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
“... models based on simple geometric shapes, ... are inadequate, if only because such shapes are symmetrical with respect to the horizontal or transverse planes, while the general swimbladder is not.” (Poole 1985)

“...fish and zooplankton should be described by simple theories and models, without acoustically-superfluous extensions.” (Medwin and Clay 1998)
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
Boundary Element Method

Calculated using Helmholtz integral for amplitude and displacement from any point on discretized surface (where $l < 1/3\lambda$)

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

\[ k = \frac{\omega}{c \cos \theta} \]
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

\[ \downarrow k_i \]
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”)

\[ \phi = (0, 2\pi) \]
\[ \nu = (0, 2\pi) \]
\[ \theta, \omega = (0, \pi) \]
\[ f(u, w) \]
\[ g(u, w) \]
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, $c = 1491 \text{ m/s}$,
$
\tau = 0.32 \text{ ms}, f = 38 \text{ kHz}
$

G. Macaulay
## Summary Model Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Organism Representation</th>
<th>Analytic Method</th>
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<tbody>
<tr>
<td>BEM</td>
<td>Anatomical, triangular mesh</td>
<td>Hemholtz equation</td>
</tr>
<tr>
<td>Conformal Mapping</td>
<td>anatomical shape</td>
<td>Hemholtz equation</td>
</tr>
<tr>
<td>DWBA</td>
<td>deformed anatomical cylinders</td>
<td>line integral</td>
</tr>
<tr>
<td>KRM</td>
<td>anatomical cylinders</td>
<td>breathing mode + Kirchhoff</td>
</tr>
<tr>
<td>Finite Difference</td>
<td>actual shape, density</td>
<td>finite difference, time domain</td>
</tr>
</tbody>
</table>
Backscatter Model Comparisons

mapping, deformed cylinder, equicylinder

Blue Whiting (*Micromesistius australis*)

McClatchie et al. 1996
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

![Graph 38 kHz]

120 kHz

![Graph 120 kHz]

Foote and Francis 2002
Workshop: Herring Results

Length

Frequency

Fish Length [m]

Frequency [kHz]

TS [dB]

TS [dB]
Workshop: Herring Results

38 kHz

Dorsal-Ventral

38 kHz

Lateral
Comparing Models to Finite Solutions

Model Comparison to Prolate Spheroid

Model Comparison to Jack Mackerel Swimbladder

PSMS: Prolate Spheroid 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

Walleye Pollock 17 - 120 kHz

Orientation: Tilt: 0.0, Roll: 0.0
Frequency: 120 kHz

Echo Level: RSL: 0.0785545, TS: -30.28

Target Strength dB:
-66.2, -33.6, -27.6, -24.1
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

Paddlefish 200 kHz

Horne et al. 2000

Hale et al. 2003
Comparing Models to Empirical Measures

Walleye pollock

38 kHz

Horne 2003

120 kHz
Fish Ensemble Visualization

Juvenile walleye pollock school in 120 kHz echosounder beam
Fish-Cam Visualization

Juvenile walleye pollock school in 120 kHz echosounder beam
Acoustic Fish Behavior Simulator
Model Applications: TS - length

Target Strength (dB)

Length (mm)

38 kHz
n= 48 fish

TS = 20 \log(L) - 66

Horne 2003
Acoustic Backscatter Characterization

- eulachon (*Thaleichthys pacificus*)
- capelin (*Mallotus villosus*)
- Pacific herring (*Clupea pallasii*)
- walleye pollock (*Theragra chalcogramma*)
- Atka mackerel (*Pleurogrammus monopterygius*)
- eulachon (*Thaleichthys pacificus*)

Gauthier & Horne 2004a
Acoustic Species Discrimination

200-12 kHz

120-38 kHz

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

Null Model
- Normal Uni-Modal Length Distribution
- 95% Target Removal
- Nearest Neighbor Fill Method

Discrete Aggregations
- Normal Bi-Modal Length Distribution
- 95% Target Removal
- Local-Window Fill Method

Density [cell^{-1}]

Jech & Horne 2001
Walleye Pollock Tilt Distributions: 8 m³ Laboratory Tank

n=932
density p=0.17
time p=0.89
W Pollock Length & Target Strengths

Bering Sea, July 2000

Walleye Pollock Lengths

- **haul 77**
  - n=427

Walleye Pollock Target Strength

- **38 kHz**
- **120 kHz**

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<table>
<thead>
<tr>
<th>Length (cm)</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>25</td>
<td>0</td>
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<tr>
<td>30</td>
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<td>55</td>
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<table>
<thead>
<tr>
<th>Target Strength (dB)</th>
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<tr>
<td>-60</td>
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<td>50</td>
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<tr>
<td>-40</td>
<td>100</td>
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<tr>
<td>-30</td>
<td>150</td>
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<tr>
<td>-20</td>
<td>200</td>
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<tr>
<th>haul 78</th>
<th>n=364</th>
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Simulating TS Distributions

38 kHz  120 kHz

In situ

Length +

Tilt +

KRM