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Modeling of a non-physical fish barrier

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MODELING OF A NON-PHYSICAL FISH BARRIER

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Introduction

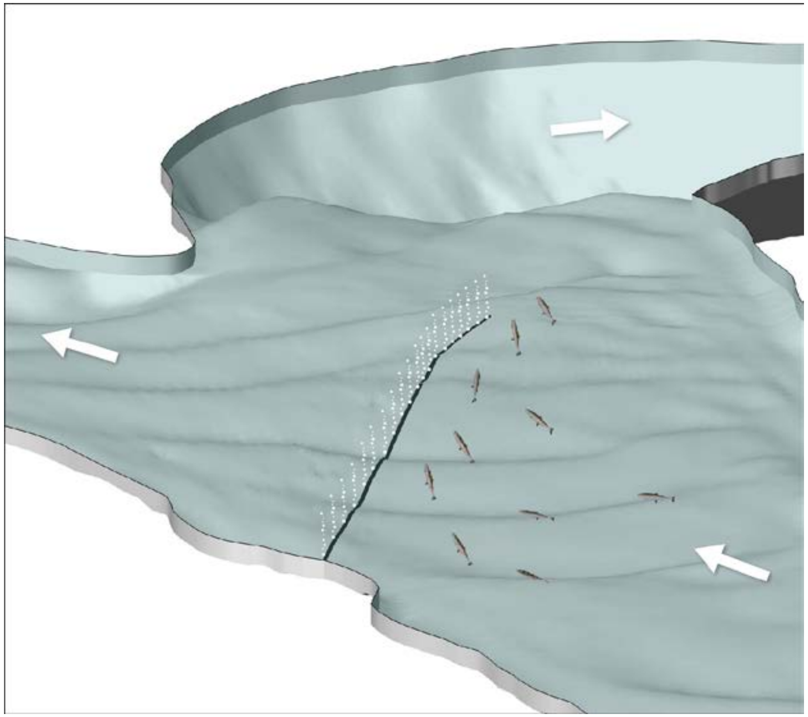
- The migration of salmonids in the San Joaquin and Sacramento Rivers is of great environmental interest. Several fish species are listed are threatened or endangered under the California Endangered Species Act.

- Juveniles encounter alternative pathways during migration to the Pacific Ocean. Passage through the interior Delta decreased the survival of juveniles. Fish diversion into the Delta may result in delayed migration, elevated risk of predation, exposure to poor water quality conditions, and mortality in pumping facilities.

Behavioral Bio-Acoustic Fish Fence

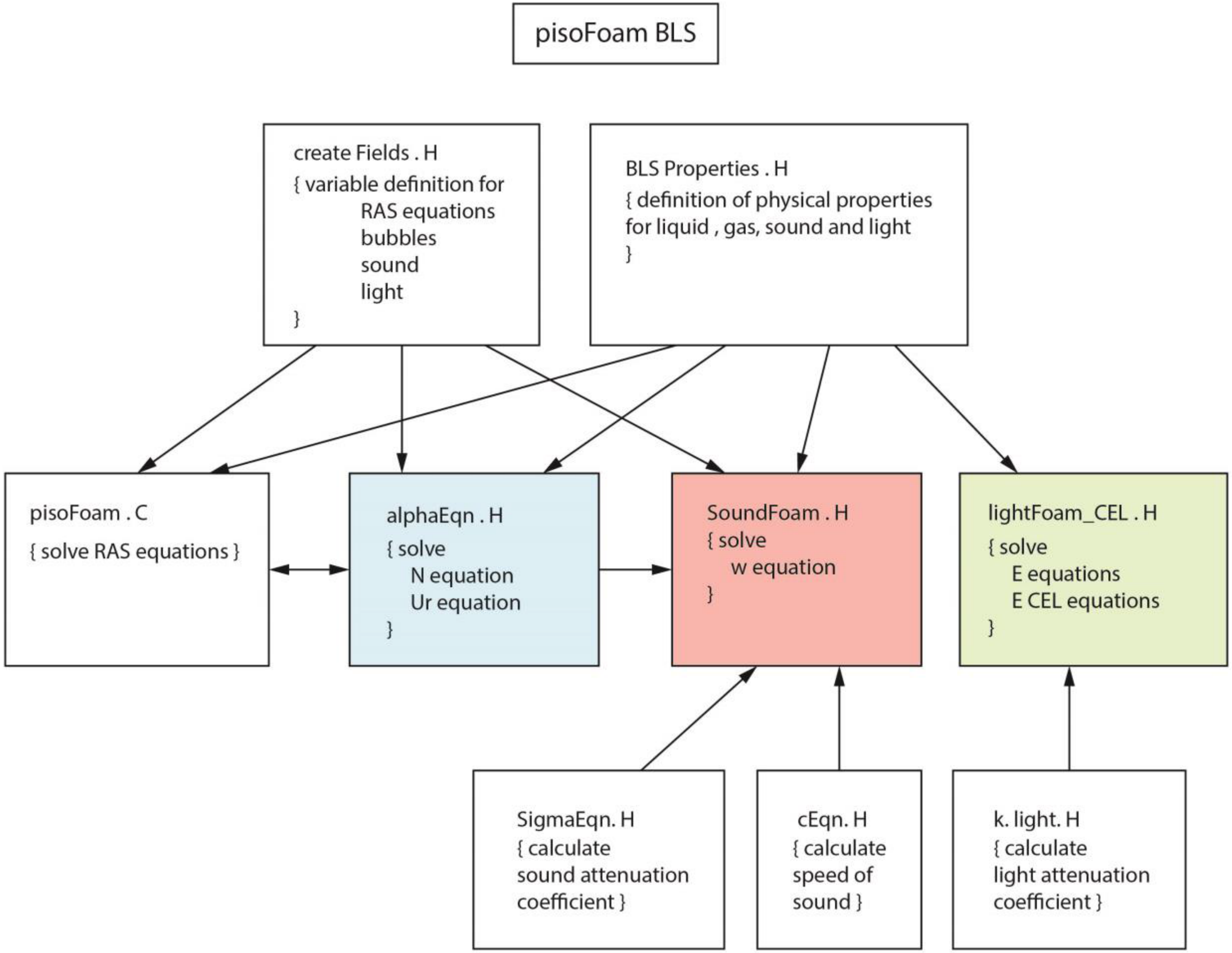
BAFF combines three stimuli to deter fish from entering an undesirable pathway without restricting flow:

- Bubble curtain
- Low-frequency sound
- LED modulated intensity lights

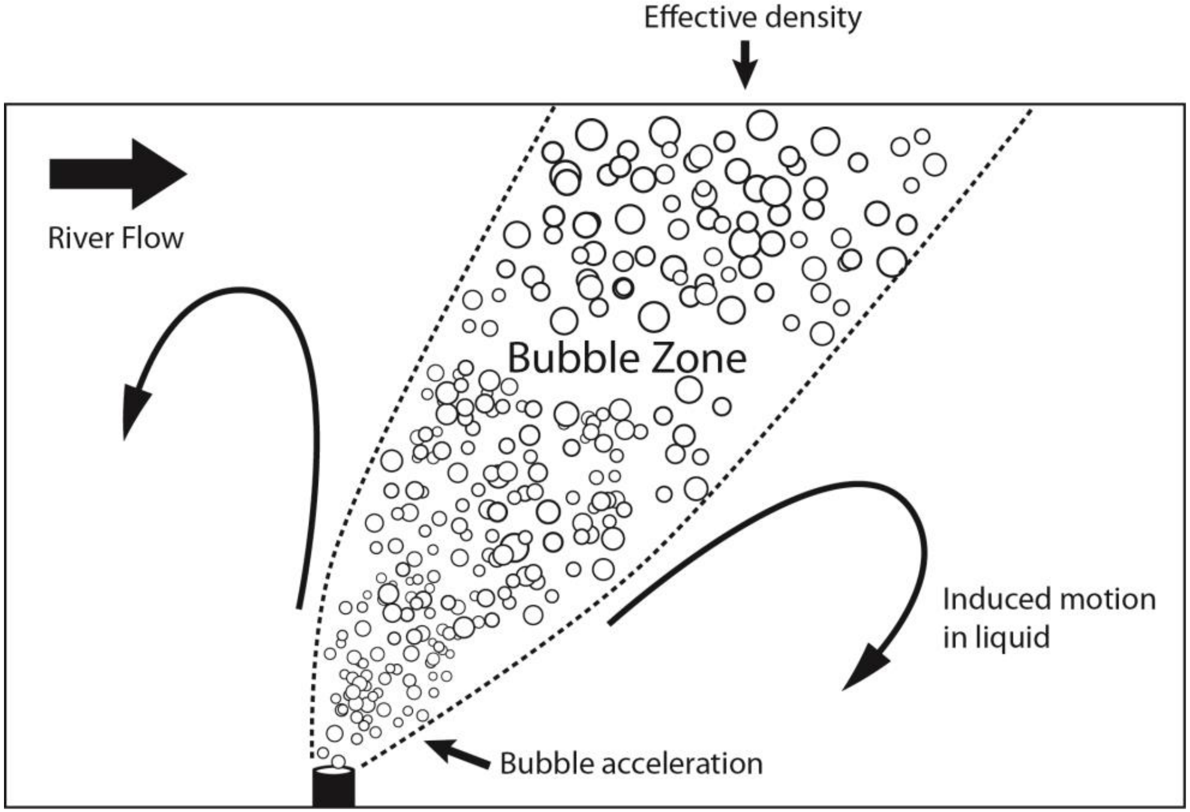


Objectives

- **Develop bubble, sound and light models**
- **Implement the models into a CFD code using a modular approach** → pisoFoamBLS
- **Validate the model against several well-known experiments**
- **Simulate a BAFF to predict bubble, sound and light fields and evaluate effects of the barrier on the river hydrodynamics**


pisoFoam BLS
create Fields . H
{ variable definition for
RAS equations
bubbles
sound
light
}
BLS Properties . H
{ definition of physical properties
for liquid , gas, sound and light
}
pisoFoam . C
{ solve RAS equations }
alphaEqn . H
{ solve
N equation
Ur equation
}
SoundFoam . H
{ solve
w equation
}
lightFoam_CEL . H
{ solve
E equations
E CEL equations
}
SigmaEqn. H
{ calculate
sound attenuation
coefficient }
cEqn. H
{ calculate
speed of
sound }
k. light. H
{ calculate
light attenuation
coefficient }

Bubble Module



Bubble Model

- Mixture model

$$\nabla \cdot \vec{u}_m = 0$$

$$\rho_l \frac{\partial}{\partial t} \vec{u}_m + \rho_l \nabla \cdot (\vec{u}_m \vec{u}_m) = -\nabla P + \nabla \cdot \left[\tau_m^{\mathrm{Re}} + \tau_m \right] + \rho_m \vec{g}$$

- Bubble number density

$$\frac{\partial N}{\partial t} + \nabla \cdot \left[\vec{u}_g N \right] = \frac{\nu^t}{Sc} \nabla^2 N$$

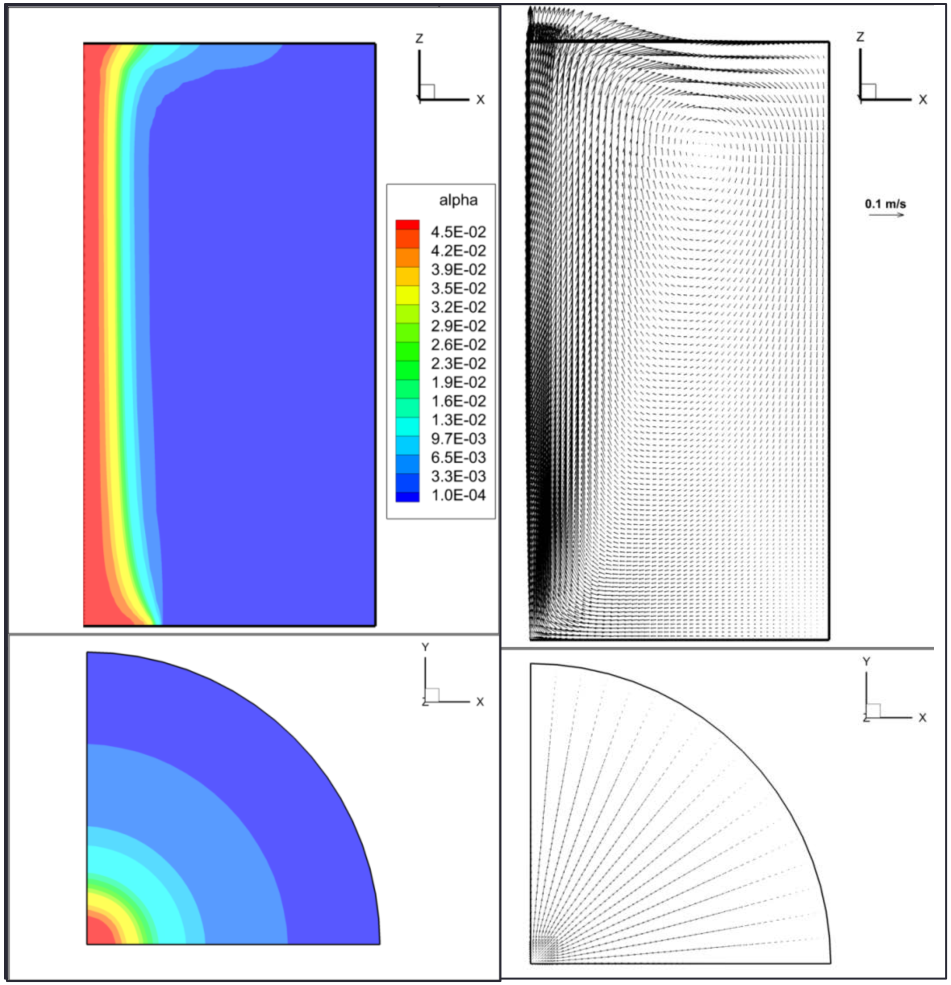
- Bubble velocity

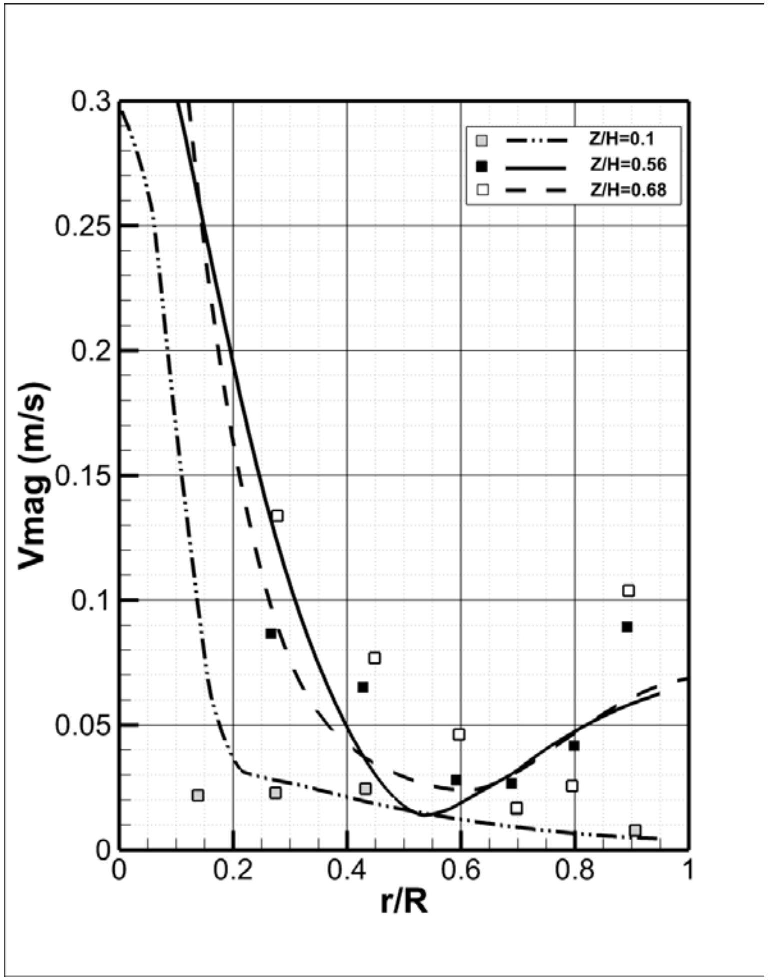
$$-\nabla \left(P + \frac{2}{3} k \right) + \frac{3}{8} \frac{C_g^D}{R} \vec{u}_r \left| \vec{u}_r \right| = 0$$

- Gas volume fraction

$$\alpha = N \frac{m_b}{\rho_b}$$

Bubble model predictions and experiments





Sound Model

- Classical formulation (Lighthill, 1978): wave equation based on compressible Navier-Stokes Equations:

$$\left(\frac{\partial^2}{\partial x_i^2} - c^{-2}\frac{\partial^2}{\partial t^2}\right)P = \frac{\partial q}{\partial t} - \frac{\partial f_i}{\partial x_i} + \frac{\partial T_{ij}}{\partial x_i \partial x_j} \sim c^{-2}\frac{\partial^2 P_h}{\partial t^2}$$

- Alternative formulation: energy formulation based on the acoustic energy *W*, the acoustic energy flux *I* and dissipation *D*

$$\frac{\partial W}{\partial t} = -\nabla \cdot \boldsymbol{I} - D$$

- The following relations are proposed to obtain an equation in *W*:

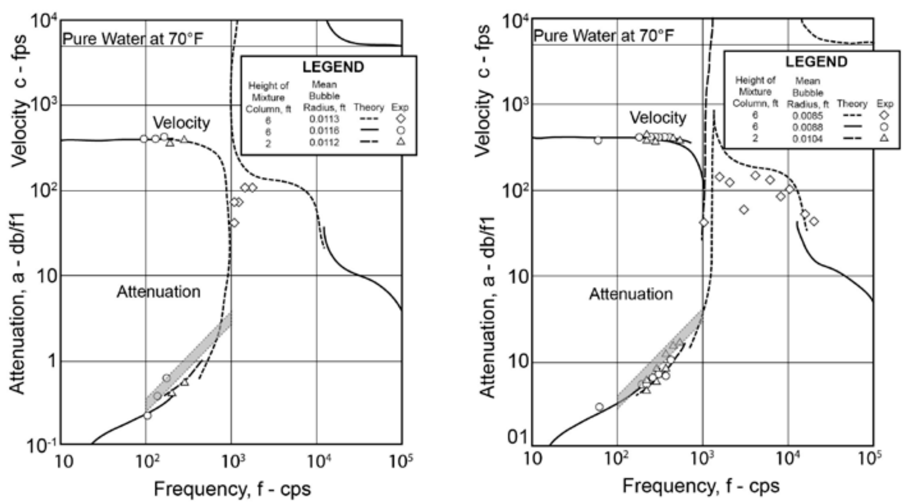
$$\boldsymbol{I} = -\boldsymbol{D_W} \cdot \nabla W; \quad D = \sigma_W W$$

Sound Model – Diffusion and attenuation coefficients

- Diffusion coefficient based on architectural models (Picaut et al. 1999):
  - Anisotropy related to length-scale of domain, an diffusion proportional to sound speed, with proportionality constant dependent on boundary reflectivity.

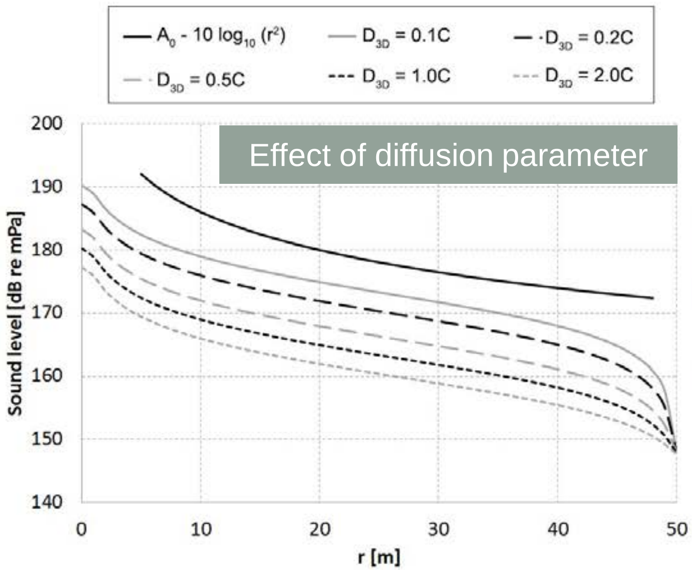
$$\boldsymbol{D_W} = \begin{vmatrix} D_{xx} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & D_{yy} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & D_{zz} \end{vmatrix} \qquad \frac{D_{xx}}{\ell_x} = \frac{D_{yy}}{\ell_y} = \frac{D_{zz}}{\ell_z} = D_{3D} \sim c$$

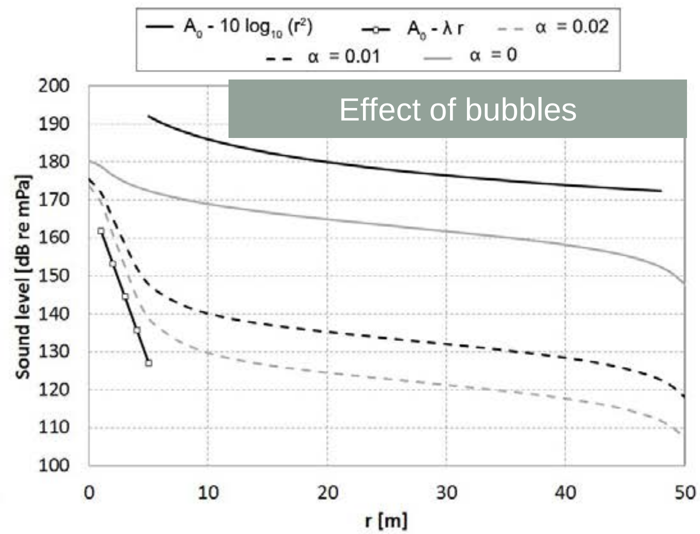
- Attenuation coefficient simplified model based on emission frequency, sound speed and void fraction $\sigma_W = 0.0124\, f_{src} c\alpha$ (MKS, isothermal)

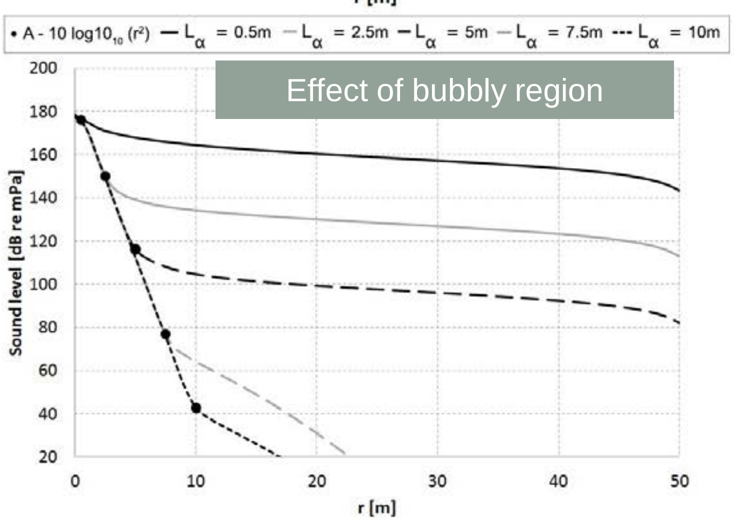


Validation of Sound Model Implementation

- A cube with 100 m on the side was simulated. A one m^3 sound source at the cube center and variable distribution of gas volume fraction were included.
- Isotropic diffusion tensor and length scale as the source dimension were used.



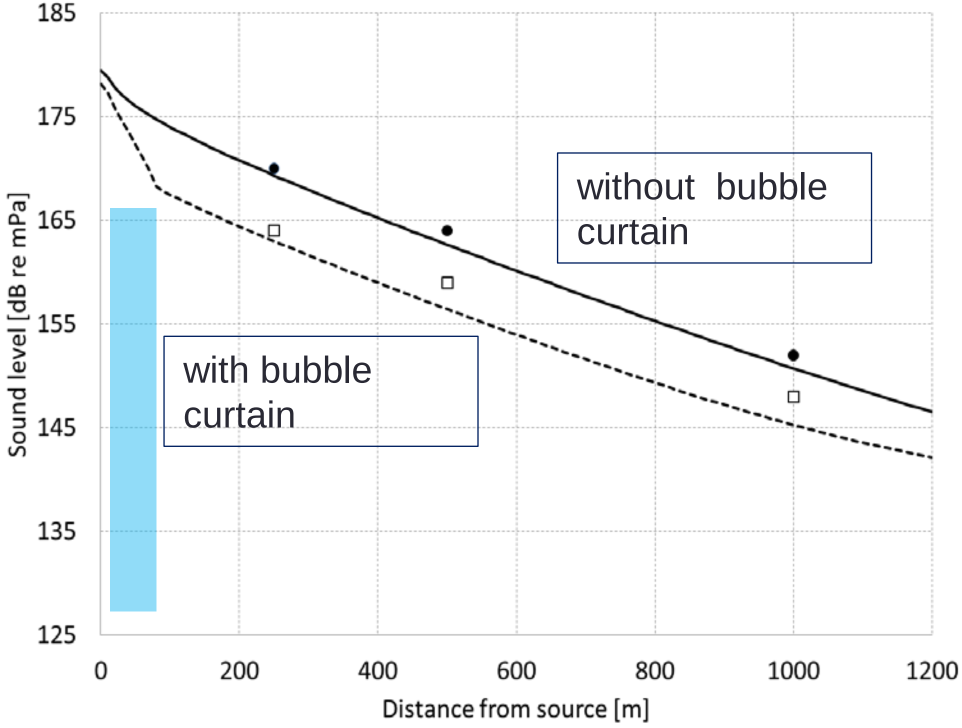




Sound level with a sound source at the origin

Sound Model - Validation

- Experiments of Wusig et al. (2000): sound from a pile driving hammer in shallow water, with and without bubble curtain



Light Model

- Classical model : Radiative Transfer Equation
  - Integro-differential equation, on position $\boldsymbol{x}$ and direction $\boldsymbol{\Omega}$ is too expensive to solve numerically for the present application

$$\Omega\nabla L(\boldsymbol{x},\theta,\varphi,\lambda) = -c_{\mathrm{E}}(\boldsymbol{x},\lambda)L(\boldsymbol{x},\theta,\varphi,\lambda) + \int_{4\pi} L(\boldsymbol{x},\theta',\varphi',\lambda)\beta_s(\boldsymbol{x},\theta',\varphi',\theta,\varphi,\lambda)d\Omega' + s_{\mathrm{E}}(\boldsymbol{x},\theta,\varphi,\lambda)$$

variation of spectral radiance *L*	absorption (a_{E}) and scattering out (b_{E}) of beam	scattering into beam	external source

- Alternatives models
  - P-N models
    - Approximate direction dependence using orthogonal series of spherical harmonics
    - Valid for high attenuation/scattering conditions
  - Superposition of elementary solutions (planar, linear and point sources)
    - Valid for low scattering conditions

Light Model - P-1 model

- Simplest of P-N models.
  - Radiance approximately by

    $L(\boldsymbol{x},\varphi,\theta) \sim \frac{1}{4\pi}\left(L^{(0)} + 3\left(L^{(1)}\cos\varphi + L^{(2)}\sin\varphi\cos\theta + L^{(3)}\sin\varphi\sin\theta\right)\right),$

    $L^{(0)} = E,$ the scalar irradiance

- Effectively results on diffusive-like equation for irradiance E,

$$-\sum_{i=1}^{3}\frac{\partial}{\partial x_i}\frac{1}{3(a_{\mathrm{E}}+b_{\mathrm{E}})}\frac{\partial E}{\partial x_i} = 4\pi s_{\mathrm{E}} - a_{\mathrm{E}}E$$

- Valid for “thick” optical media, $(a_{\mathrm{E}}+b_{\mathrm{E}})\,\ell \gg 1$, with ℓ a characteristic length-scale

Light Model: Superposition of elementary solutions

- Elementary solutions
  - Planar source: $E(z) = E_0 \exp(-Kz)$
  - Point source: $E(r) = \frac{r_0^2}{r^2} E_0 \exp(-Kr)$
- Elementary solutions can be represented numerically by solving $\nabla \cdot (\mathbf{u}_{\mathrm{E}} E) = S_{\mathrm{E}} - KE$, with imposed ‘advective’ $\mathbf{u}_{\mathrm{E}}$.
- Scattering by media cannot be modeled, only attenuation, valid for ‘thin’ optical media
- Reflections from boundaries can be included if the reflection direction distribution is imposed and discretized
- Examples of possible boundary conditions are
  - specular reflection
  - Lambertian cosine law (diffuse reflection)
  - Partial transmission

Light Model: Scattering and attenuation coefficients

- For modeling purposes it was assumed that all attenuation was caused by the water and dissolved solids and all scattering by the bubbles

  - Attenuation coefficient $K_D = K_{w+DOC} + K_c\, C_c + K_s\, C_{TSS}$

  - Scattering coefficient
    - Non-interacting (dilute) scatterers : $c_{\text{dilute}} = \frac{3}{4}\frac{\alpha}{R}$
    - Interacting scatterers (VF > 8%): $c_{\text{E}} = \gamma c_{\text{dilute}}, \gamma = 1 + \frac{3}{2}\alpha - \frac{3}{4}\alpha^2$

Validation of Light Model Implementation – Closed Cavity

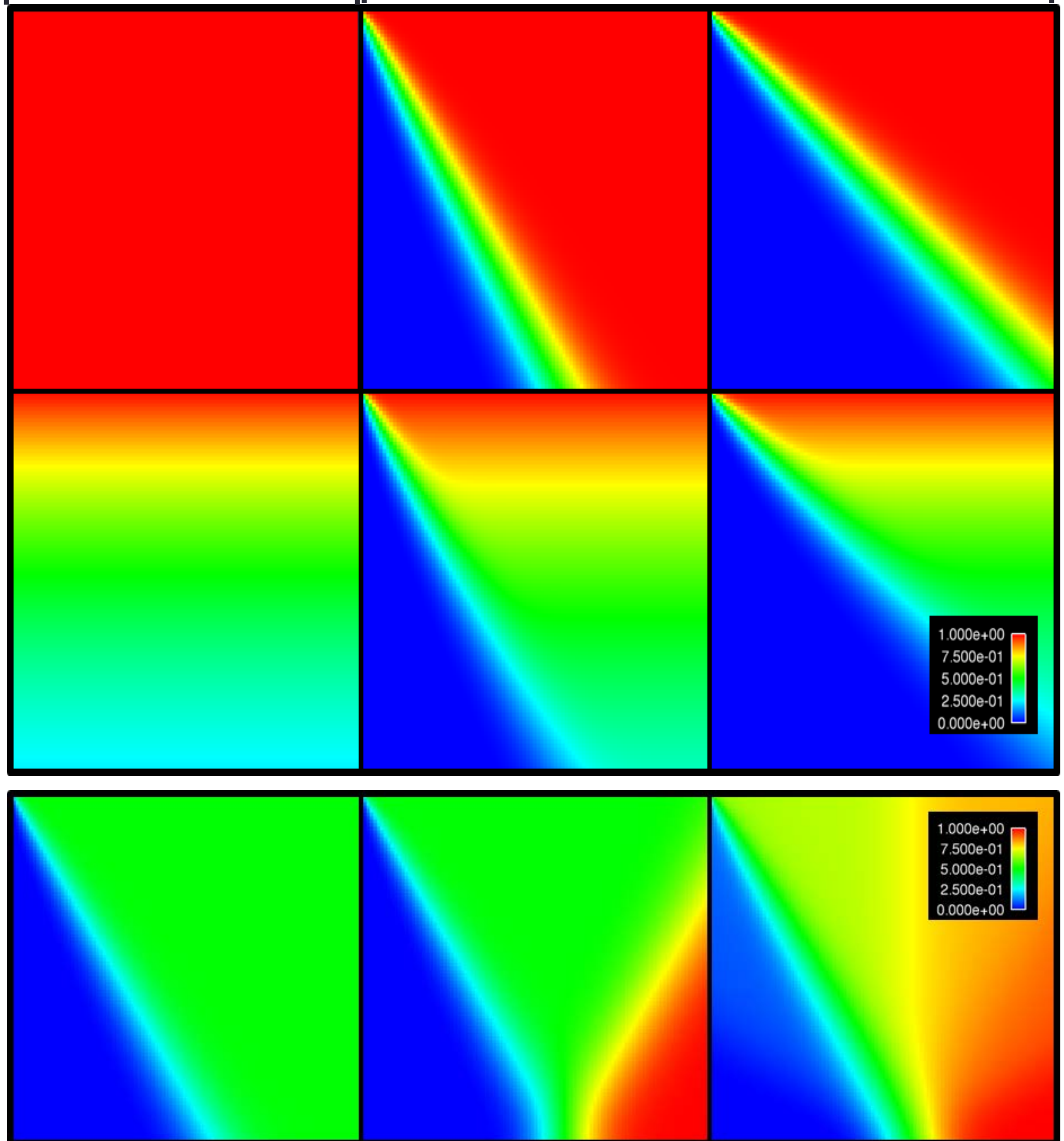
Normal sunlight

Sunlight with a zenith angle

No reflection
No attenuation

Attenuation of
radiation by
medium

Reflection

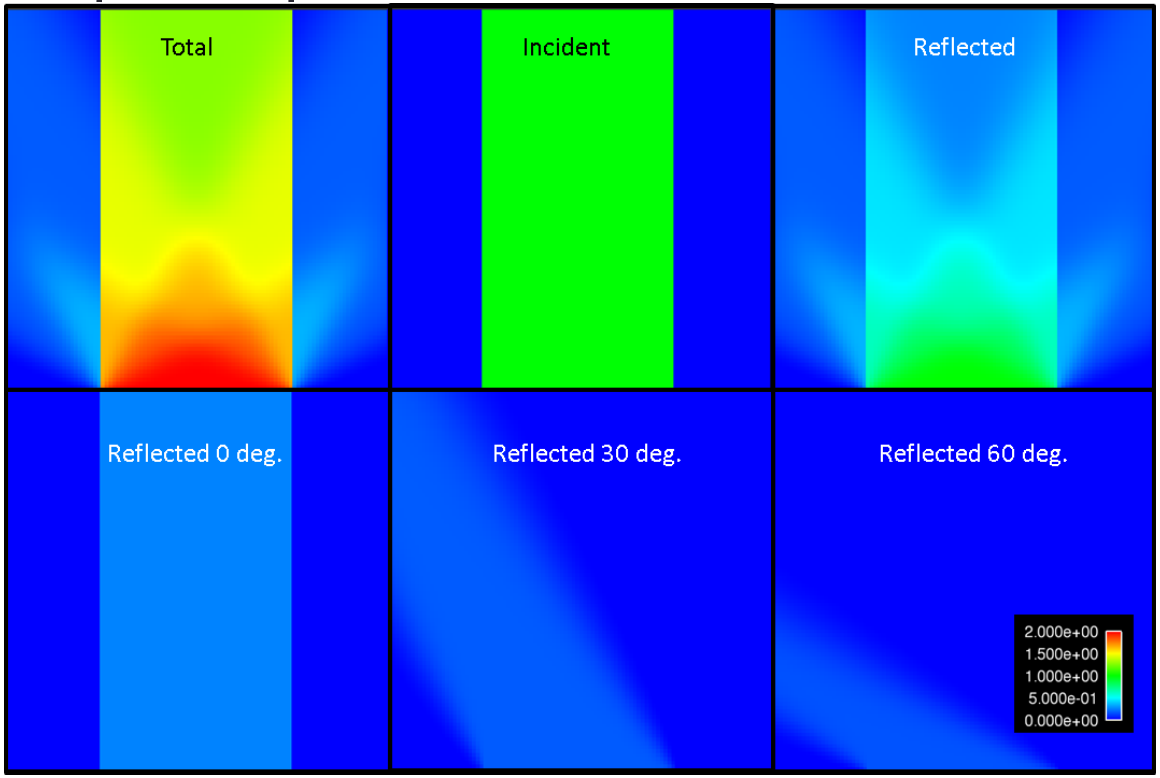


Dimensionless
Irradiance

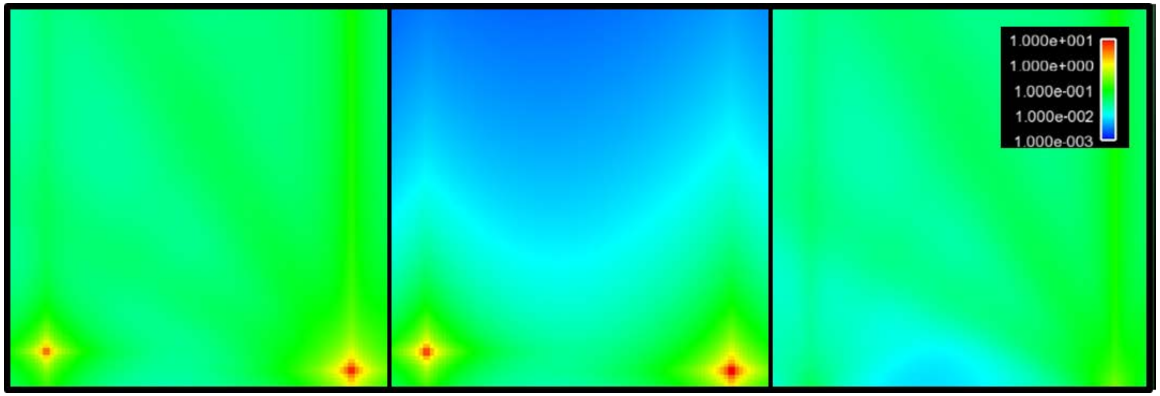
Validation of Light Model Implementation – Closed Cavity

Normal sunlight

No attenuation

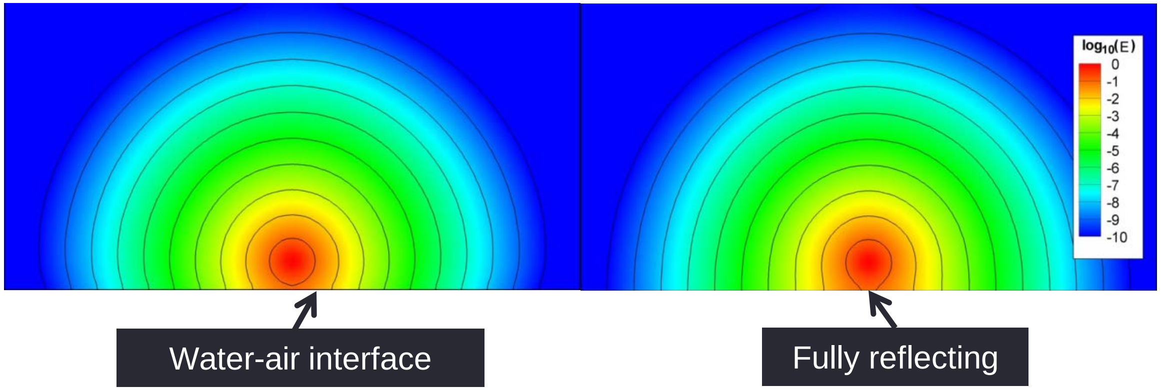


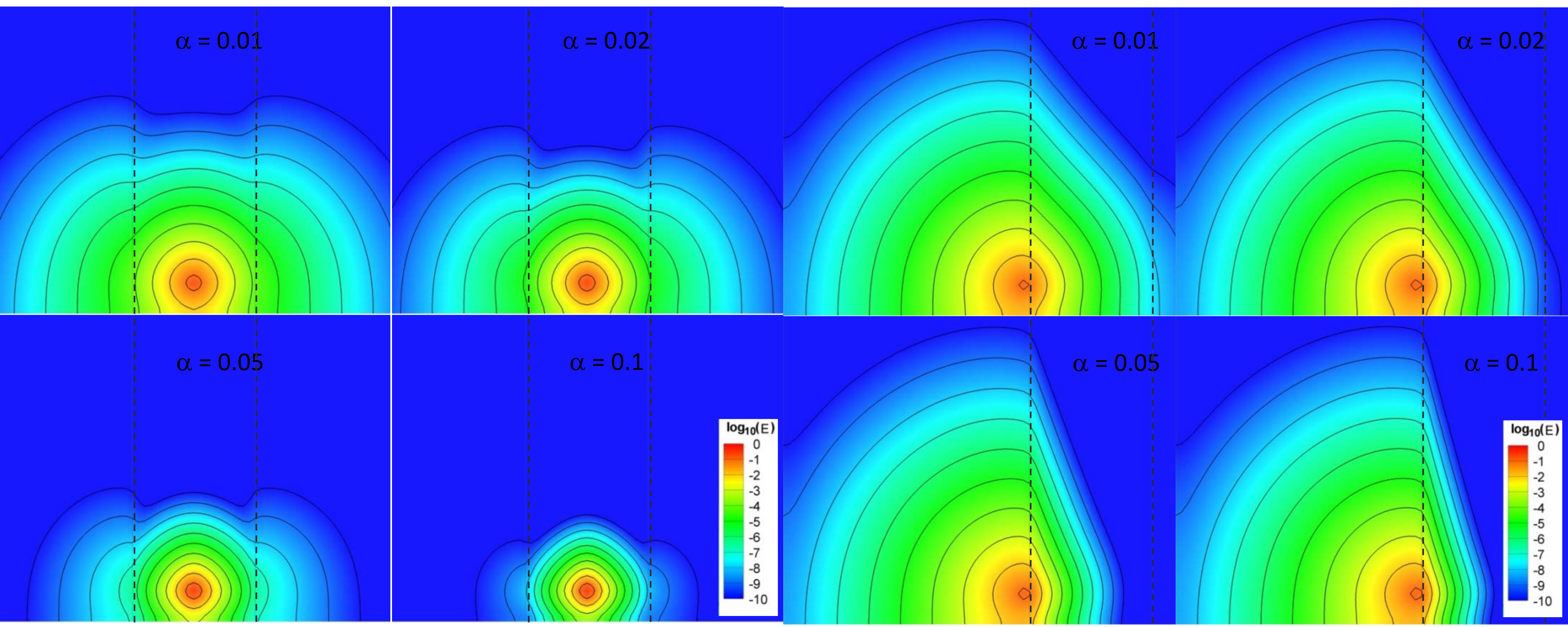
Point sources



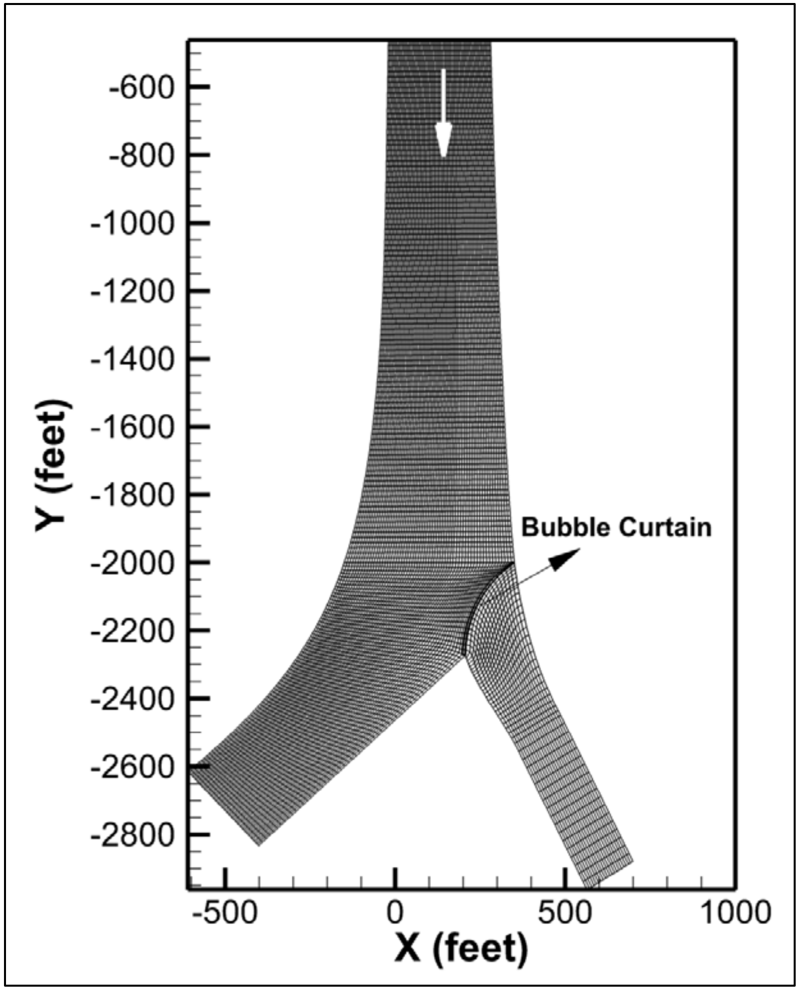
Dimensionless Irradiance

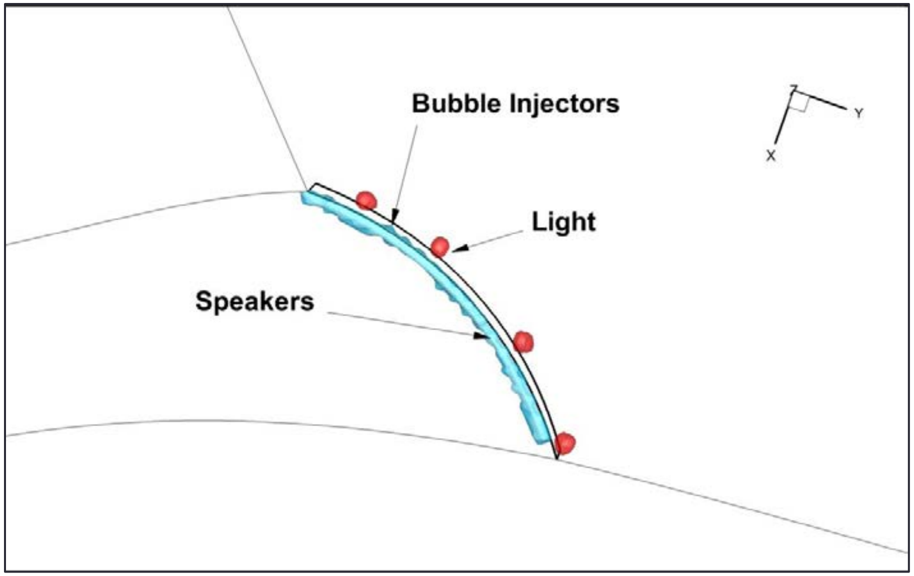
Validation of Light Model Implementation – Contours of Irradiance with P1 Model



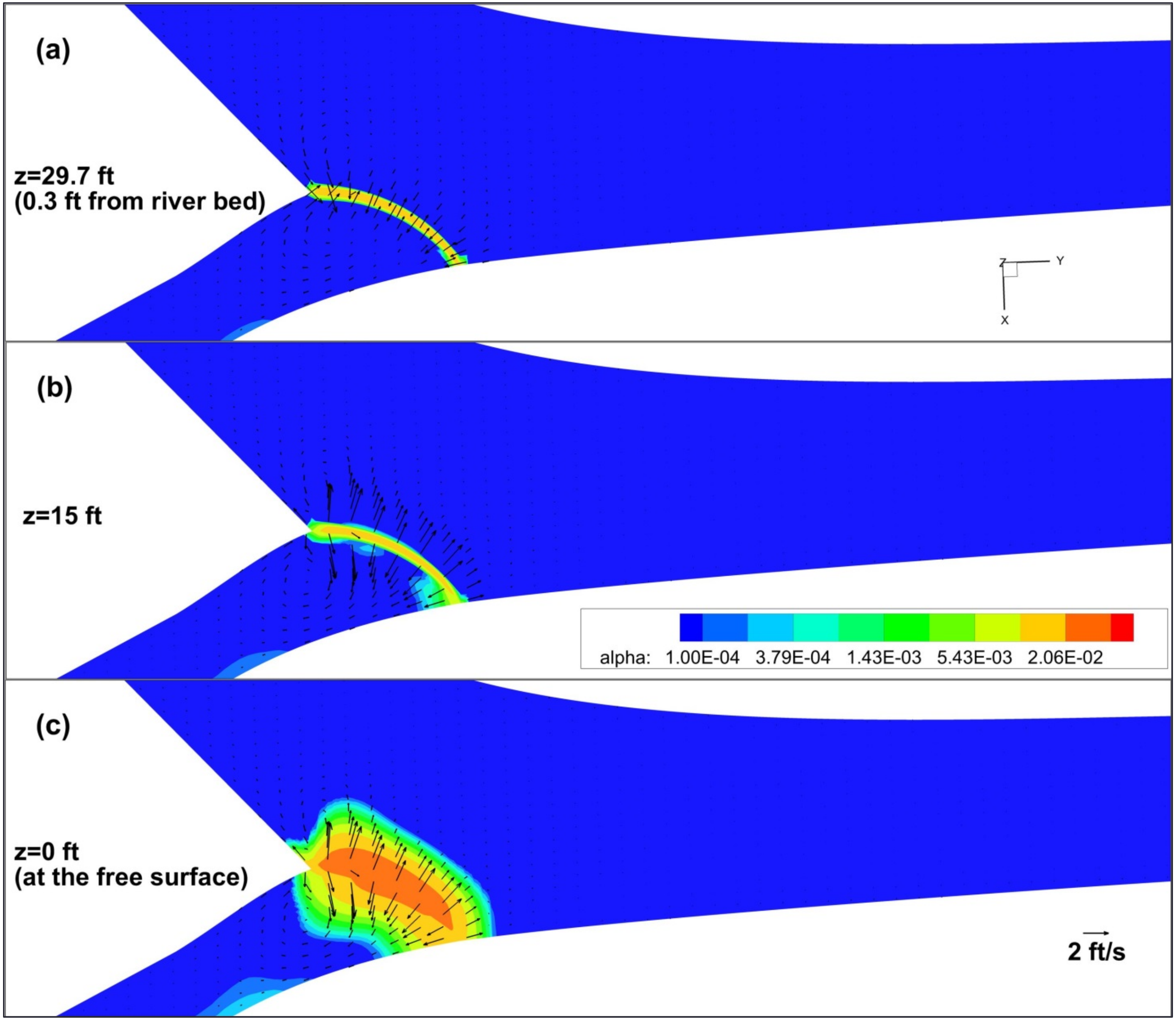


Simulation of a BAFF

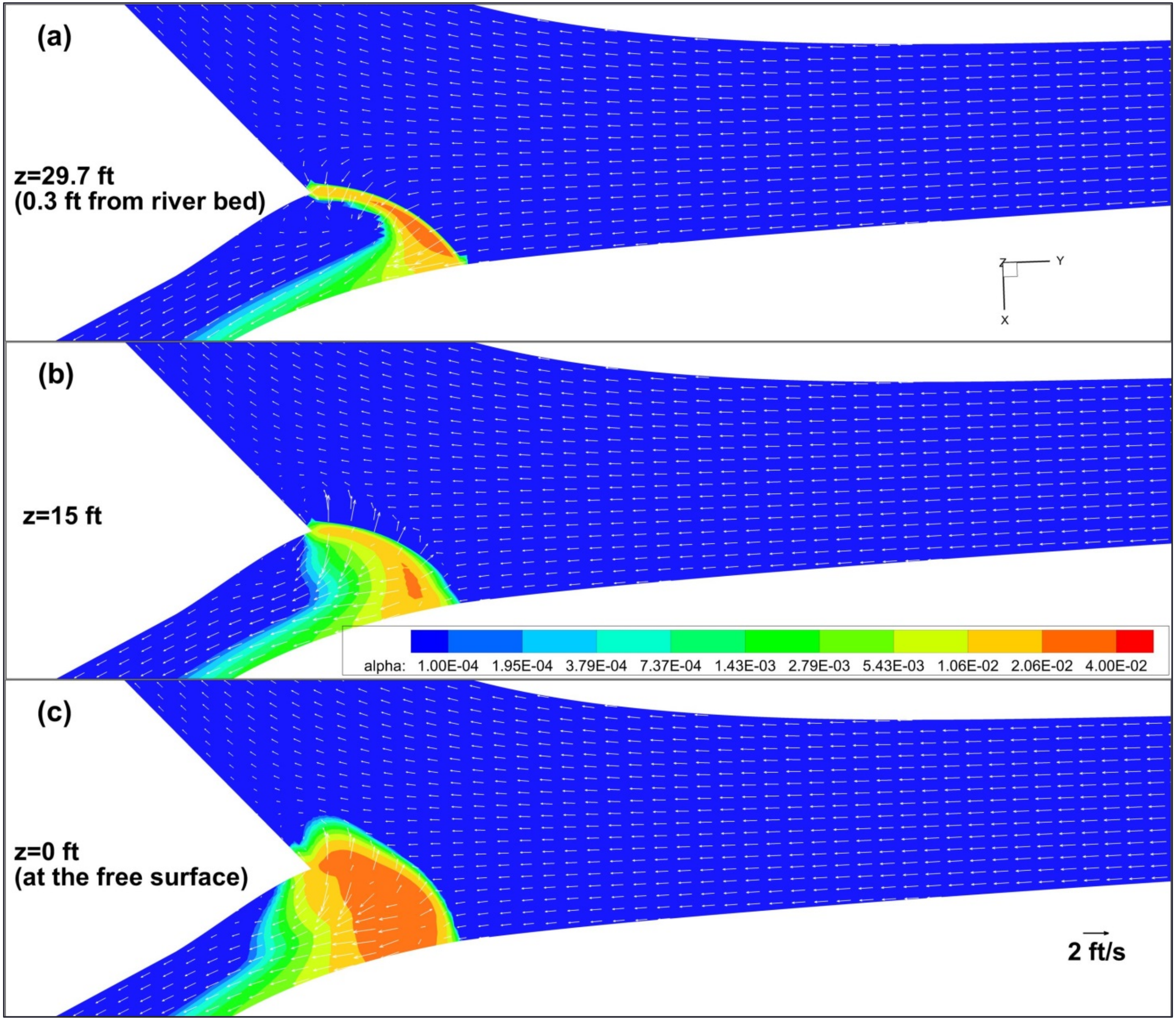




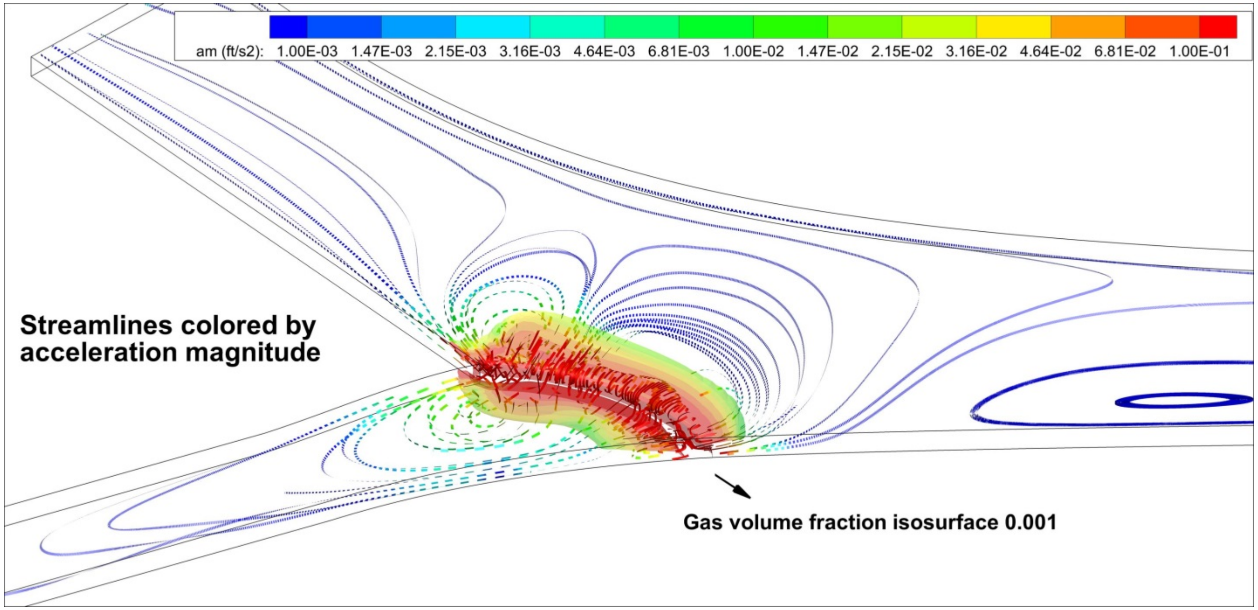
Fish Barrier in a Quiescent Medium – Bubble distribution and velocity vectors



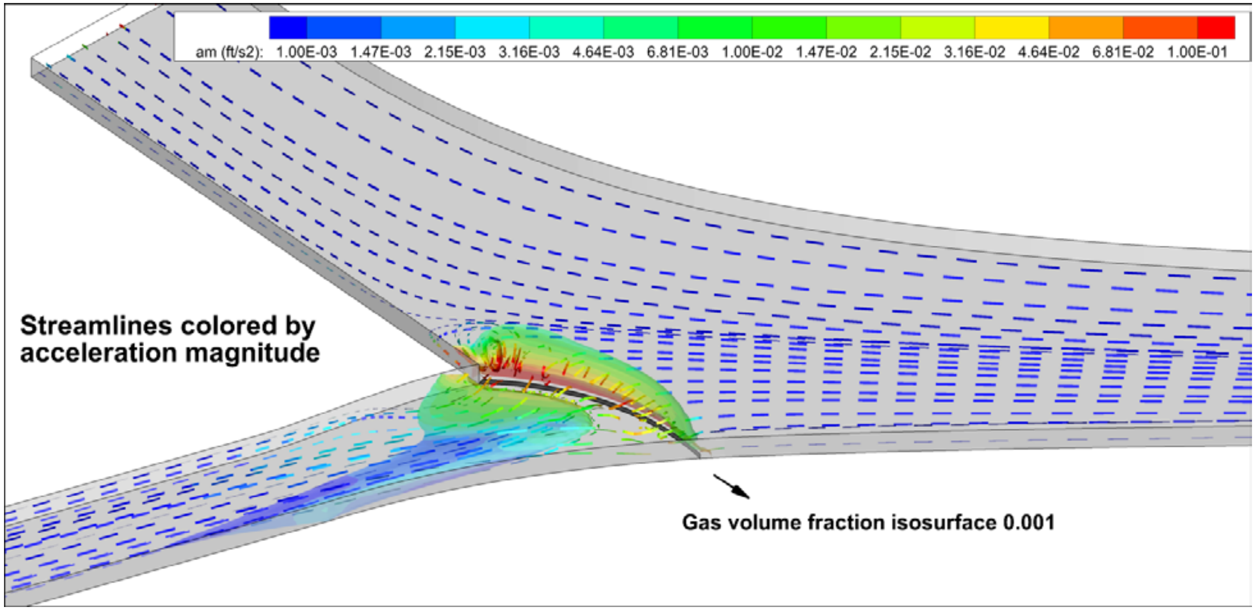
Fish Barrier in a River– Bubble distribution and velocity vectors



Streamlines colored by acceleration

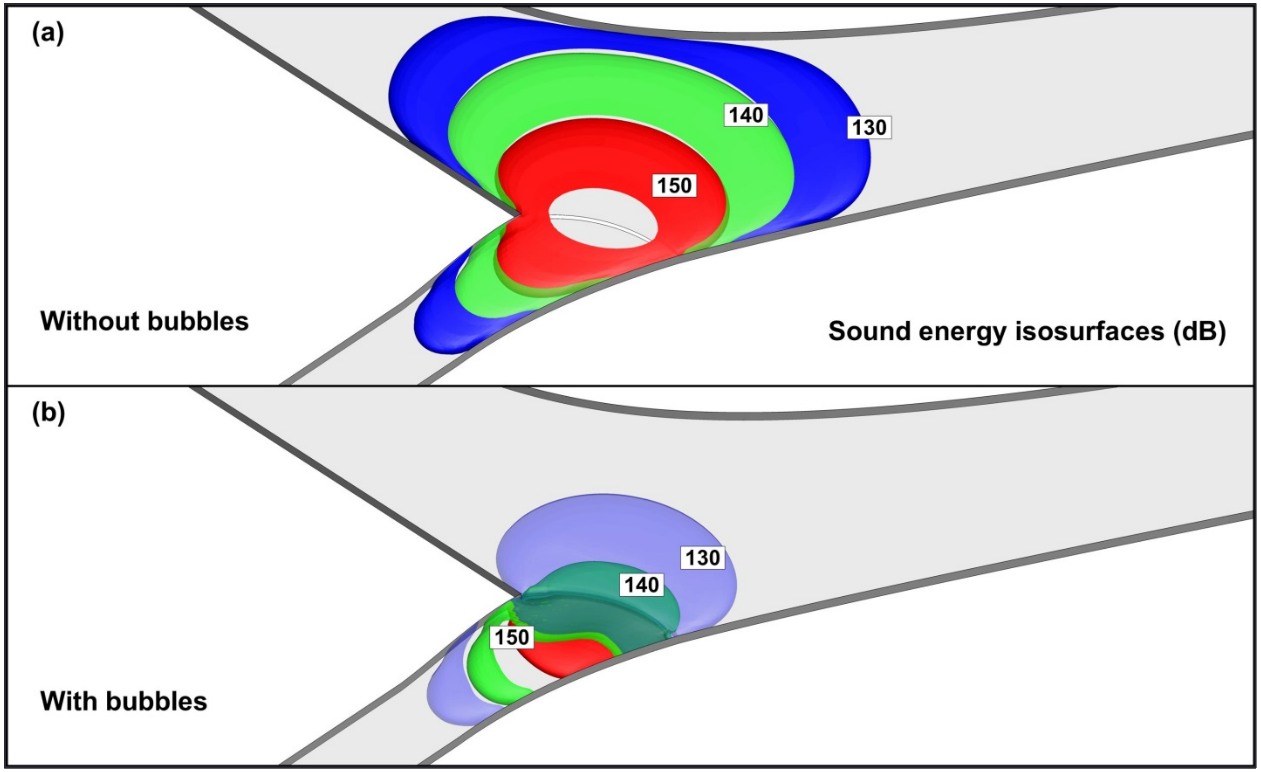


Quiescent Medium

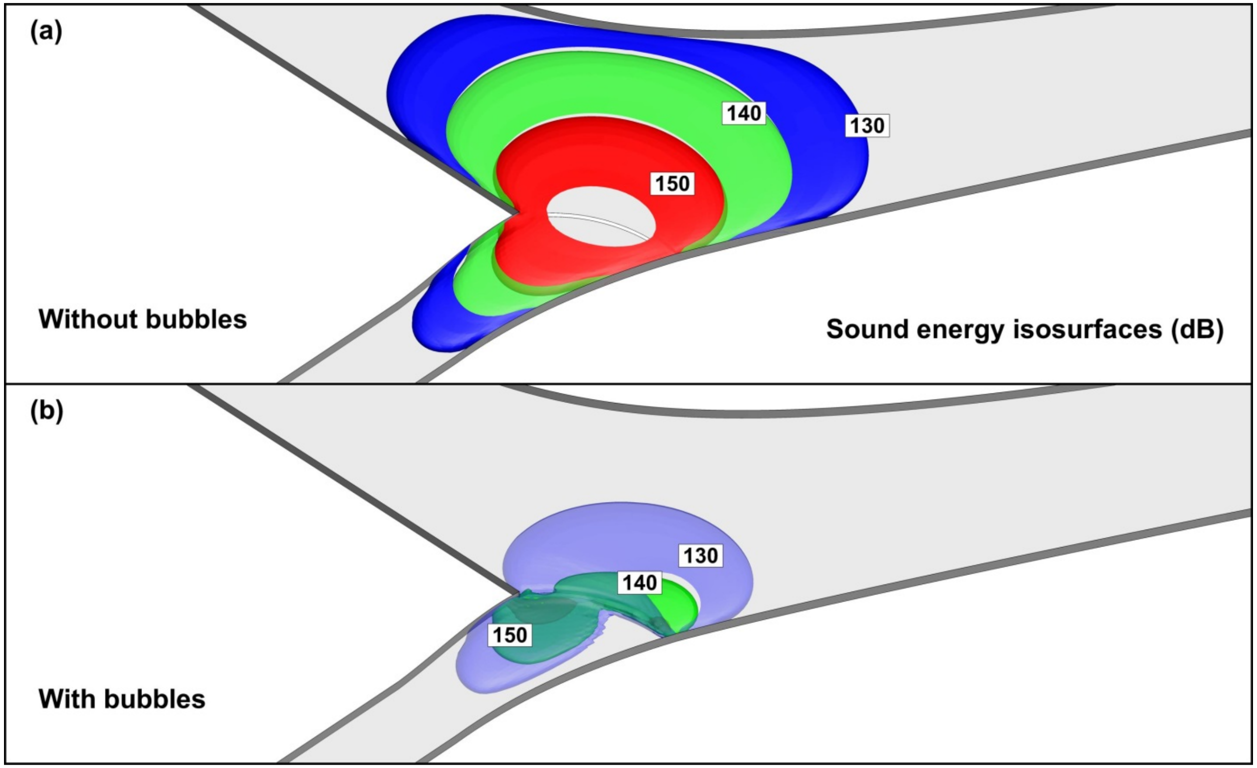


River

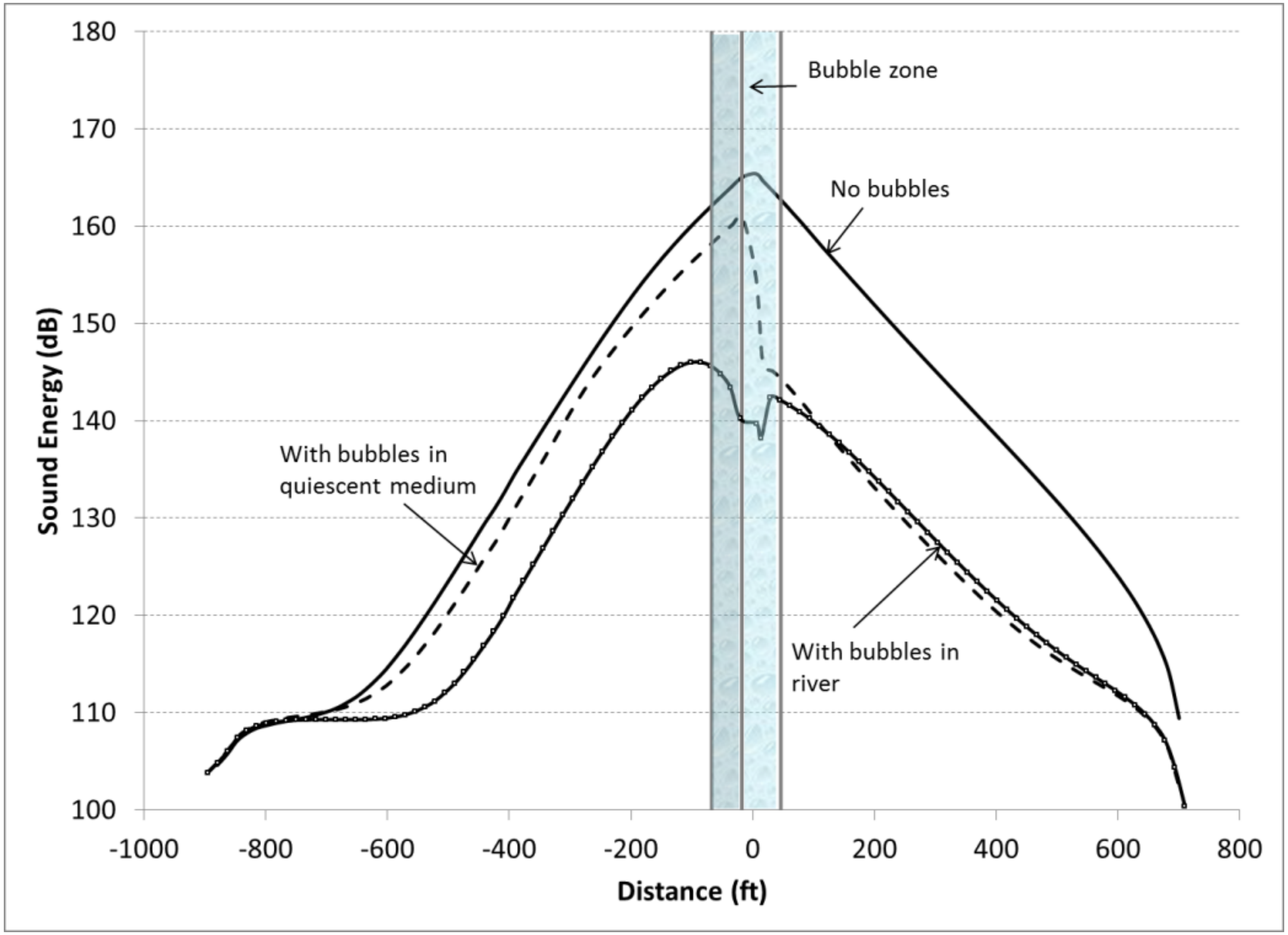
Fish Barrier in a Quiescent Medium – Sound energy

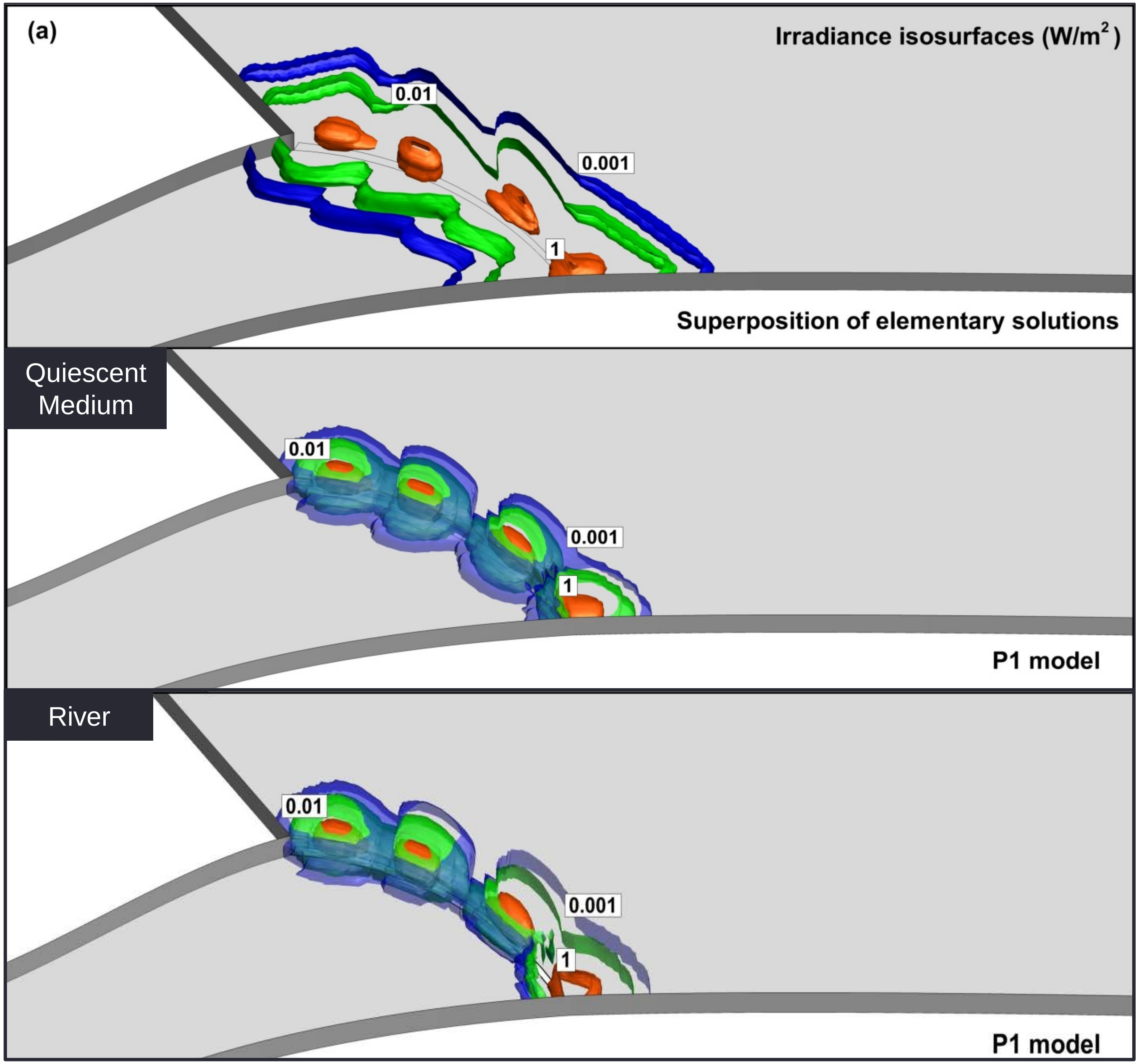


Fish Barrier in a River– Sound energy



Fish Barrier – Sound energy attenuation




(a)
Irradiance isosurfaces (W/m^2)
0.01
0.001
1
Superposition of elementary solutions
Quiescent Medium
0.01
0.001
1
P1 model
River
0.01
0.001
1
P1 model

COMMENTS AND QUESTIONS