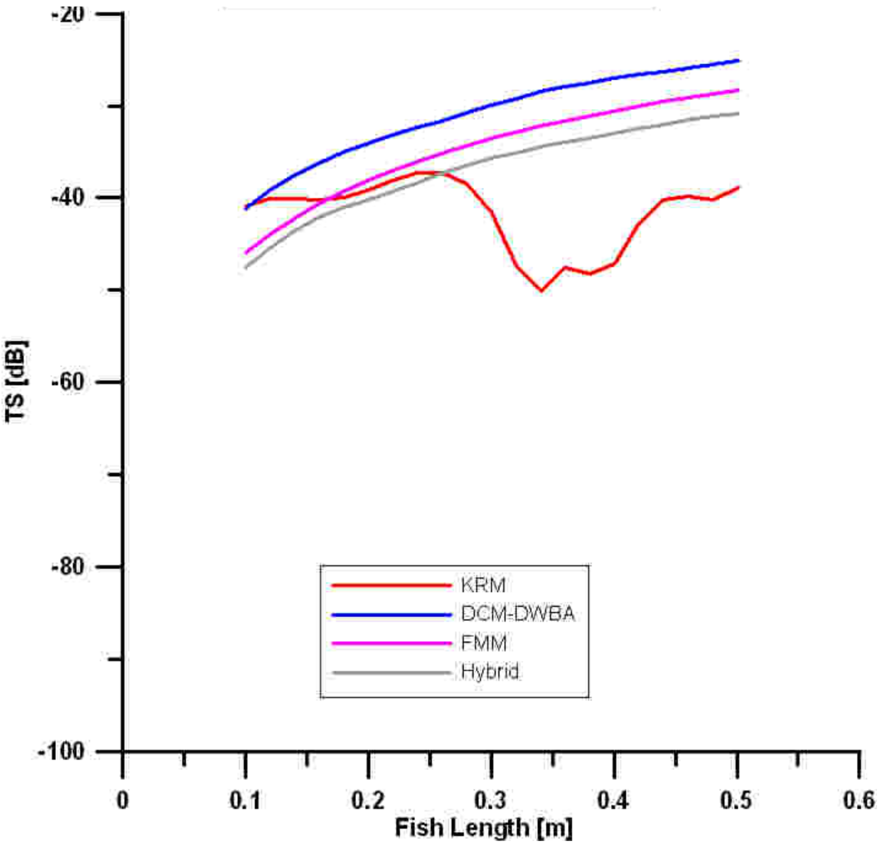


Tilt angle (deg)

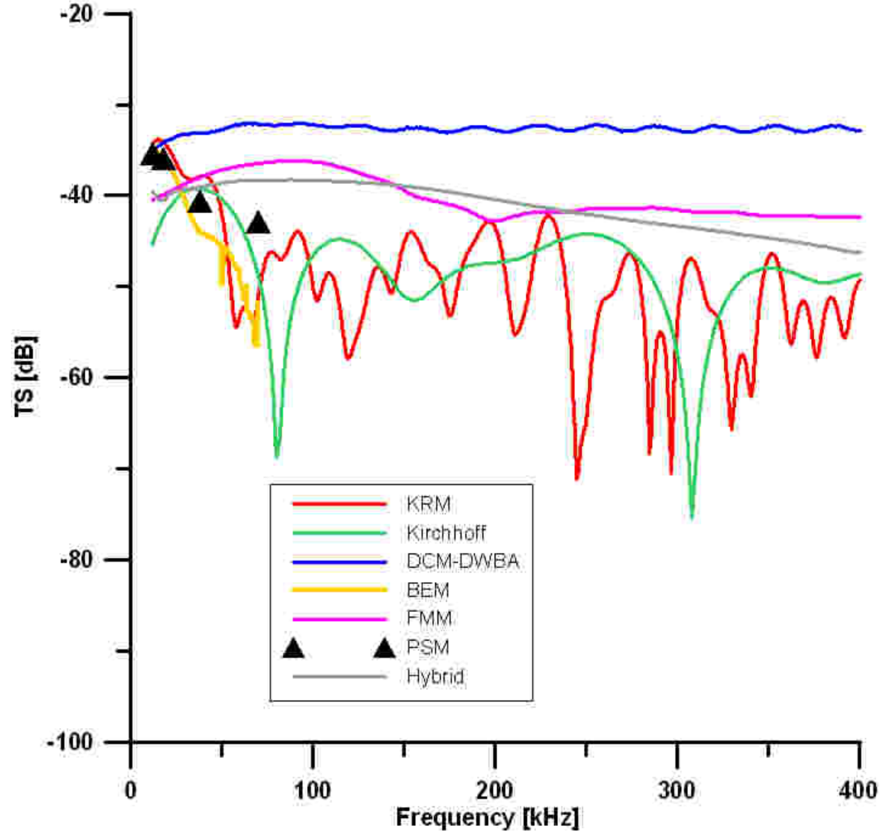
Foote and Francis 2002

Workshop: Herring Results

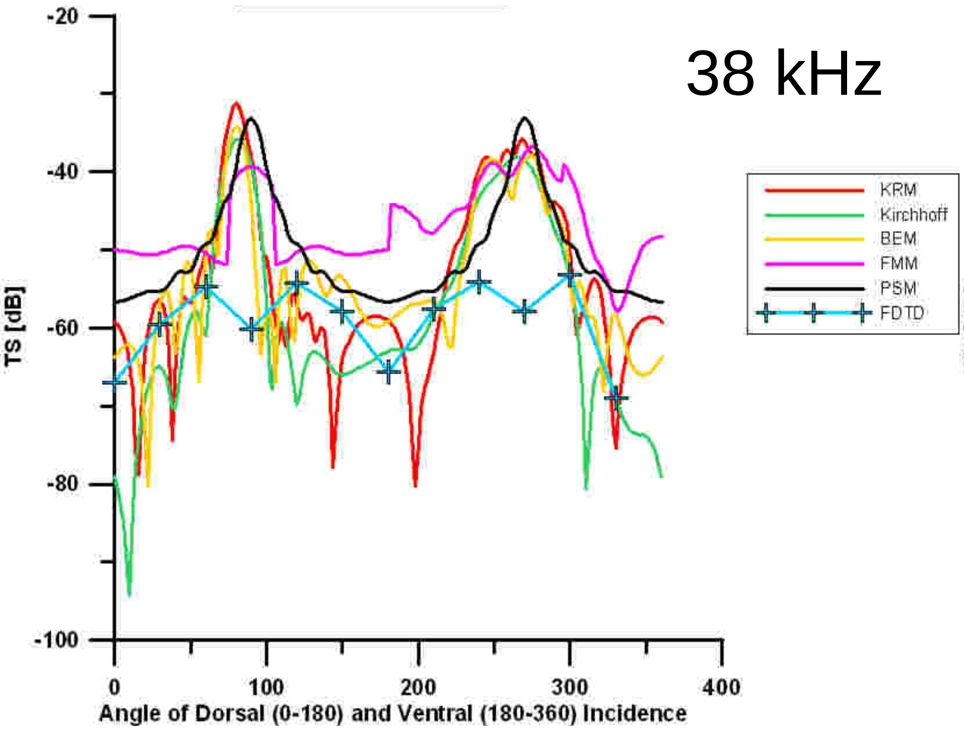
Length



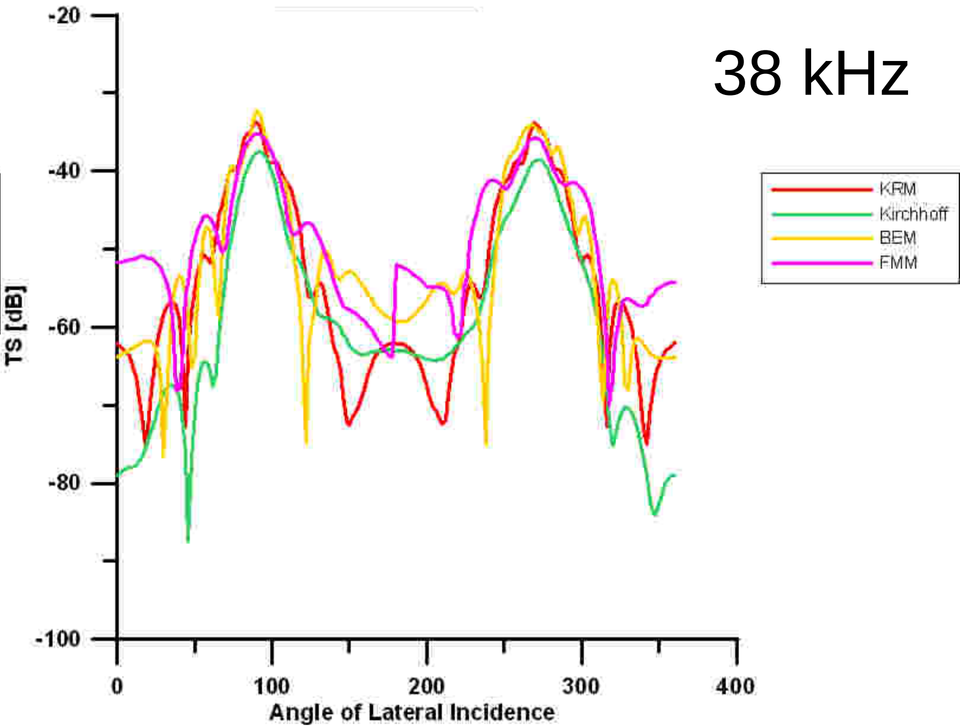
Frequency



Workshop: Herring Results



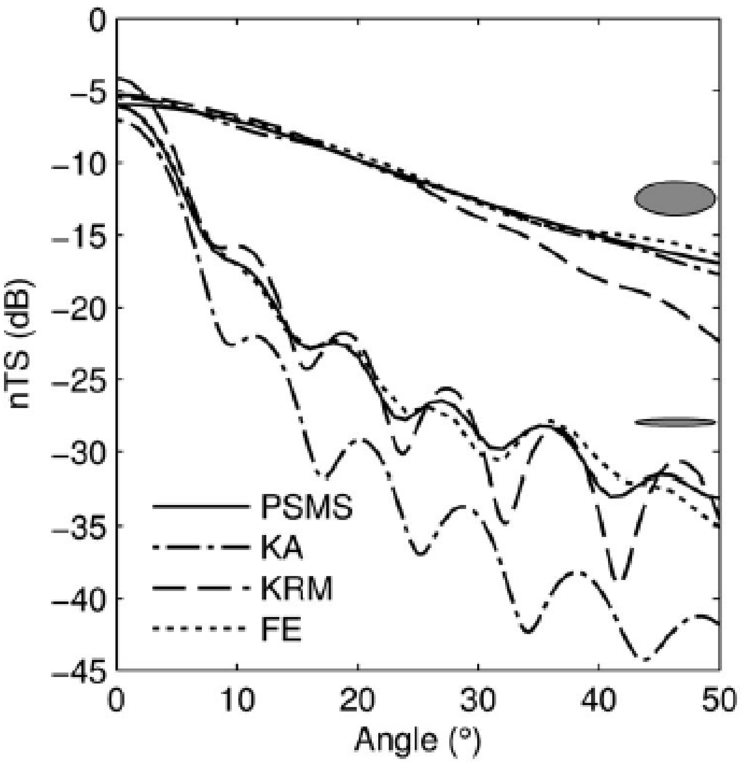
Dorsal-Ventral



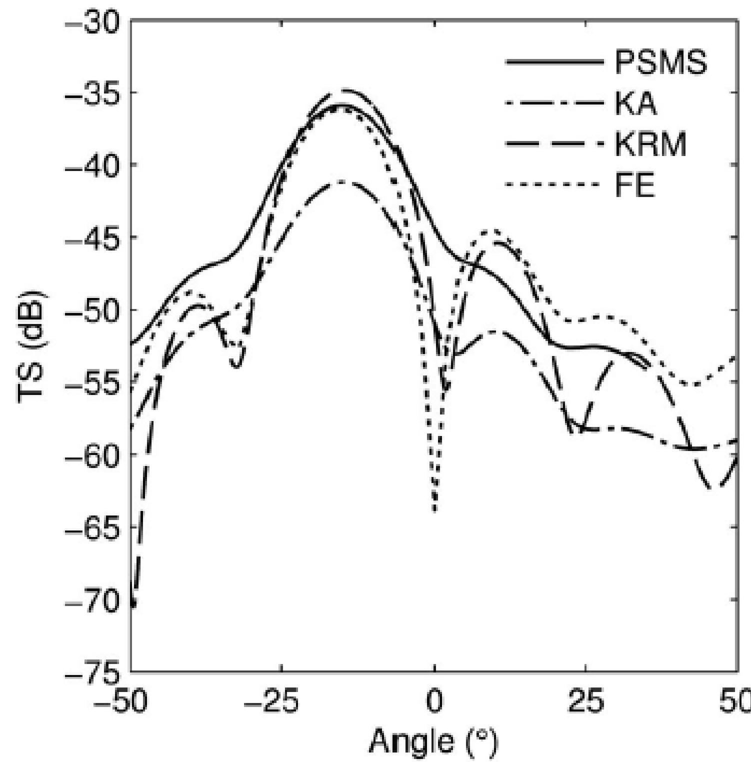
Lateral

Comparing Models to Finite Solutions

Model Comparison to Prolate Spheroid



Model Comparison to Jack Mackerel Swimbladder



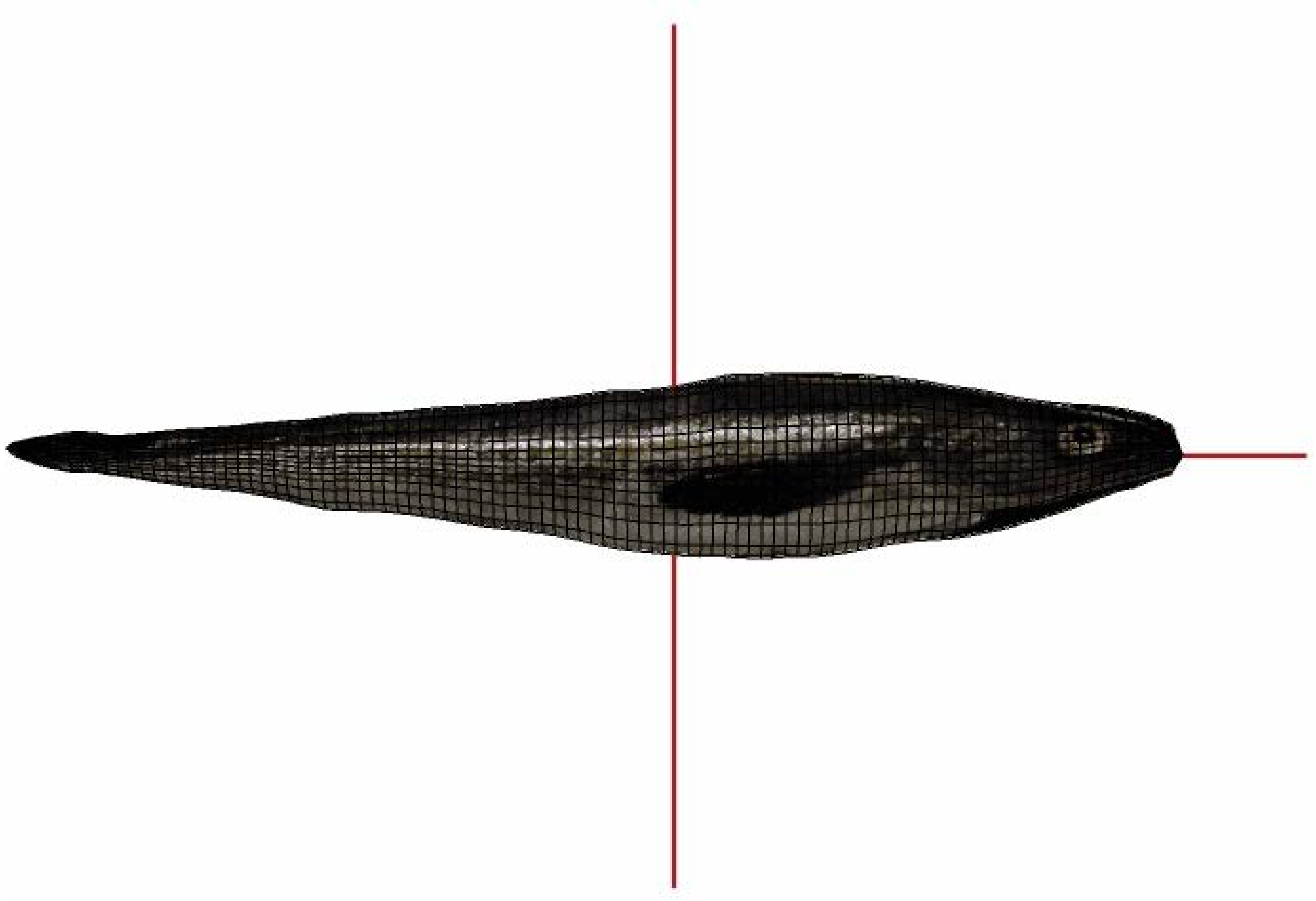
PSMS: Prolate Spheriod Modal Series; KA: Kirchhoff Approximation; KRM: Kirchhoff Ray Mode; FE: Finite Element

Macaulay et al. 2013

Backscatter Modeling Conclusions

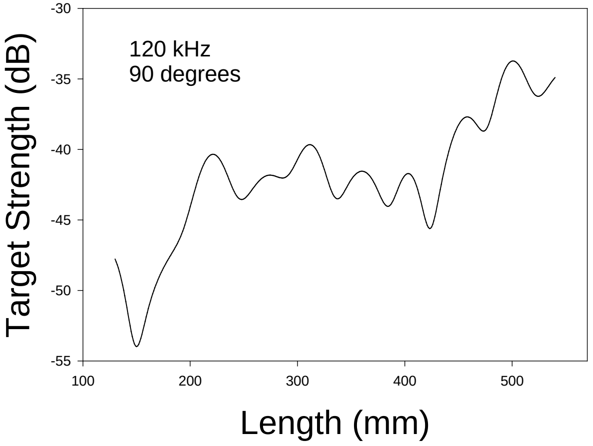
- Organism representations evolved from geometric shapes to anatomical detail, exact to numeric solutions
- Image resolution continues to increase, no standard
- Validation by comparison to exact solutions, other models, empirical measures
- Gradual evolution with punctuations

Kirchhoff-Ray Mode Model

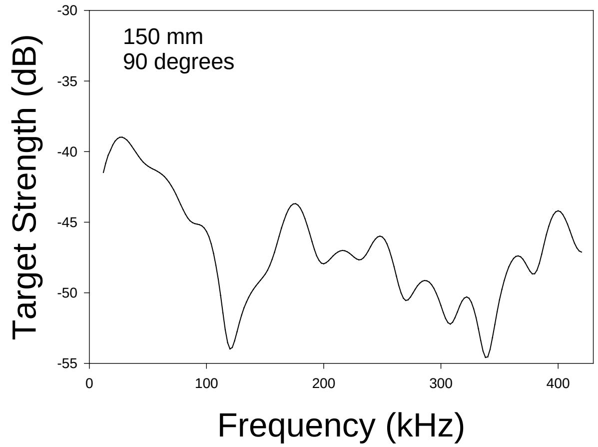


KRM Backscatter Predictions

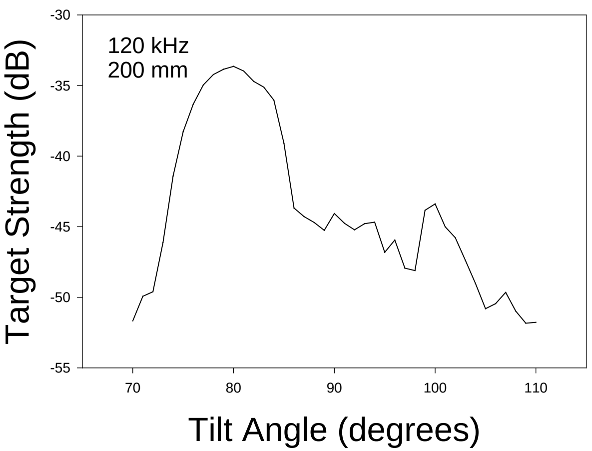
Length



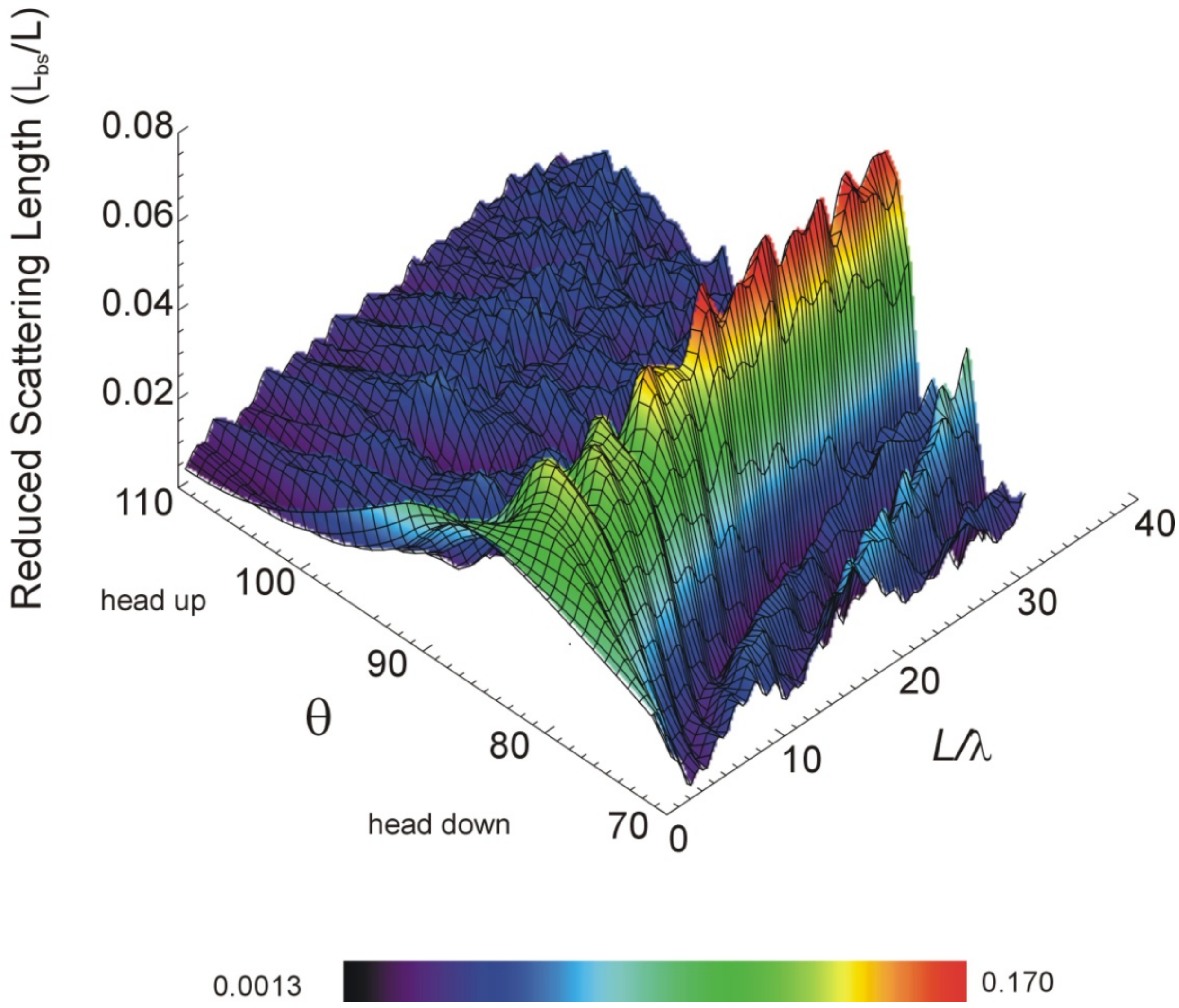
Frequency



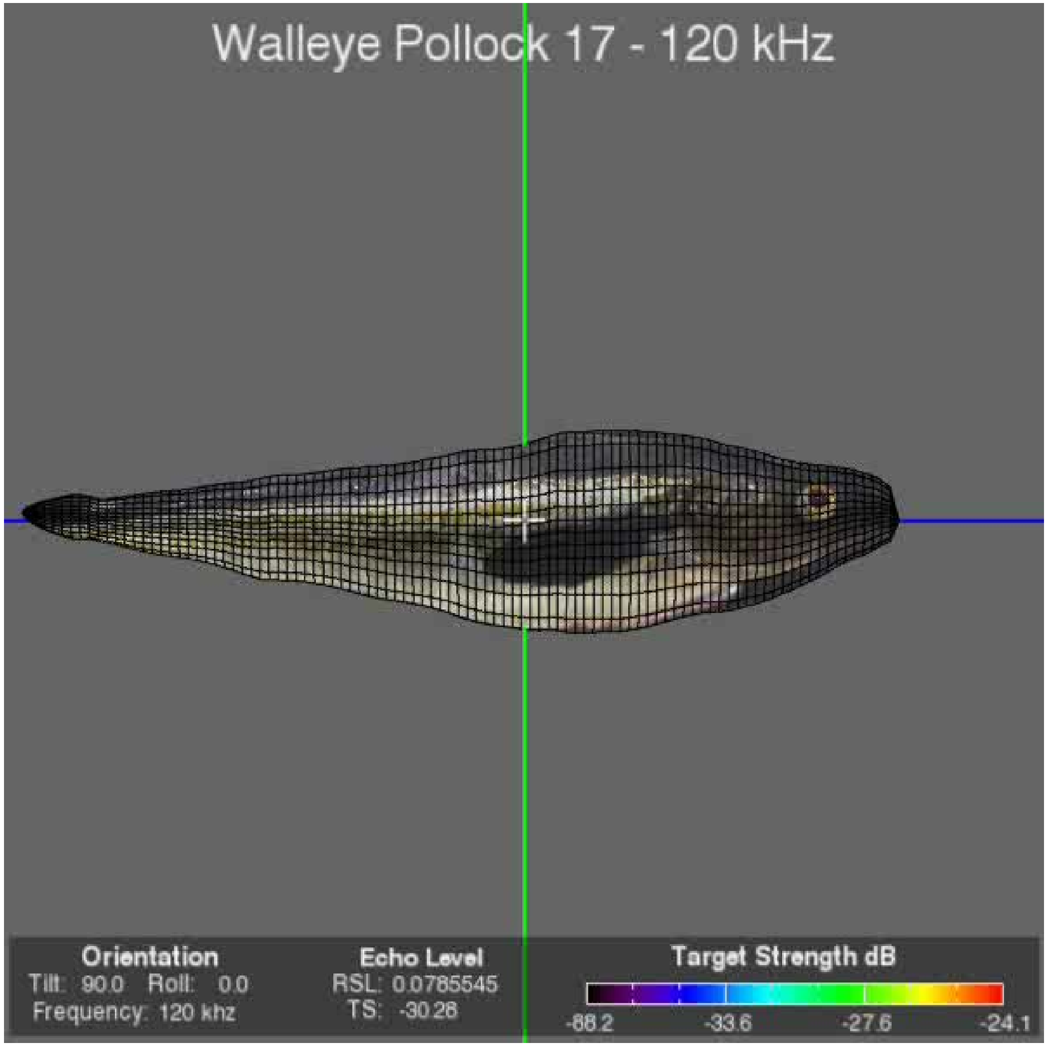
Tilt



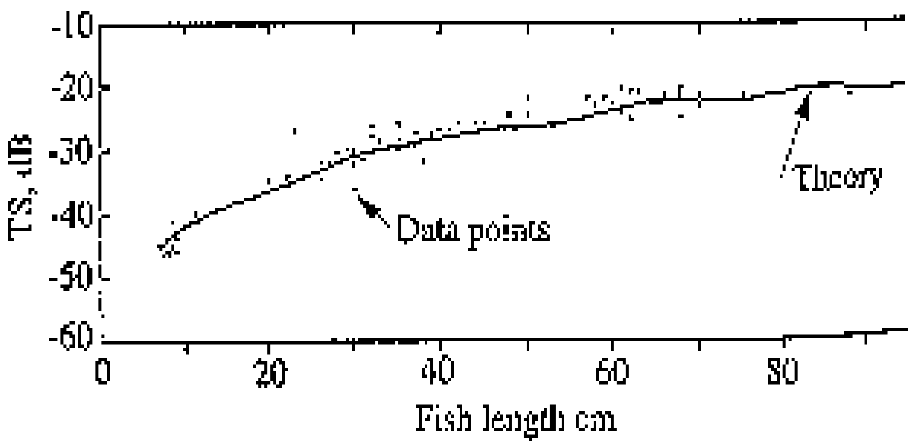
Backscatter Response Surface: Walleye Pollock

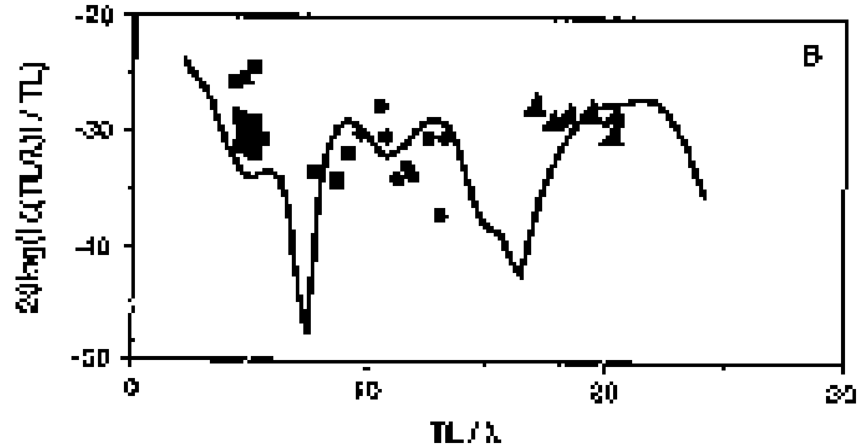


KRM Backscatter Ambit



Validation of Kirchhoff-Ray Mode Model



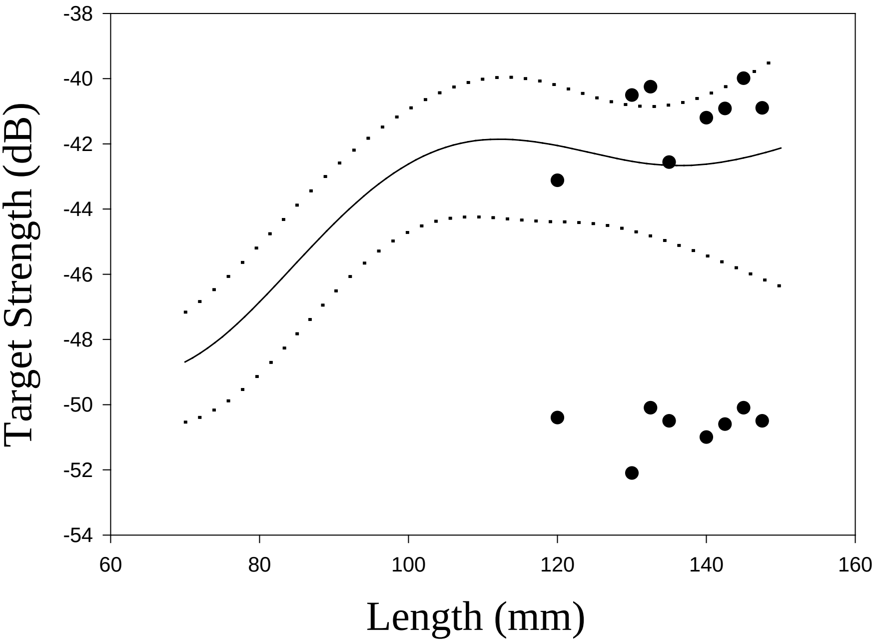


Comparison to Nakken and Olsen (1977) Atlantic cod (*Gadus morhua*) maximum target strength measurements at 38 kHz

Comparison to Jech et al. (1995) Threadfin shad (*Dorosoma petenense*) target strength measurements at 120, 200, and 420 kHz.

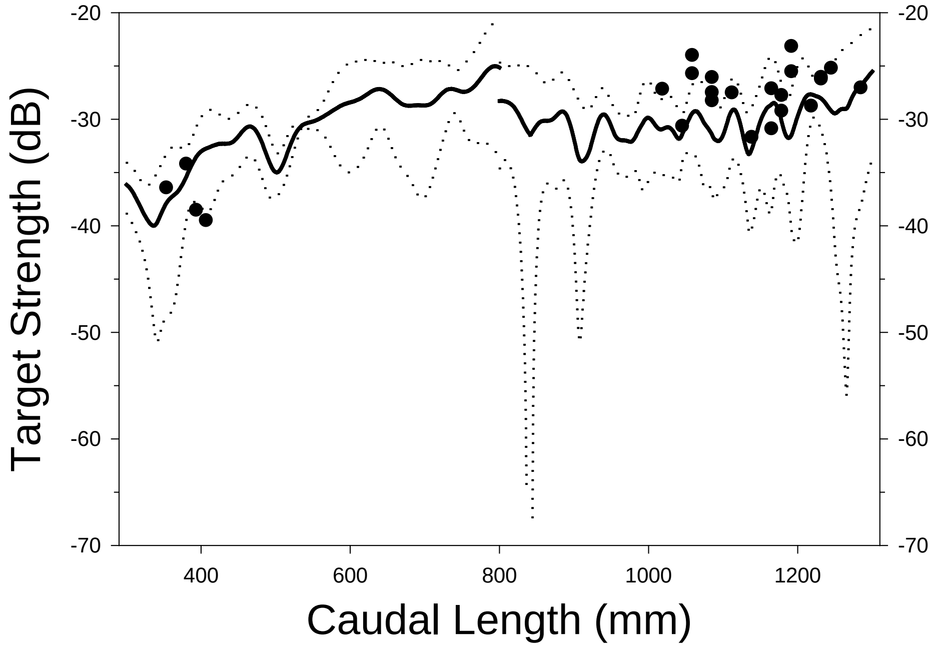
Comparing Models to Empirical Measures

Lavnun 120 kHz



Horne et al. 2000

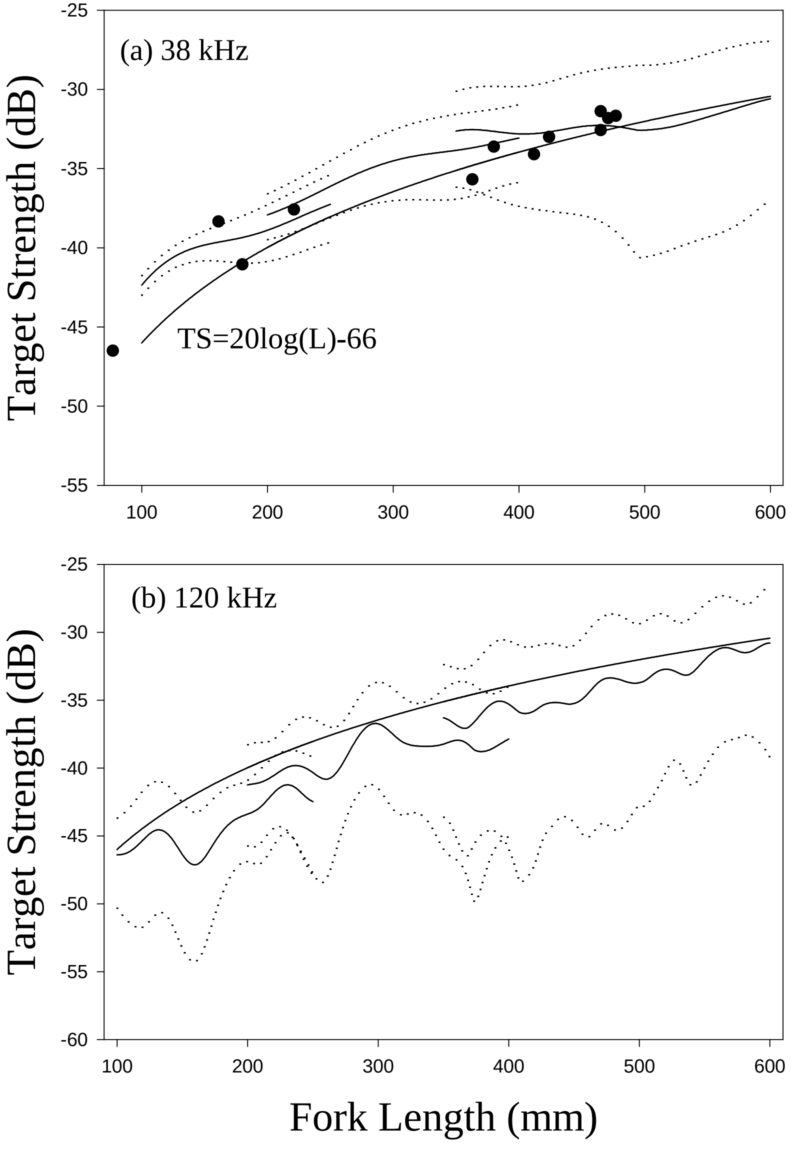
Paddlefish 200 kHz



Hale et al. 2003

Comparing Models to Empirical Measures

Walleye pollock

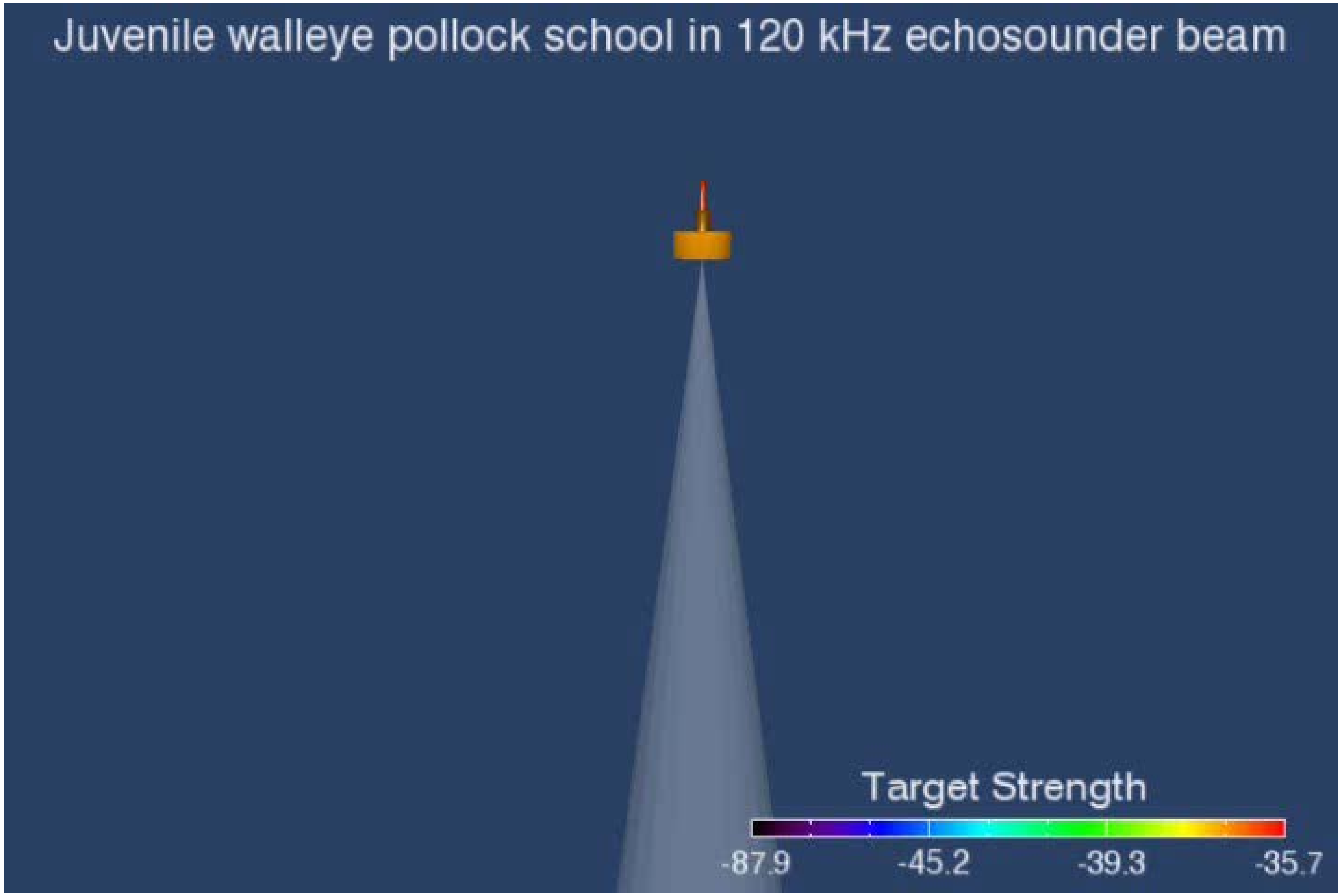


38 kHz

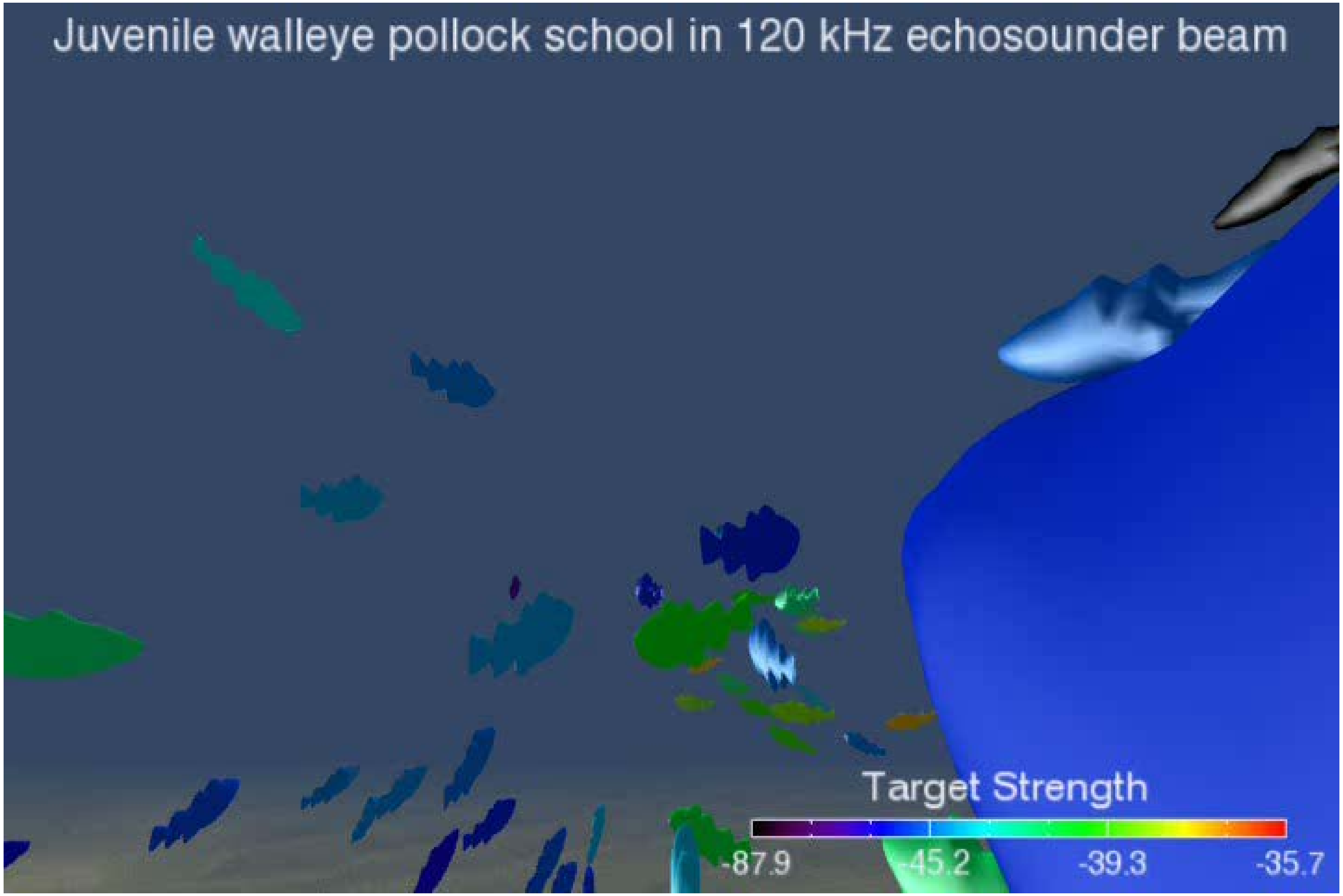
120 kHz

Horne 2003

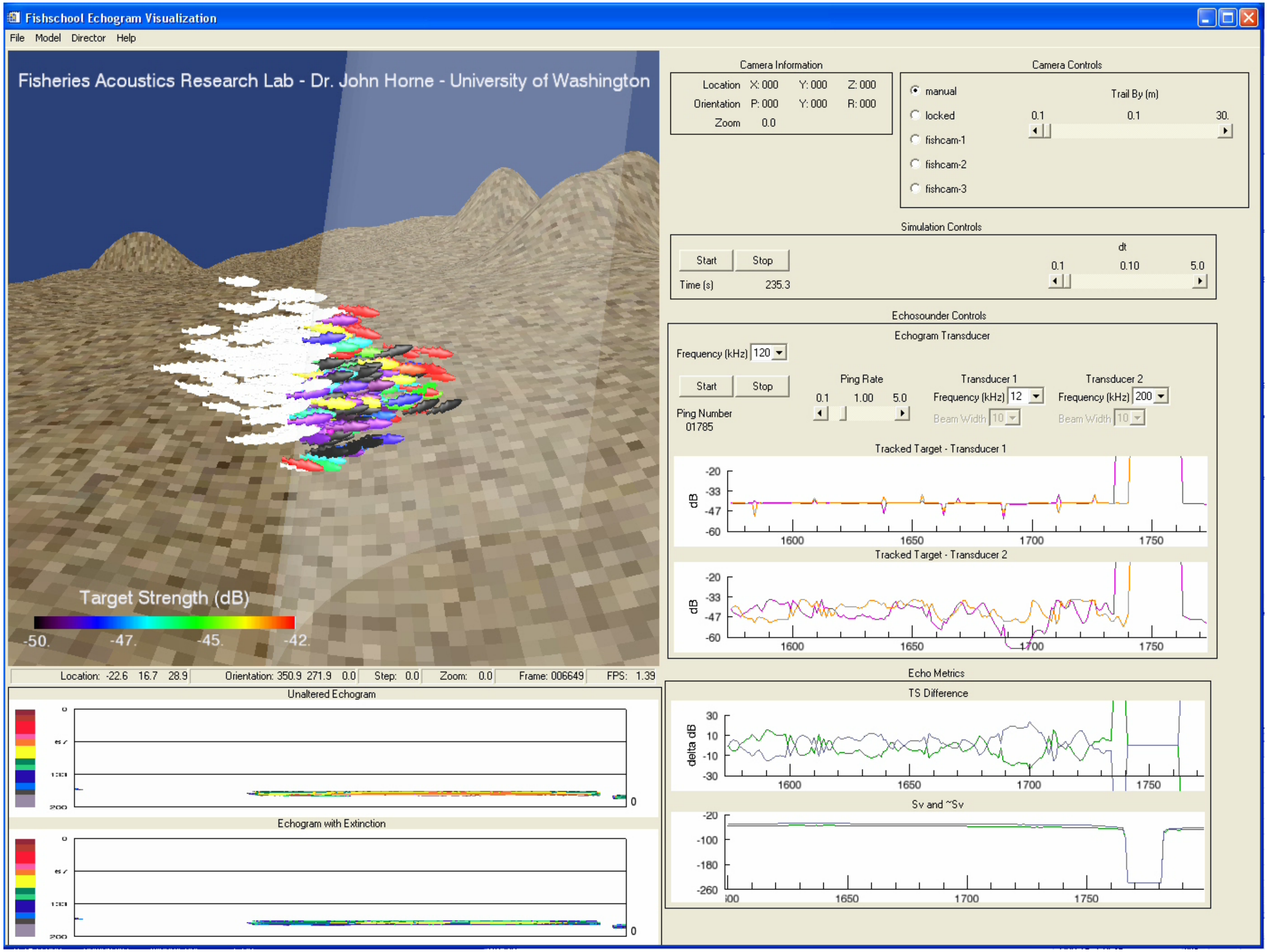
Fish Ensemble Visualization



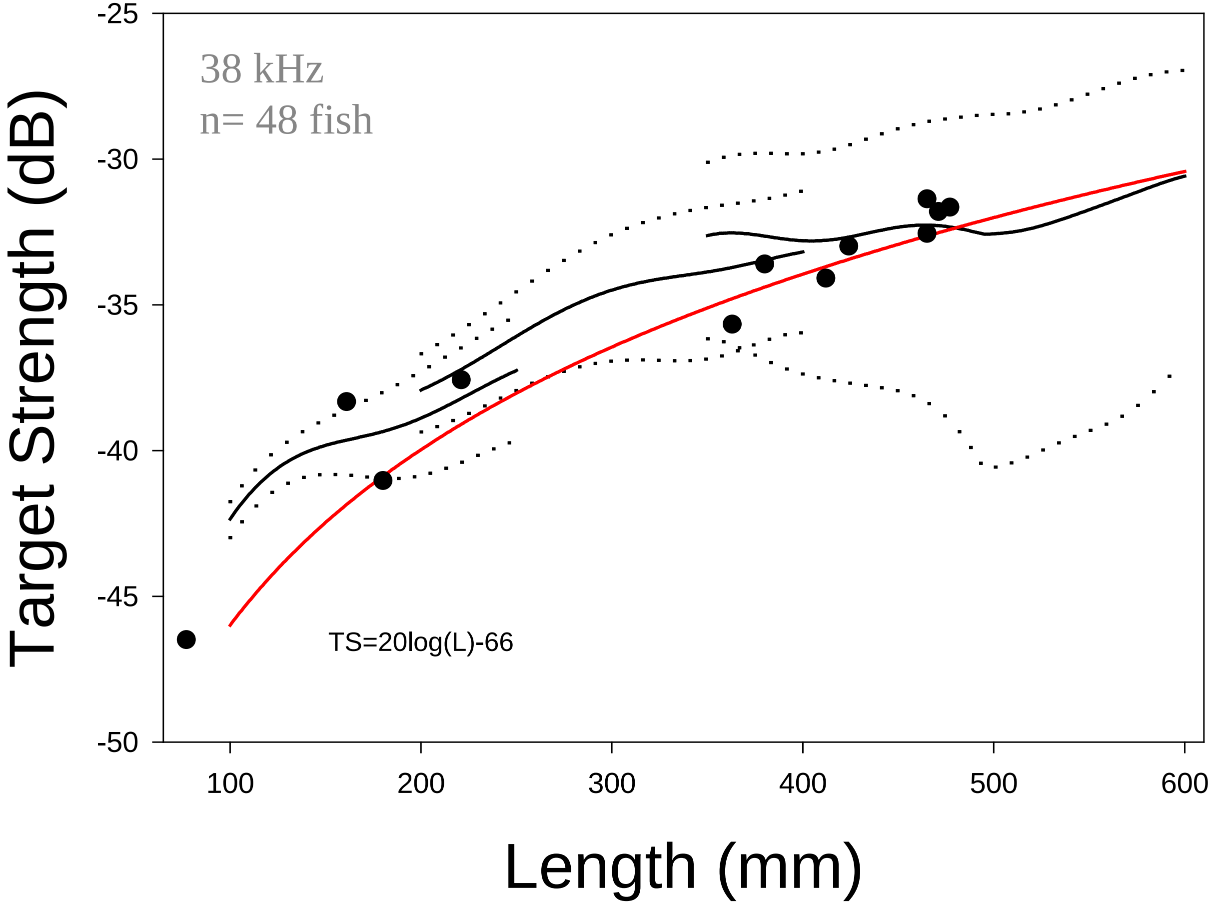
Fish-Cam Visualization



Acoustic Fish Behavior Simulator



Model Applications: TS - length



Horne 2003

Acoustic Backscatter Characterization

capelin

(*Mallotus villosus)*

Pacific herring

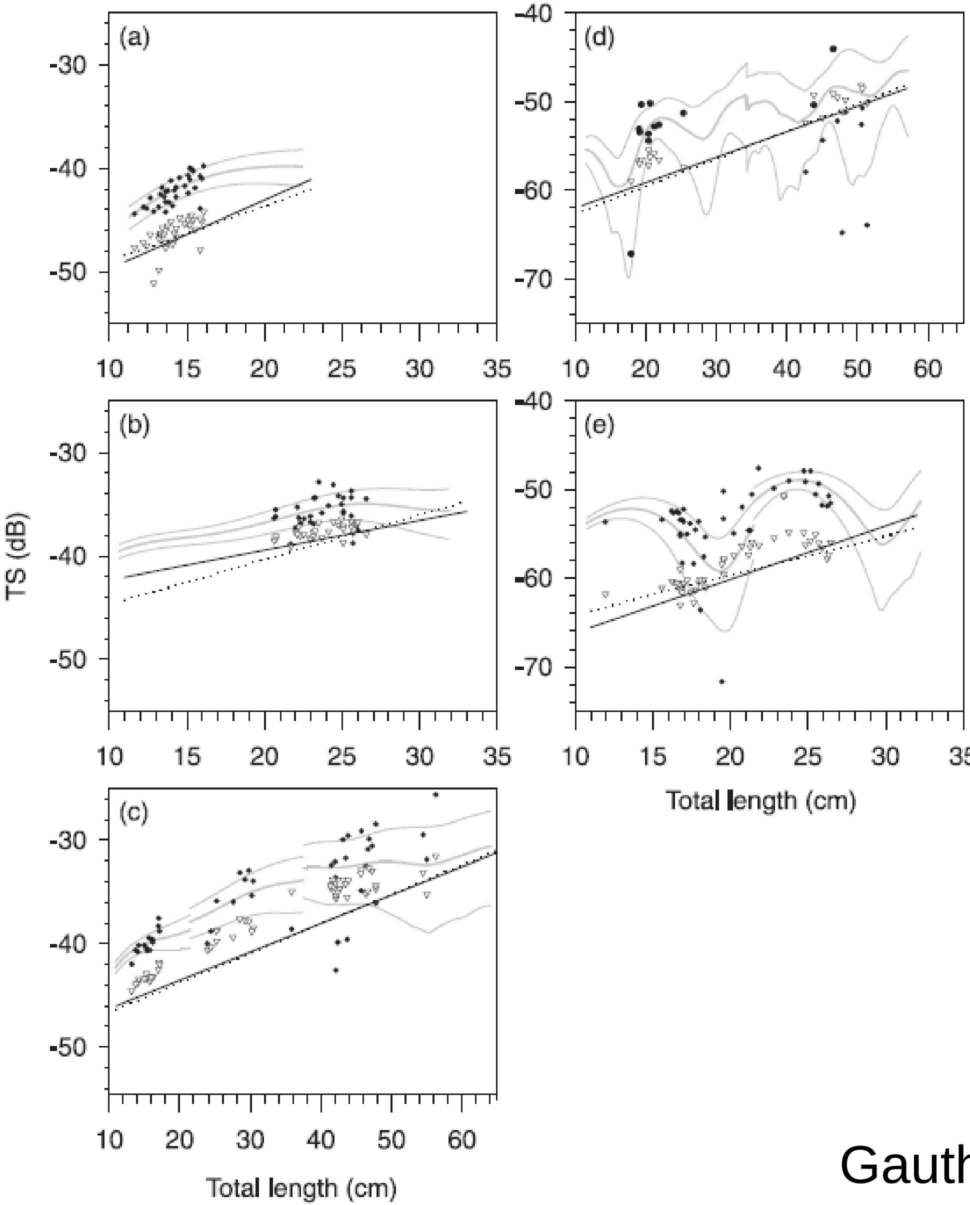
(*Clupea pallasii)*

walleye pollock (*Theragra chalcogramma*)

Atka mackerel (*Pleurogrammus monopterygius*)

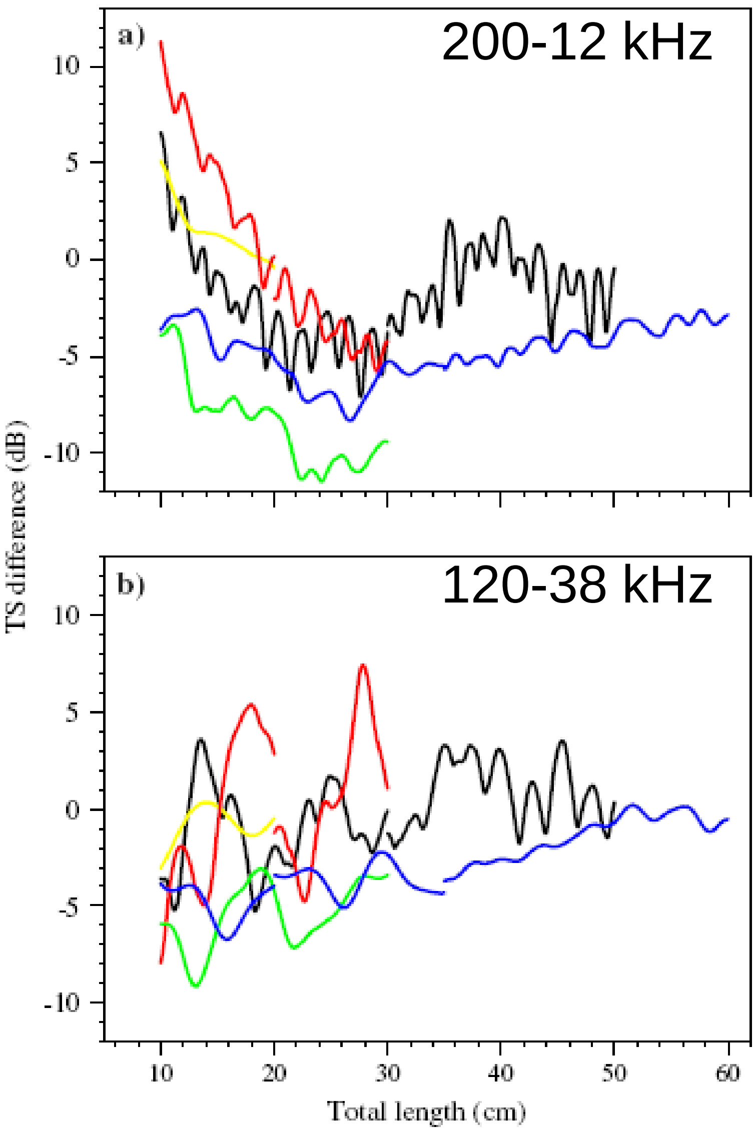
eulachon

(*Thaleichthys pacificus*)



Gauthier & Horne 2004a

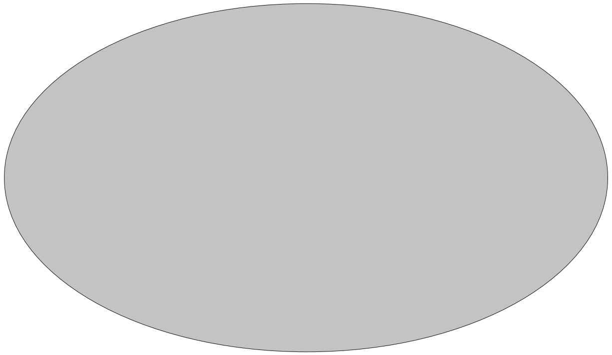
Acoustic Species Discrimination



capelin
Pacific herring
walleye pollock
Atka mackerel
eulachon

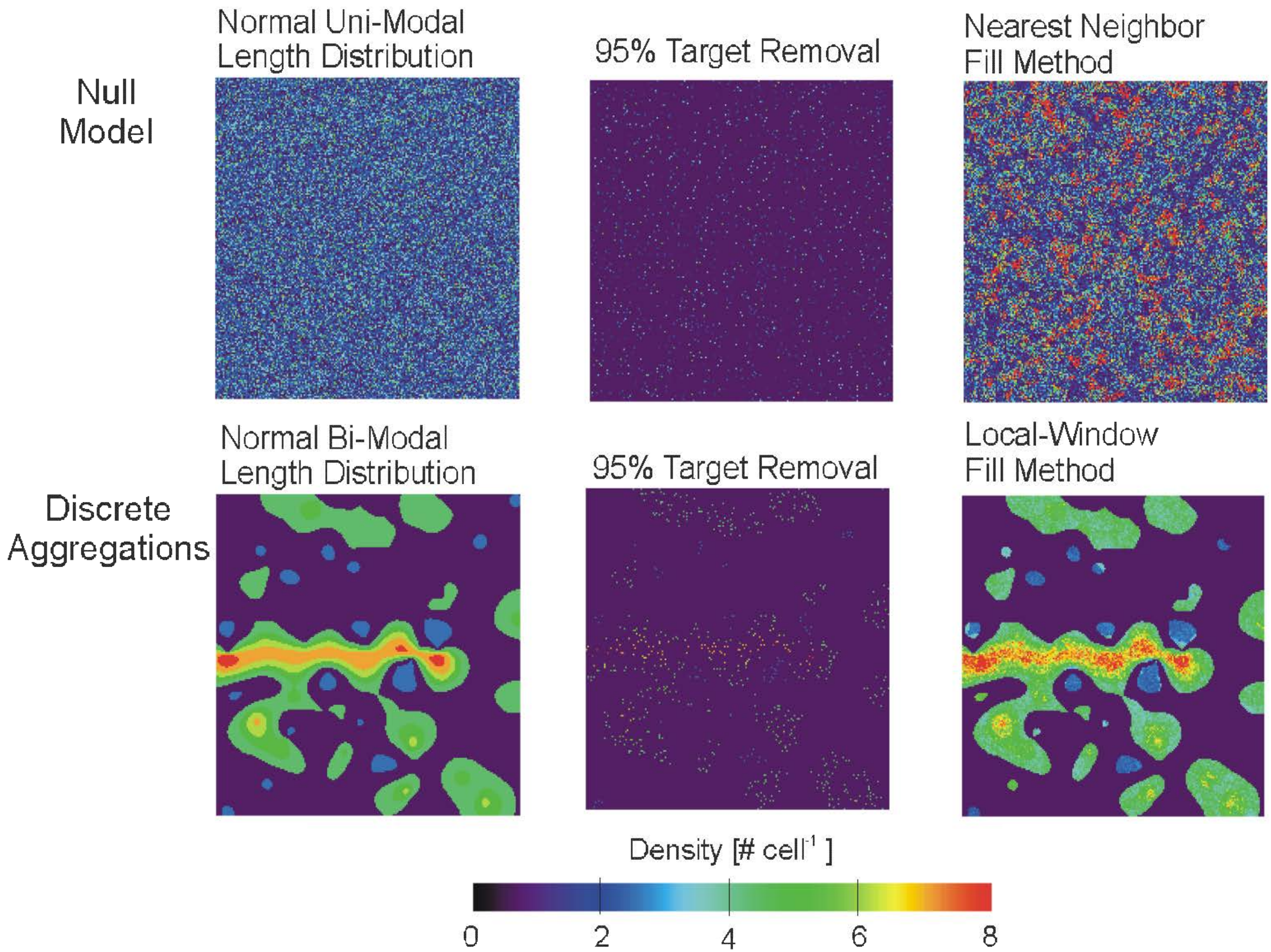
Gauthier & Horne 2004b

Aquatic Organism Distributions



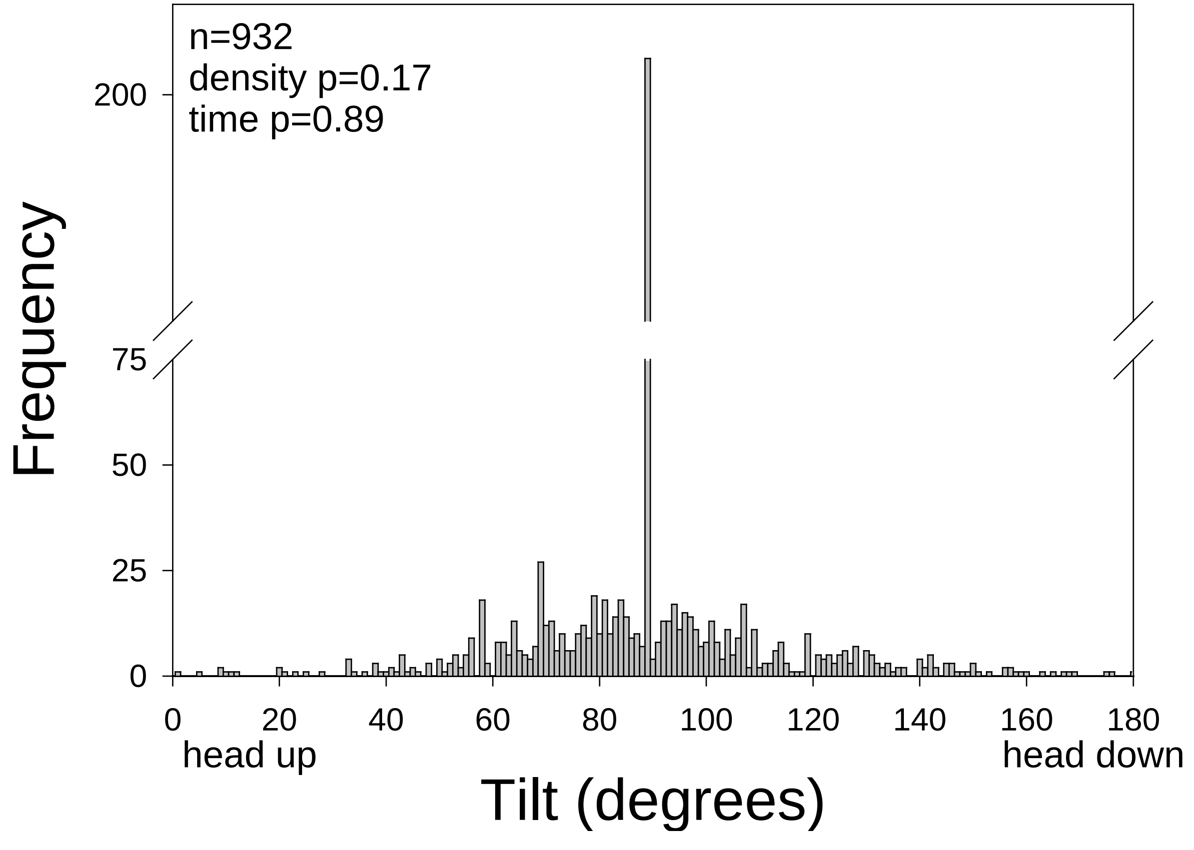
Aggregation types: individuals; small pure groups; mixed resolvable groups; unresolvable groups

Estimating Population Abundance



Jech & Horne 2001

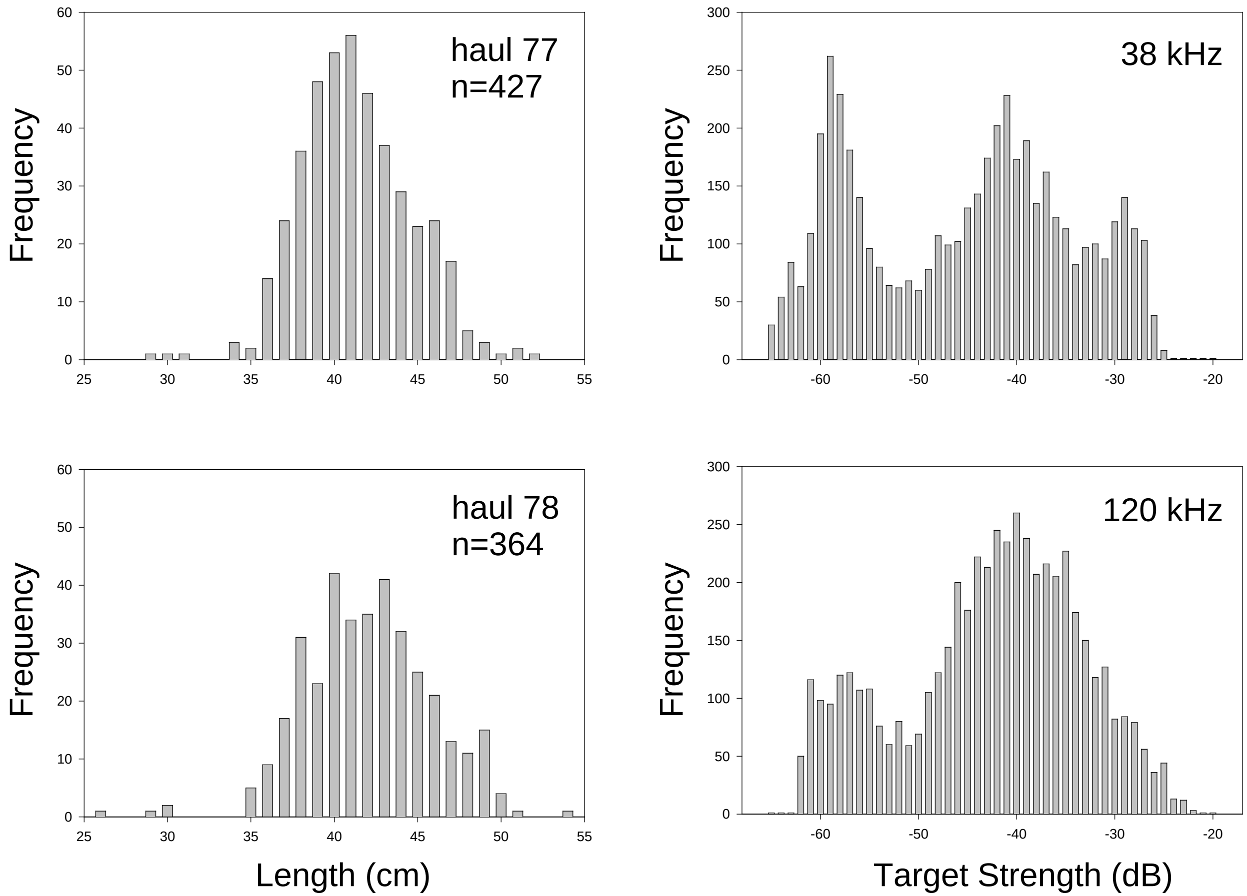
Walleye Pollock Tilt Distributions: 8 m^3 Laboratory Tank



W Pollock Length & Target Strengths

Bering Sea, July 2000

Walleye Pollock Lengths | Walleye Pollock Target Strength



Simulating TS Distributions

38 kHz 120 kHz

In situ

Length +

Tilt +

KRM