Decomposition of Volumetric Path-Tracing for In-Water Radiative Transfer: A Hybrid Beam, Path, and Forward Scattering Approach

Adam Goodenough and Scott Brown
Digital Imaging and Remote Sensing Laboratory
Rochester Institute of Technology
goodenough@cis.rit.edu

Goals

- Create an alternative to so-called plane-parallel codes (e.g. HydroLight) in order to model inhomogeneous natural waters

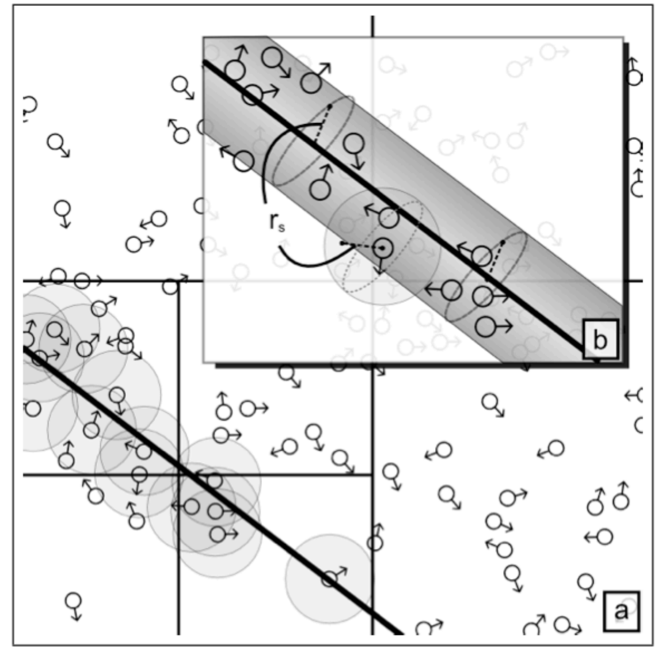
- Integrate with the **D**igital **I**maging and **R**emote **S**ensing **I**mage **G**eneration (DIRSIG) model

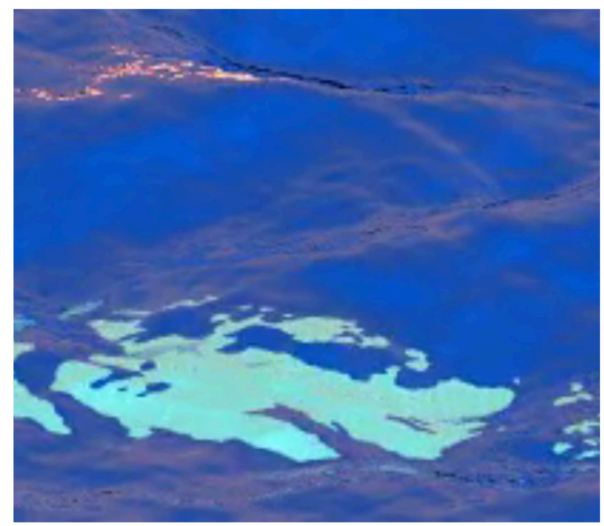
- Comparable convergence criteria and performance to multiple scattering radiometry in the atmosphere (e.g. a tree canopy)

- Use input models and features common to the water modeling community as well as a plugin-based environment for defining new features and models

Prior RT Approaches

- Proxy surface for water (before 2007)
  - *(BRDF only)*
- Photon mapping (2007)
  - *Two-pass MC approach*
    (difficult to setup and too slow for imaging)
- Open water approximation (2015)
  - *Direct single-scattering solution plus reduced photon map for multiple scattering*
    (only valid under very limited conditions)





Radiative Transfer (Volume)

- Basic equation governing radiance along a medium path

distance traveled in medium

location dependent absorption and scattering coefficients

scattering coefficient

scattering phase function

incoming radiance from direction corresponding to integrated solid angles

$$L = \int_0^T e^{-(a+b)t} \left(\int_\Omega b\tilde{\beta} L_\nu \, d\omega \right) dt$$

resulting observer radiance at distance 0

attenuation of each in-scattered contribution along path

in-scattered contribution at a point distance t along path

sphere around the current path point

- Naïve MC solution *(pure path-tracing)*

expected value of the absorption weighted internal integral is the MC solution to the scattering portion of the equation

$$L = \frac{1}{b}\mathbf{E}\left\{ e^{-a\,\mathbf{t}} \left(\int_\Omega b\tilde{\beta} L_\nu \, d\omega \right) \right\} = \mathbf{E}\left\{ e^{-a\,\mathbf{t}} \left(\int_\Omega \tilde{\beta} L_\nu \, d\omega \right) \right\}$$

$$L = \mathbf{E}\left\{ e^{-a\,\mathbf{t}} L_{\mathbf{t},\boldsymbol{\nu}} \right\}$$

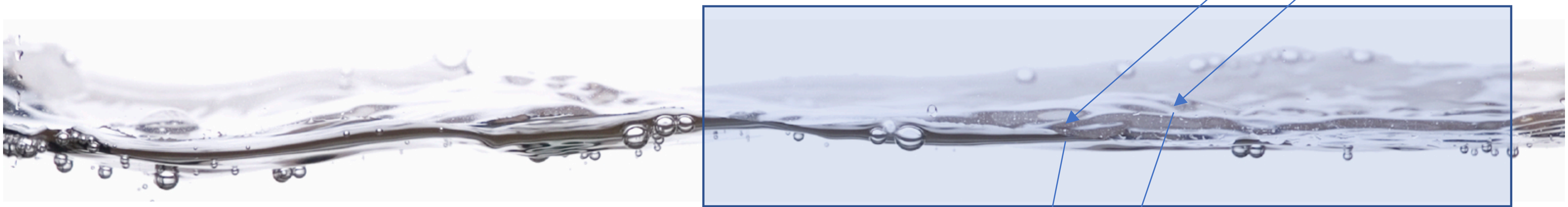
integrated in-scattering can be incorporated into the expected value (the scattering phase function is equivalent to the probability density function)

distance sampled from scattering attenuation

direction sampled from scattering phase function

...correct,
but unable to
handle non-diffuse sources well

Priority: Direct Solar Term



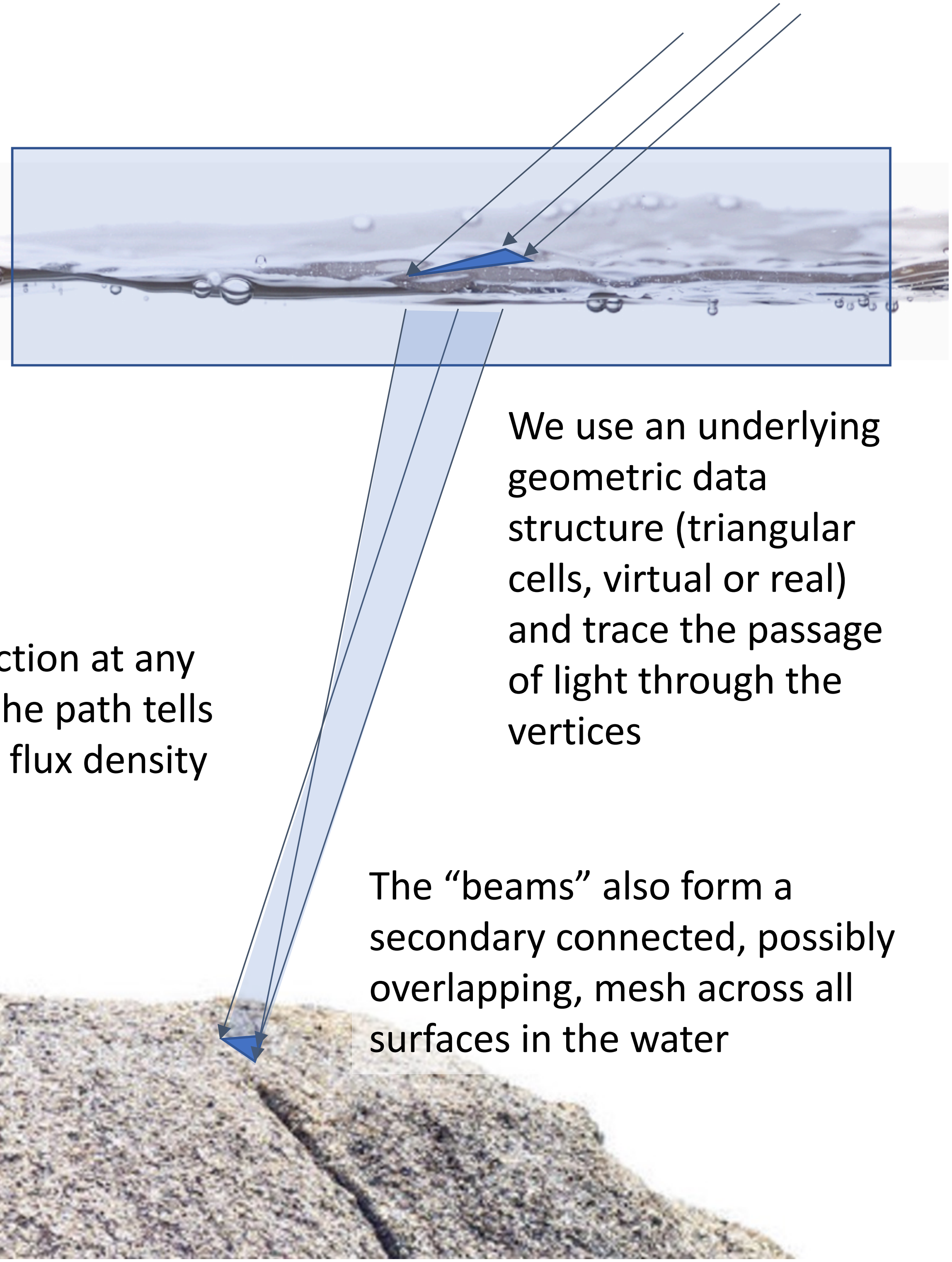
The fundamental difficulty in modeling water is knowing where light is coming from underneath an arbitrary interface

A single, unidirectional source may be "imaged" more than once onto a surface or through the volume

Or, simply, the flux density can be different at any point in the volume

Beams

The first component models what happens to light once it enters the water, before interacting with any surfaces or scattering



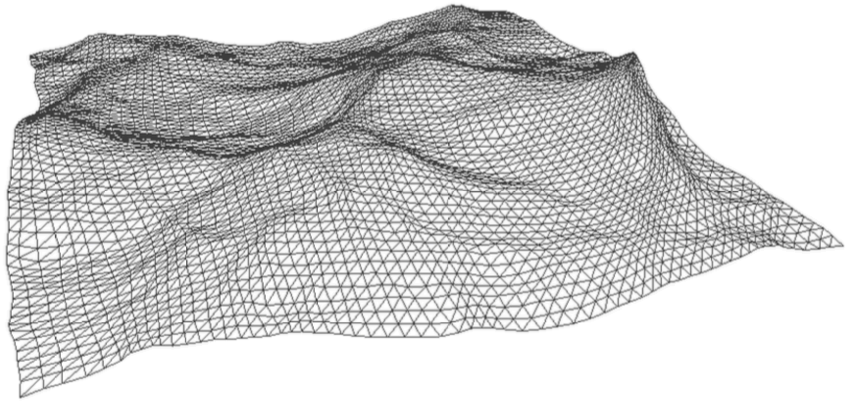
We use an underlying geometric data structure (triangular cells, virtual or real) and trace the passage of light through the vertices

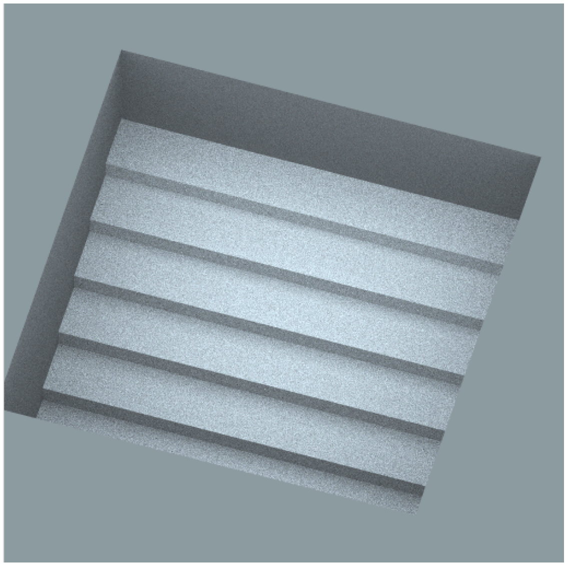
The cross-section at any point along the path tells us about the flux density changes

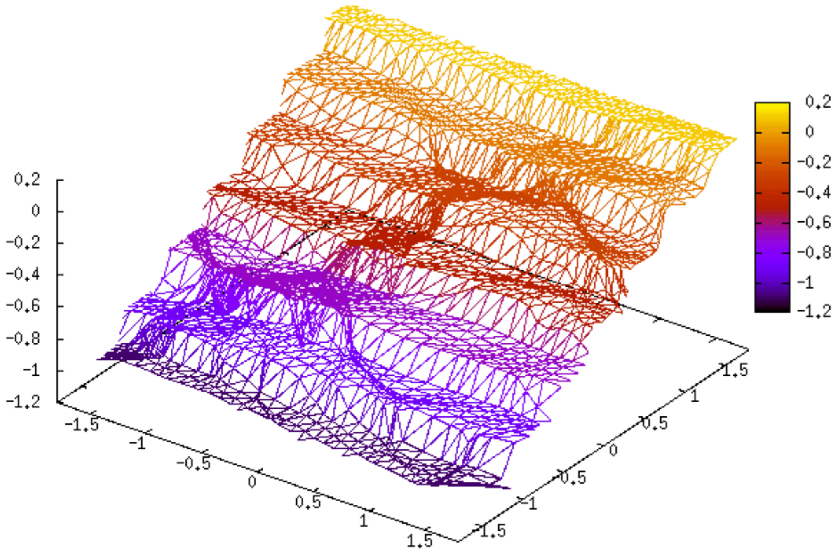
The “beams” also form a secondary connected, possibly overlapping, mesh across all surfaces in the water

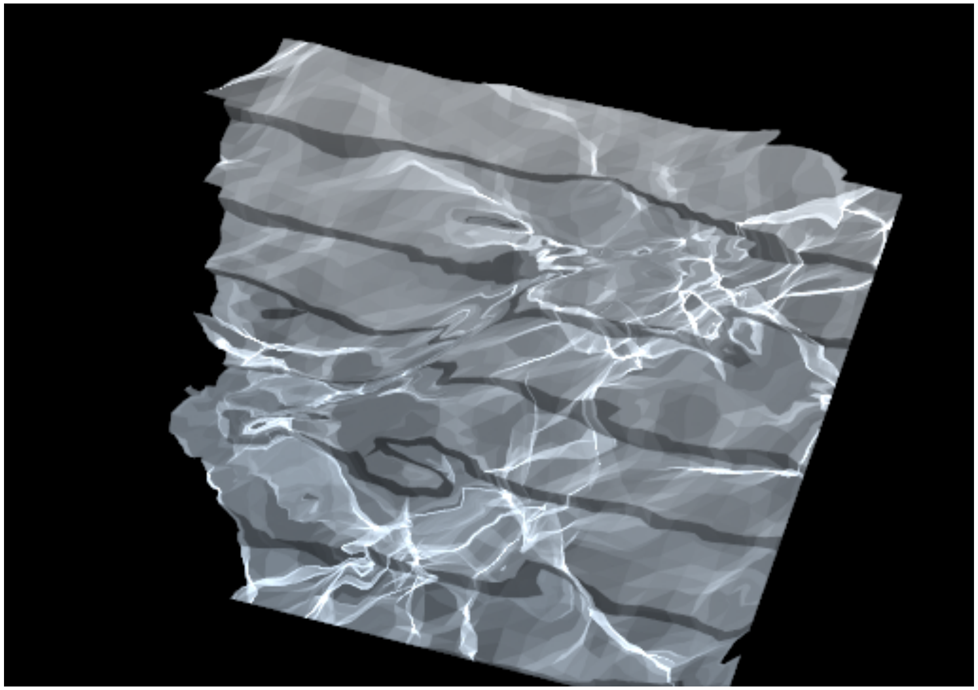
Surface Component: Example

Simple stepped pool scene with a static wave mesh applied to define the medium interface









The resulting surface mesh contains the solar-projected cells after refraction (cells overlap where waves focus light); connected cells form the beams

Radiative Transfer (Volume)

- We decompose the governing function in two parts

propagated irradiance from non-diffuse, bright sources

*sphere solid angle **without** direct source angles*

$$L = \int_0^T e^{-(a+b)t} \left(\sum_{i=1}^{n_s} b\tilde{\beta} E_i \right) dt + \int_0^T e^{-(a+b)t} \left(\int_{\Omega'} b\tilde{\beta} L_\nu \, d\omega \right) dt$$

explicitly calculated contribution for each "direct" source

recursive portion of the integral

recursion

$$L = \int_0^T e^{-(a+b)t} \left(\sum_{i=1}^{n_s} b\tilde{\beta} E_i \right) dt \cdot$$

uses beams to find direct source contributions, i.e. n_s is the number of beams intersecting a point along the path at distance t

Beams

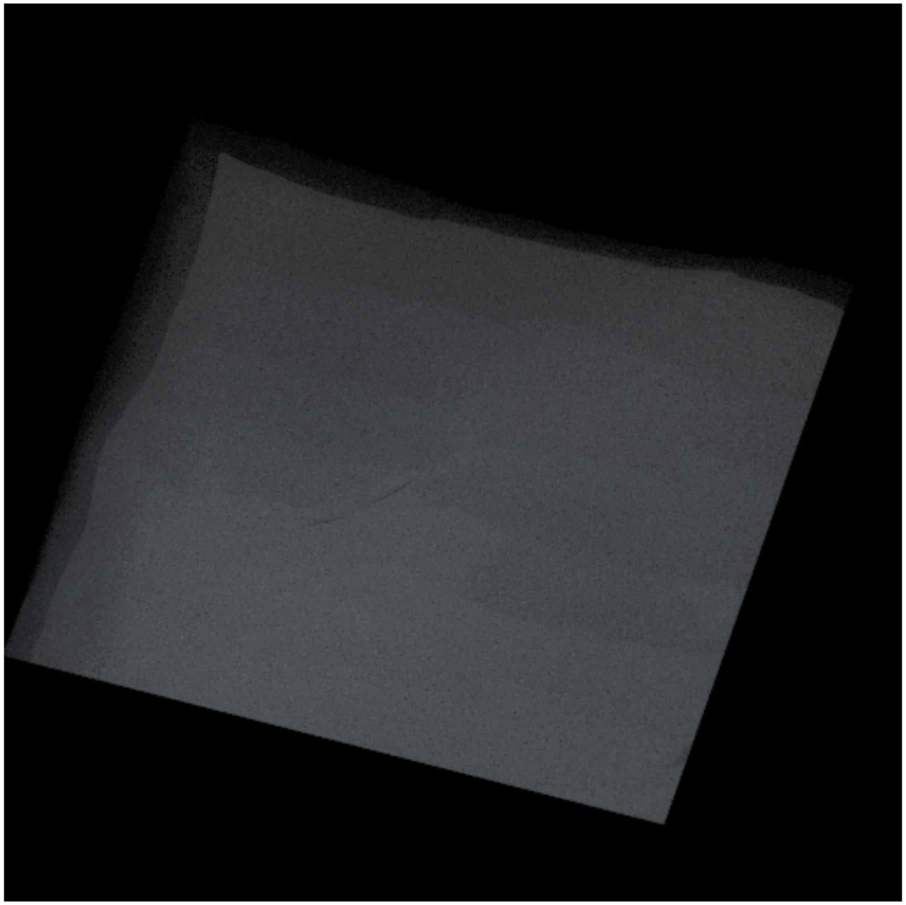
$$L = \mathbf{E} \left\{ e^{-a\,\mathbf{t}} L_{\mathbf{t},\boldsymbol{\nu}} \right\}$$

uses the general path-tracing framework to build scattered paths within the volume; we ensure that we don't "double-up" on direct sources

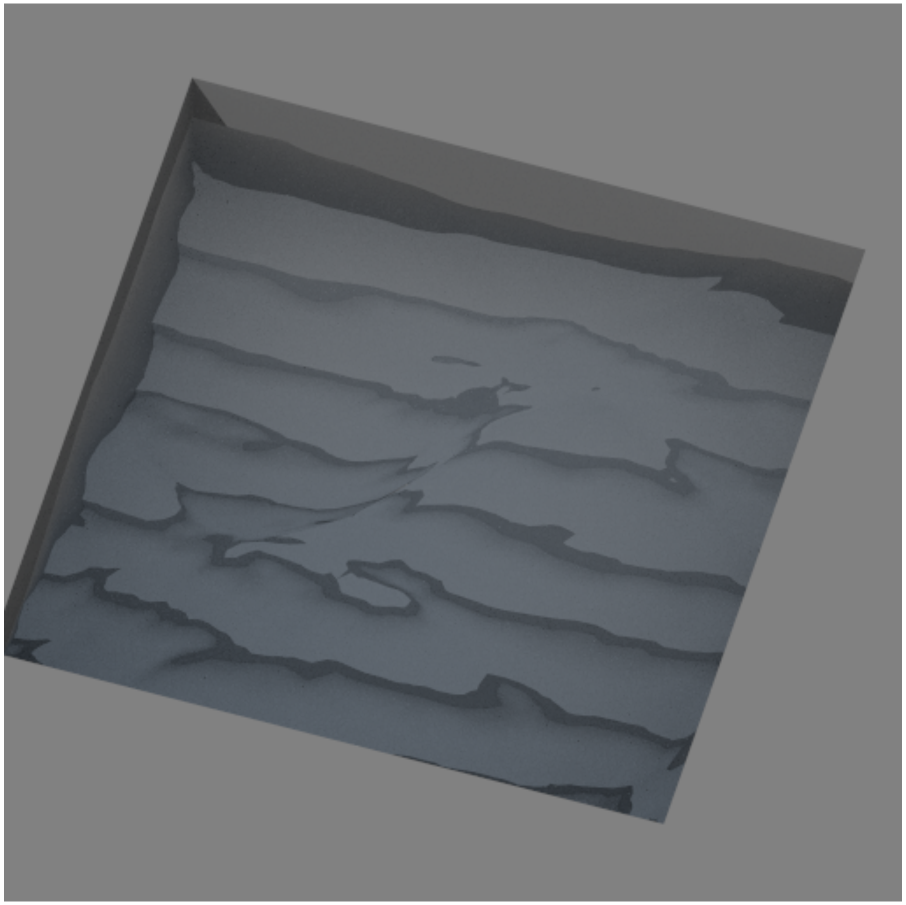
Pure Path-Tracing

Radiative Transfer (Volume)

- We decompose the governing function into two parts



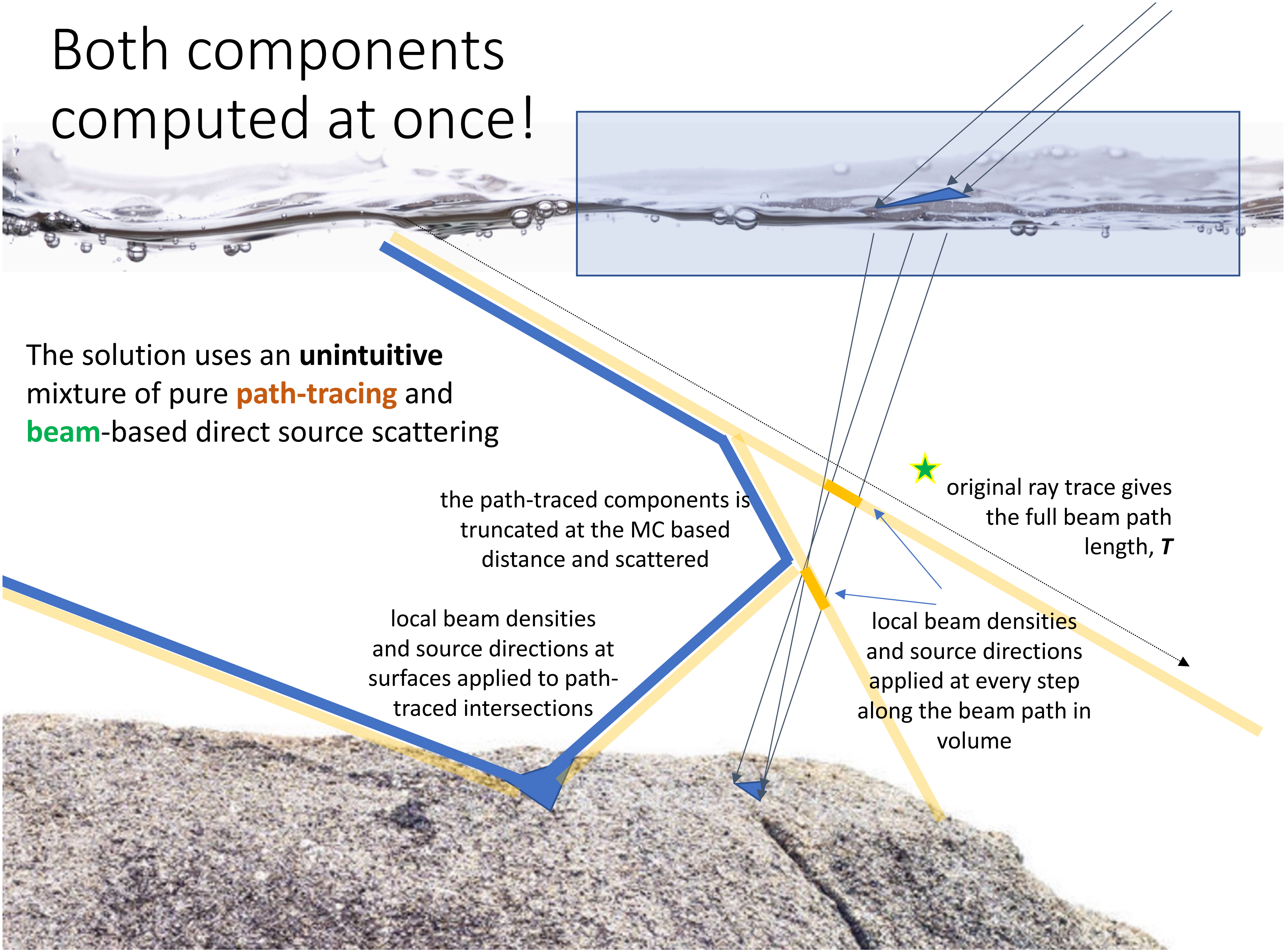
Beams



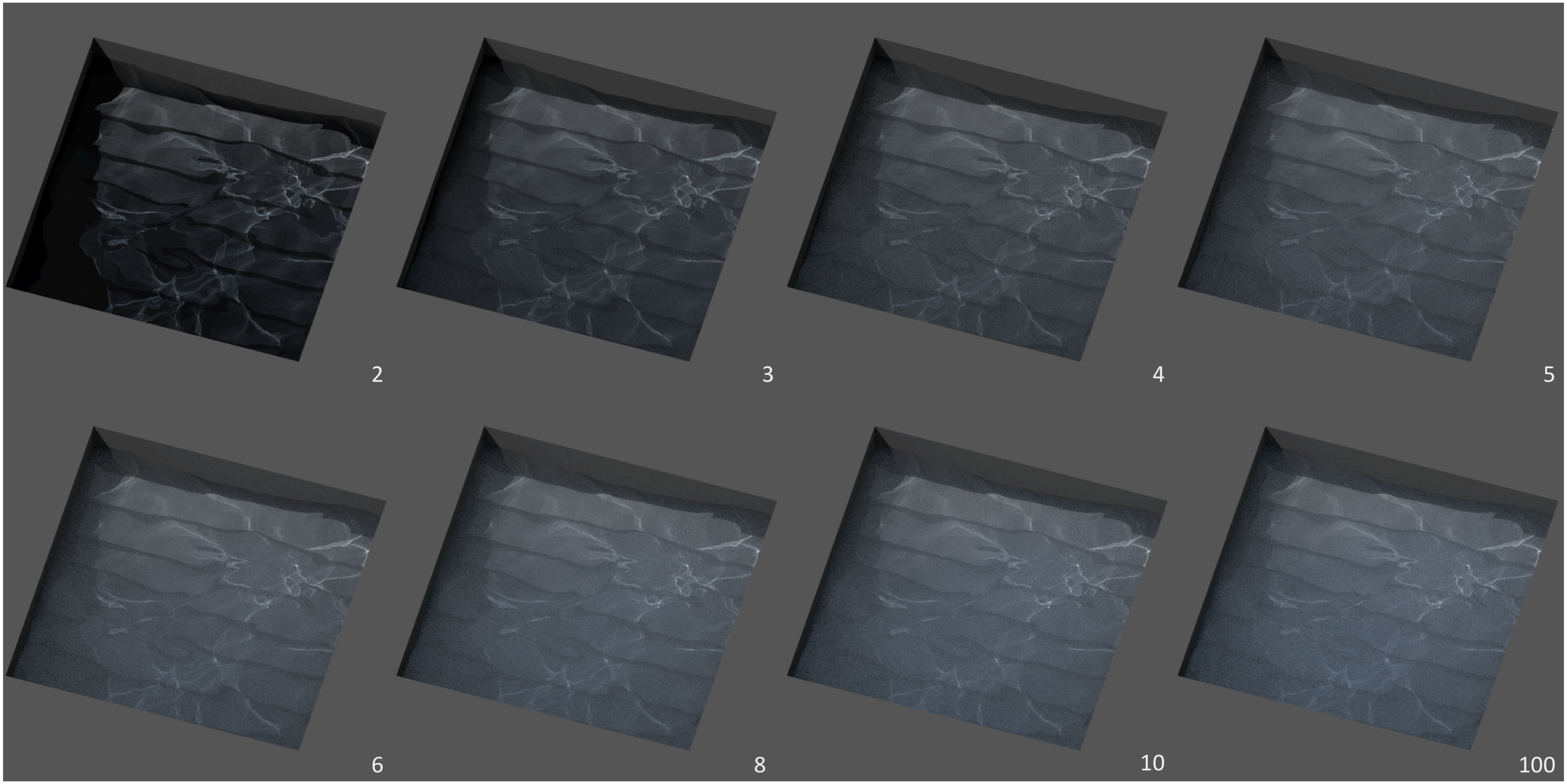
Pure Path-Tracing

Both components computed at once!

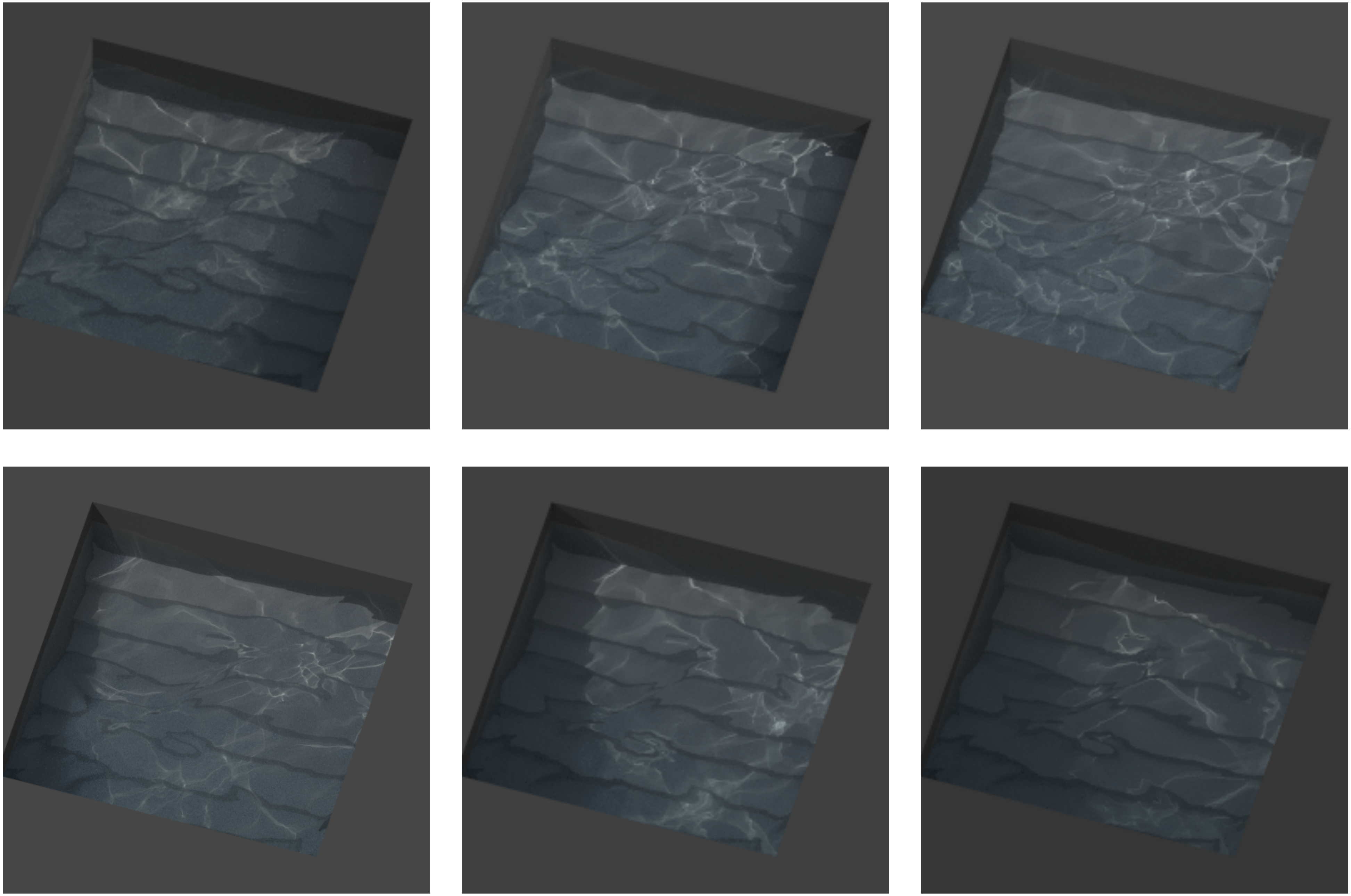
The solution uses an **unintuitive** mixture of pure **path-tracing** and **beam**-based direct source scattering



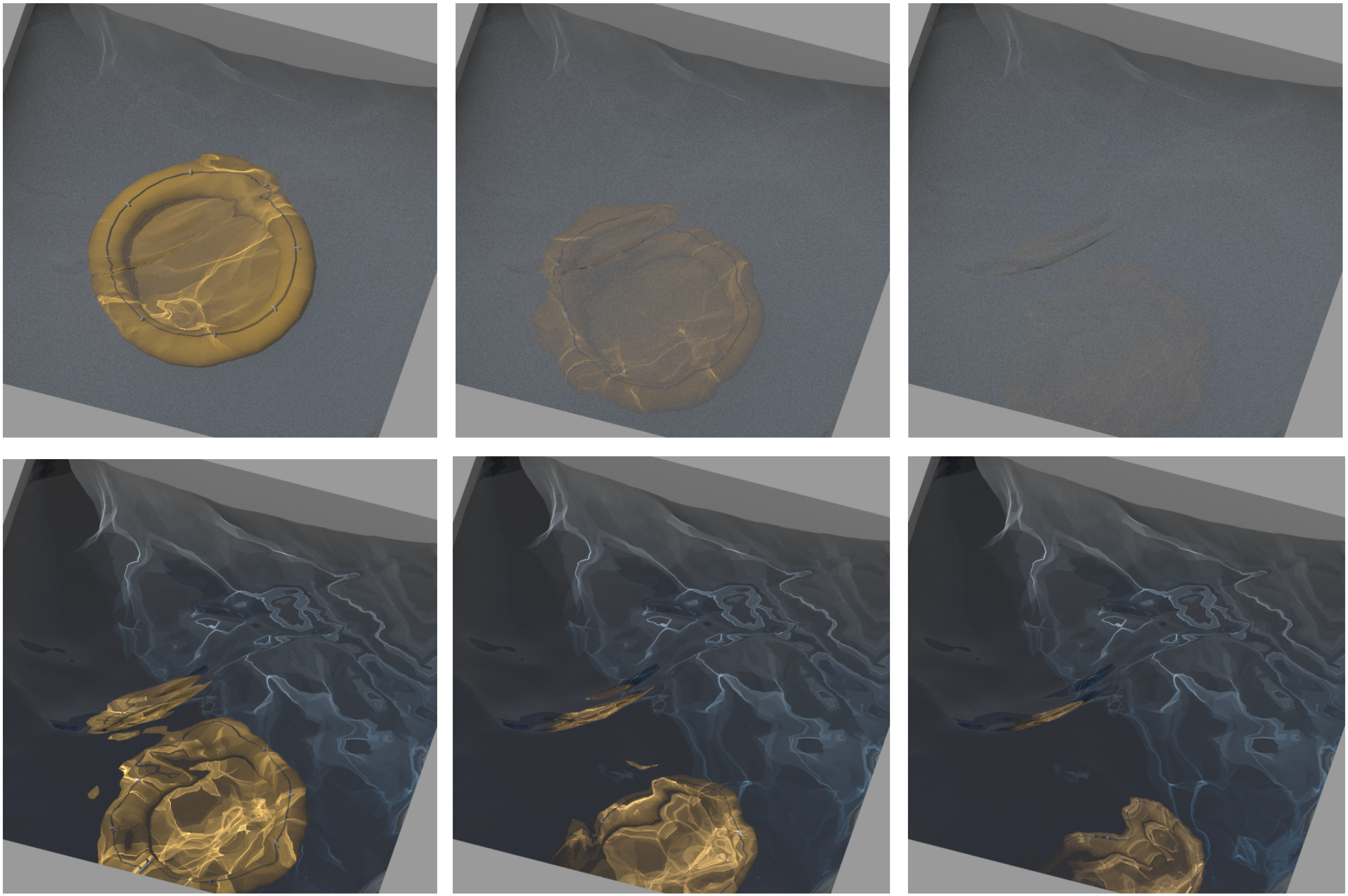
Path Recursion to Multiple Scattering..



Beams quickly updated for any source change…

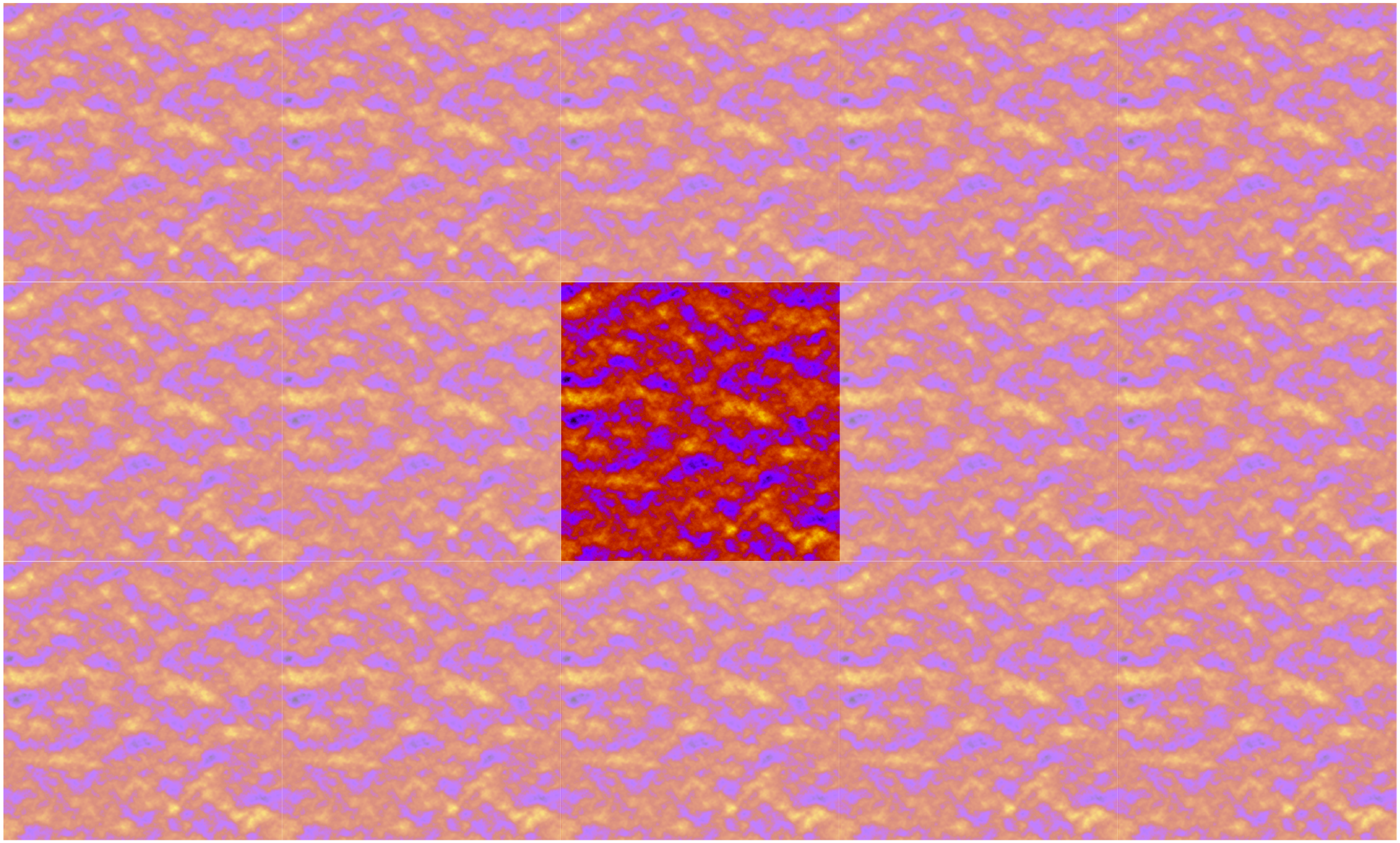


Geometry within volume is arbitrary…



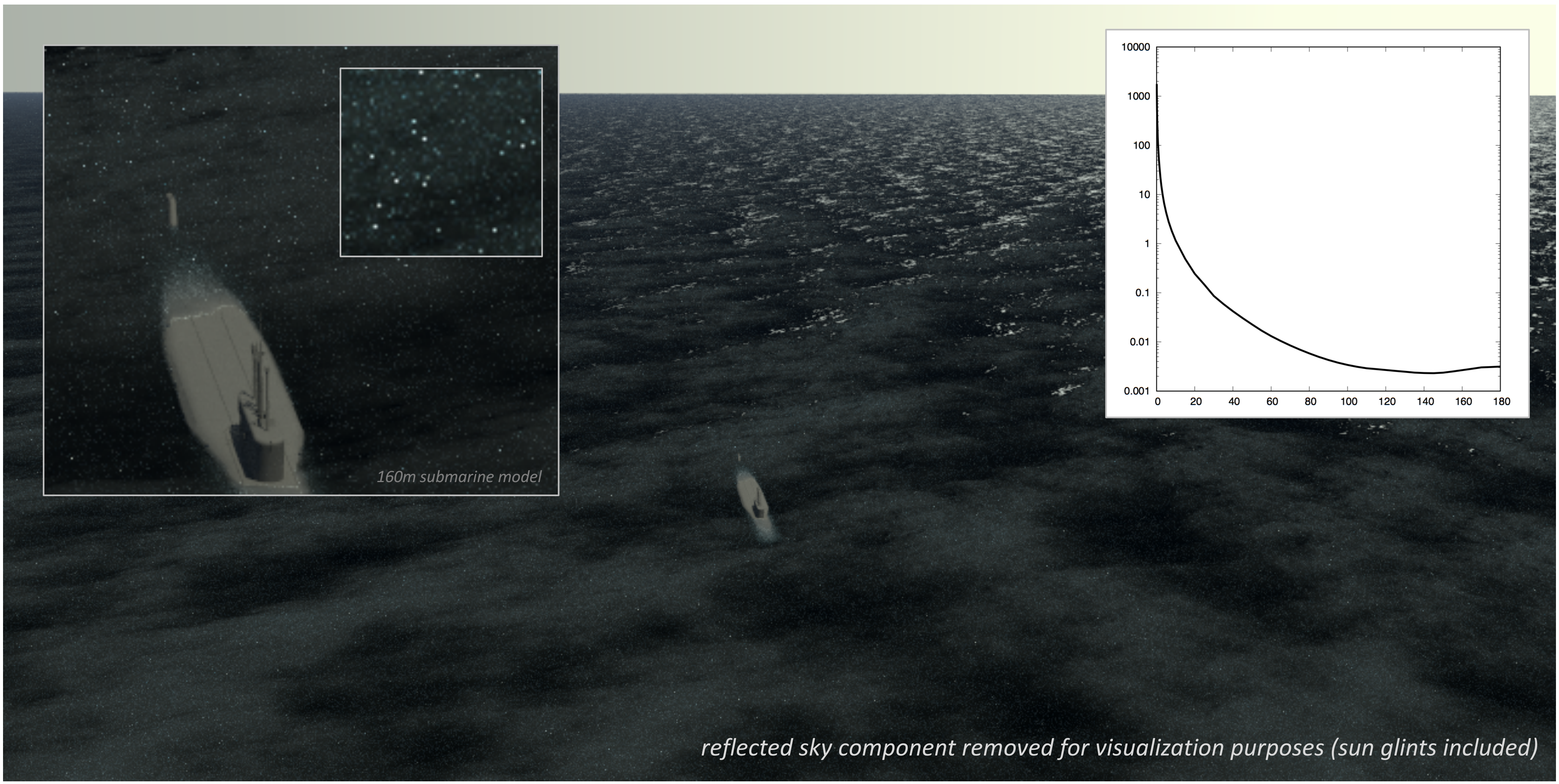
Extension to non-trivial scenes

- Height field and slope gradients derived from wave models
- Surface regions outside of primary scene tiled with original
- Realistic inherent optical properties and atmospheric conditions

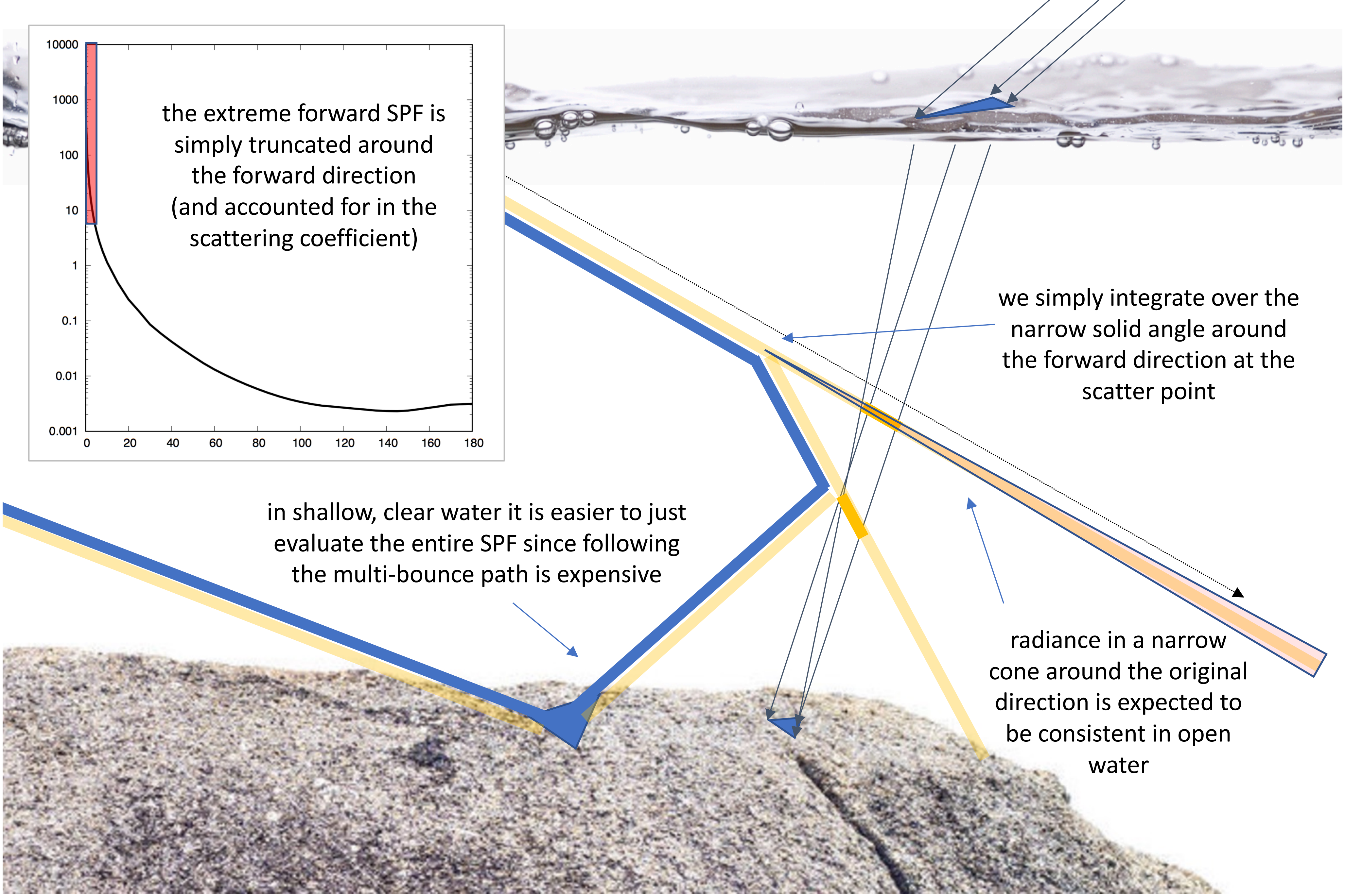


A new problem…

- Natural waters are highly forward scattering (Petzold SPF)
- "Spike" in scattering occurs when path heads towards the transmitted sun
- Occurrence is rare but fundamental to signal



We already have the solution!

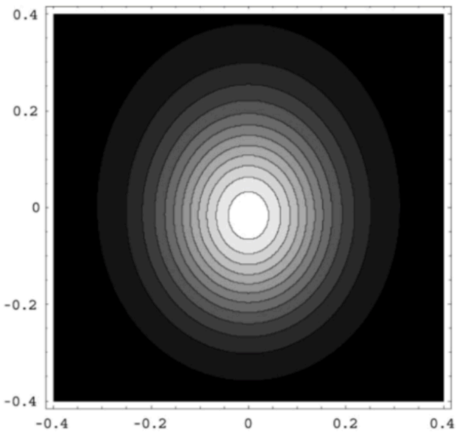


Maintain radiometry, mitigate noise

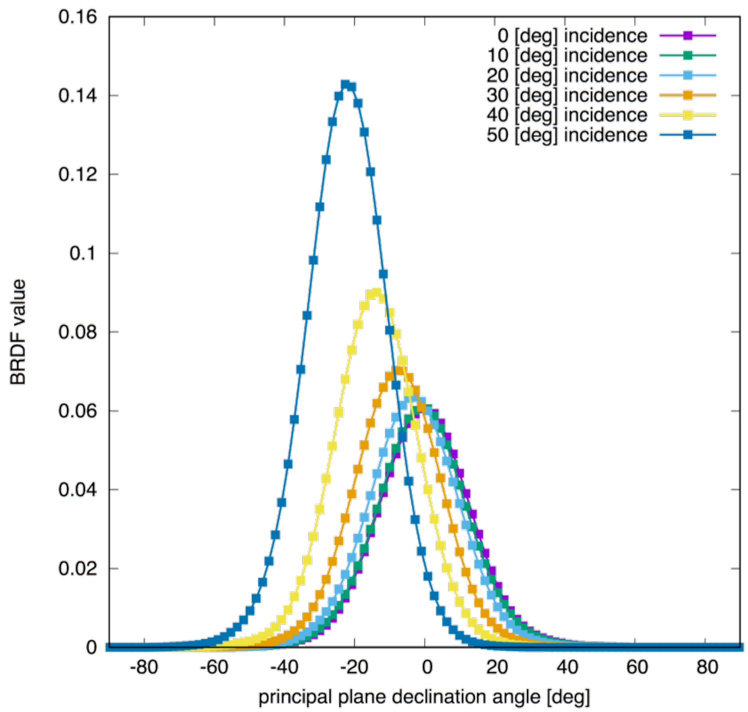
reflected sky component removed for visualization purposes (sun glints included)

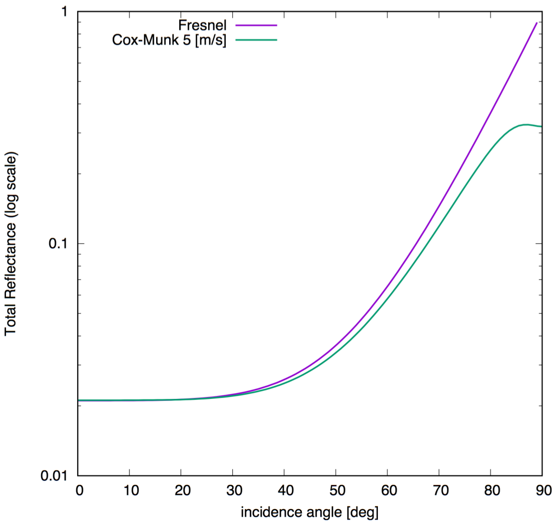
Unresolved Surface Structure

- Wind-roughened waters have structure down to roughly centimeter scale
- Portion of wave structure unresolved by height field and sensor
- Model aggregate sub-pixel structure as a BRDF based on slope distributions



Tatarskii (2003) Multi-Gaussian fit to Cox-Munk (1954) wave slope measurements (original PDF had negative values at grazing angles)

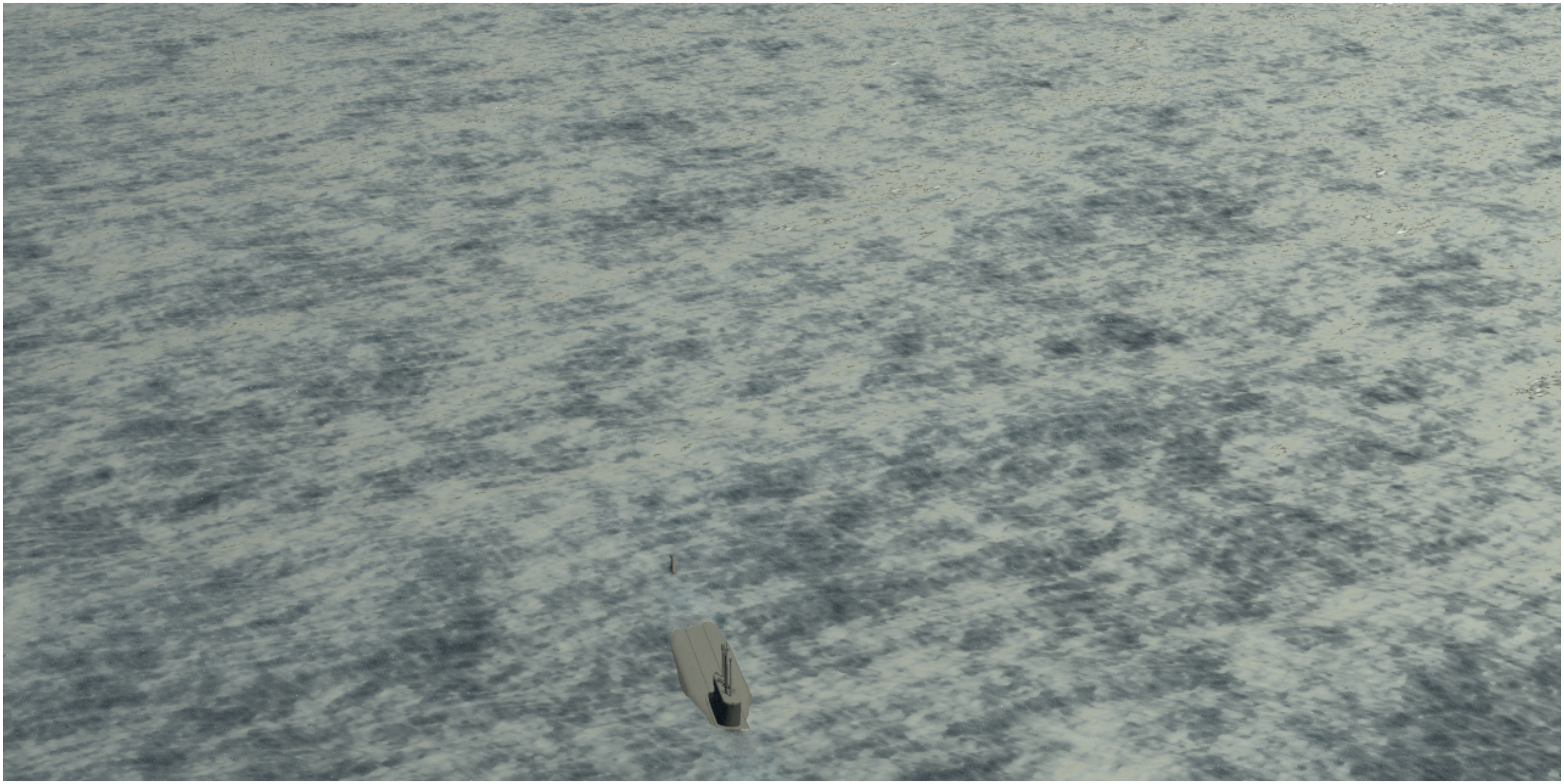




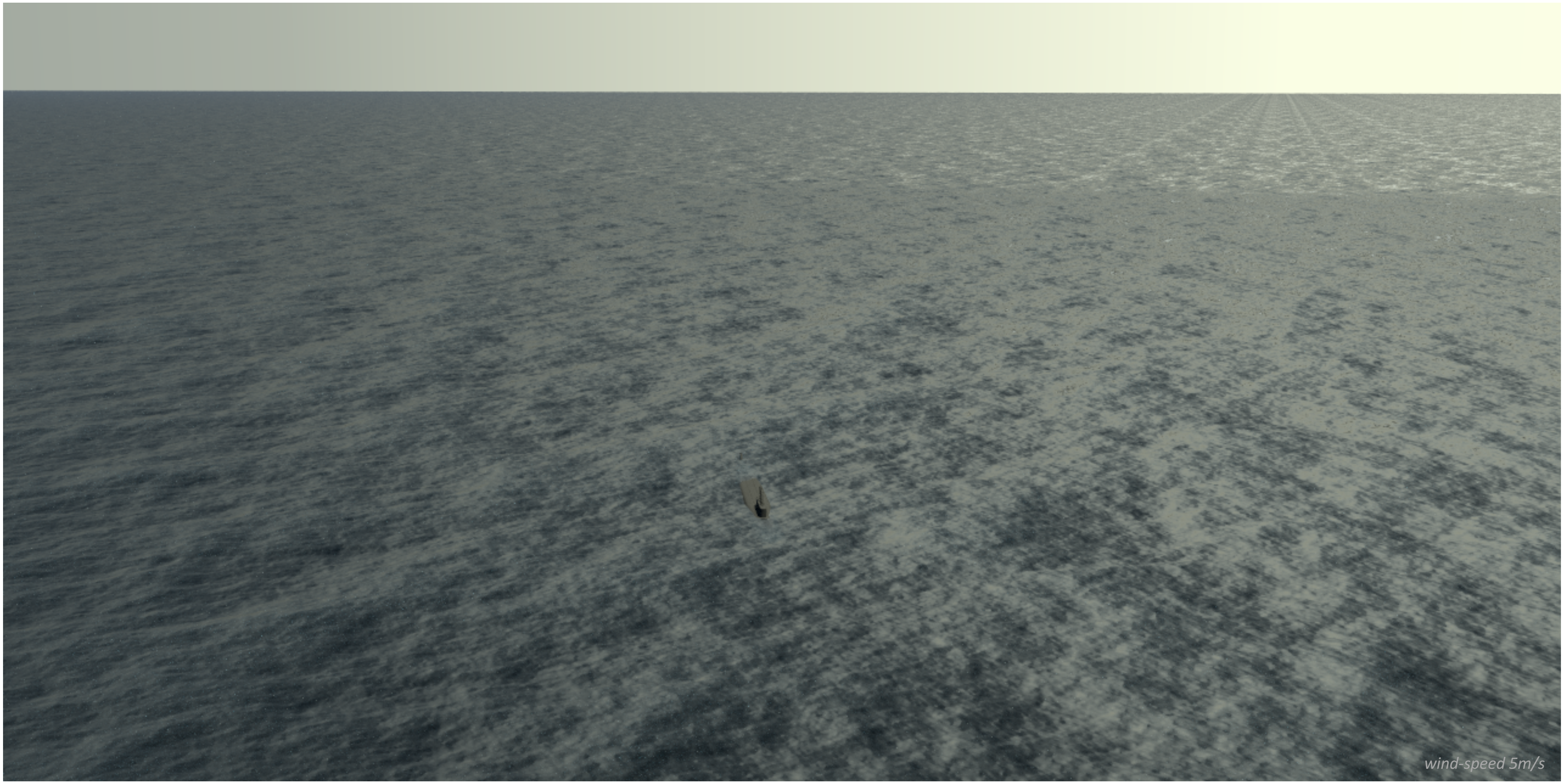
Total Reflectance deviates from Fresnel at grazing angles

We use the slope PDF to find a normal vector PDF in the context of a Bidirectional Reflectance Distribution Function (BRDF) and generate SQTs

Putting it all together…

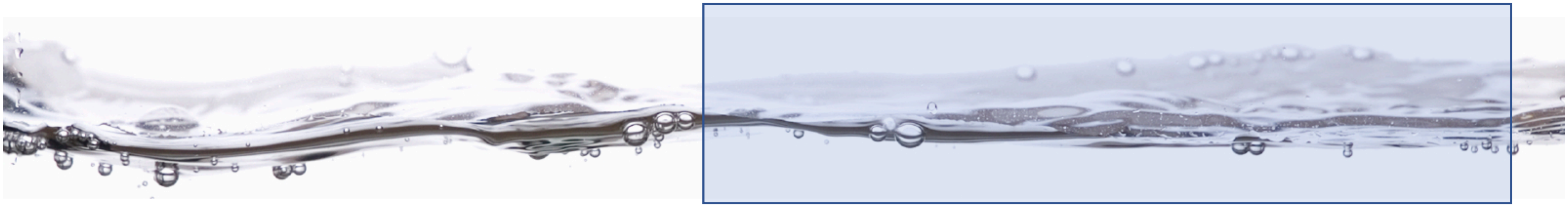


Putting it all together…



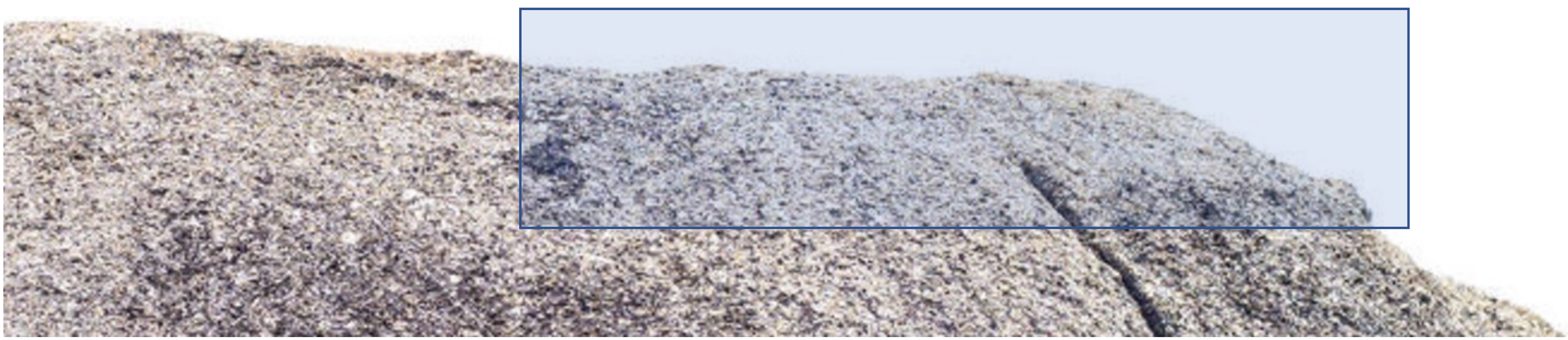
User Interface

*the interface is driven by a **plugin** that describes the geometry of the surface as well as BRDF/BTDFs*

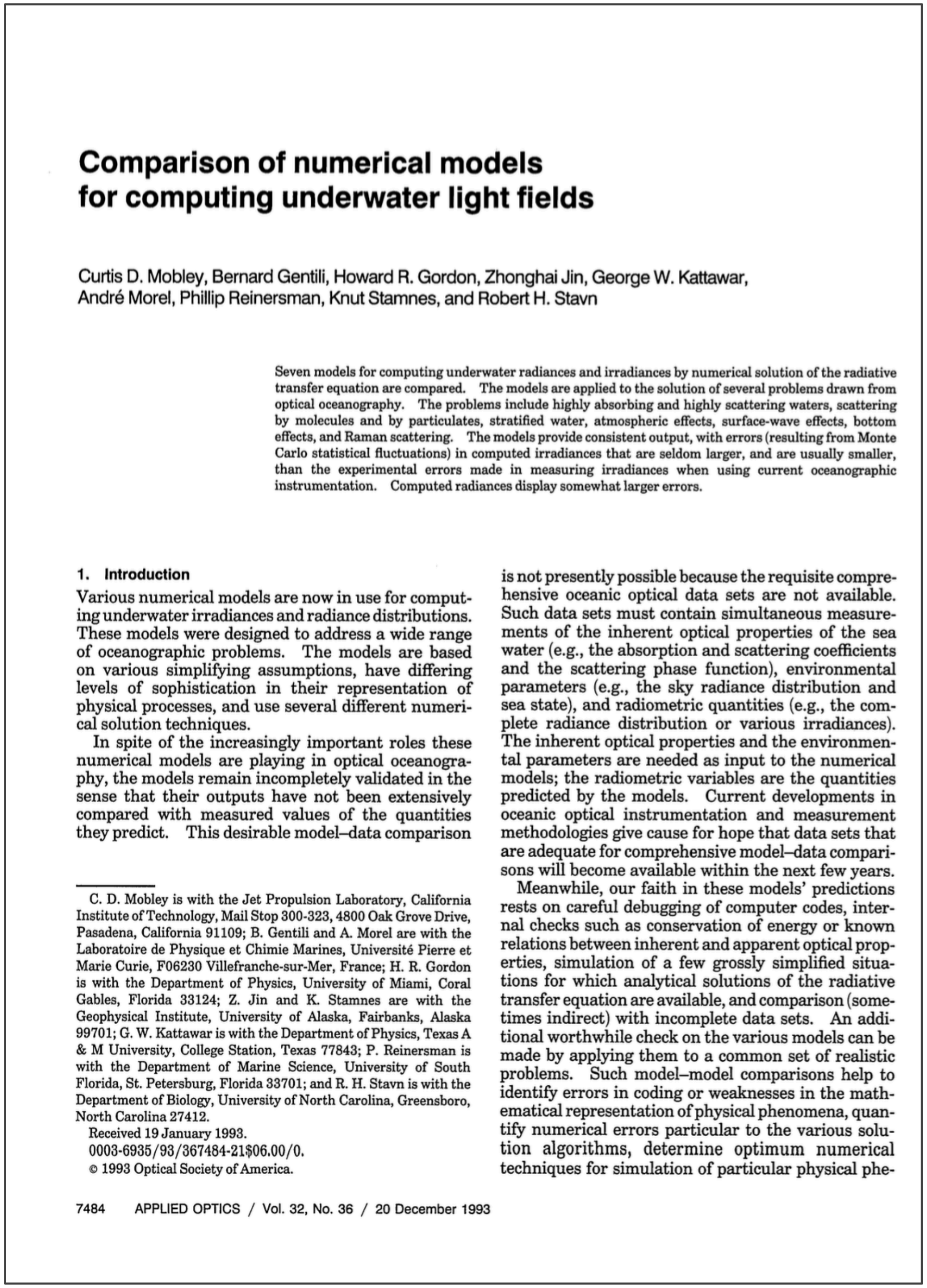


*inherent optical properties of the medium are driven by a **plugin** that provides properties at any point*

surfaces within a medium are defined exactly like normal surfaces in DIRSIG (geometry plus materials)



Code Verification



Comparison of numerical models for computing underwater light fields

Curtis D. Mobley, Bernard Gentili, Howard R. Gordon, Zhonghai Jin, George W. Kattawar, André Morel, Phillip Reinersman, Knut Stamnes, and Robert H. Stavn

Seven models for computing underwater radiances and irradiances by numerical solution of the radiative transfer equation are compared. The models are applied to the solution of several problems drawn from optical oceanography. The problems include highly absorbing and highly scattering waters, scattering by molecules and by particulates, stratified water, atmospheric effects, surface-wave effects, bottom effects, and Raman scattering. The models provide consistent output, with errors (resulting from Monte Carlo statistical fluctuations) in computed irradiances that are seldom larger, and are usually smaller, than the experimental errors made in measuring irradiances when using current oceanographic instrumentation. Computed radiances display somewhat larger errors.

1. Introduction

Various numerical models are now in use for computing underwater irradiances and radiance distributions. These models were designed to address a wide range of oceanographic problems. The models are based on various simplifying assumptions, have differing levels of sophistication in their representation of physical processes, and use several different numerical solution techniques.

In spite of the increasingly important roles these numerical models are playing in optical oceanography, the models remain incompletely validated in the sense that their outputs have not been extensively compared with measured values of the quantities they predict. This desirable model–data comparison is not presently possible because the requisite comprehensive oceanic optical data sets are not available. Such data sets must contain simultaneous measurements of the inherent optical properties of the sea water (e.g., the absorption and scattering coefficients and the scattering phase function), environmental parameters (e.g., the sky radiance distribution and sea state), and radiometric quantities (e.g., the complete radiance distribution or various irradiances). The inherent optical properties and the environmental parameters are needed as input to the numerical models; the radiometric variables are the quantities predicted by the models. Current developments in oceanic optical instrumentation and measurement methodologies give cause for hope that data sets that are adequate for comprehensive model–data comparisons will become available within the next few years.

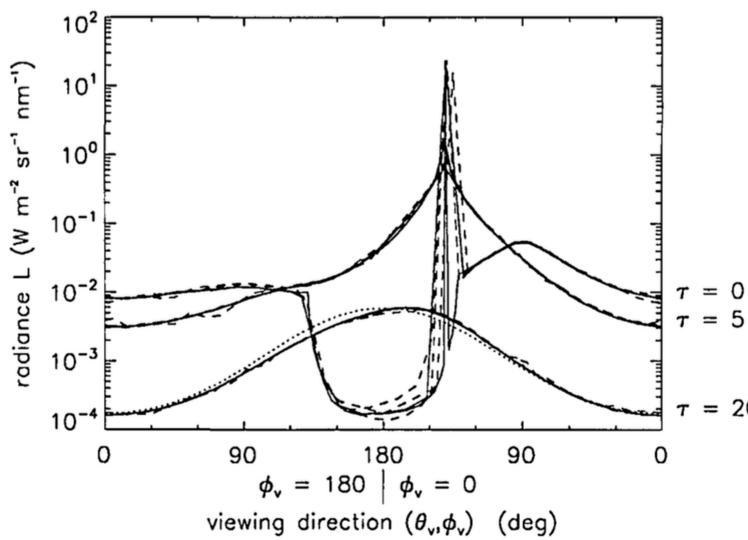
Meanwhile, our faith in these models' predictions rests on careful debugging of computer codes, internal checks such as conservation of energy or known relations between inherent and apparent optical properties, simulation of a few grossly simplified situations for which analytical solutions of the radiative transfer equation are available, and comparison (sometimes indirect) with incomplete data sets. An additional worthwhile check on the various models can be made by applying them to a common set of realistic problems. Such model–model comparisons help to identify errors in coding or weaknesses in the mathematical representation of physical phenomena, quantify numerical errors particular to the various solution algorithms, determine optimum numerical techniques for simulation of particular physical phe-

C. D. Mobley is with the Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 300-323, 4800 Oak Grove Drive, Pasadena, California 91109; B. Gentili and A. Morel are with the Laboratoire de Physique et Chimie Marines, Université Pierre et Marie Curie, F06230 Villefranche-sur-Mer, France; H. R. Gordon is with the Department of Physics, University of Miami, Coral Gables, Florida 33124; Z. Jin and K. Stamnes are with the Geophysical Institute, University of Alaska, Fairbanks, Alaska 99701; G. W. Kattawar is with the Department of Physics, Texas A & M University, College Station, Texas 77843; P. Reinersman is with the Department of Marine Science, University of South Florida, St. Petersburg, Florida 33701; and R. H. Stavn is with the Department of Biology, University of North Carolina, Greensboro, North Carolina 27412.

Received 19 January 1993.
0003-6935/93/367484-21$06.00/0.

Mobley (JPL) paper from 1993 describes a number of "canonical" problems for numerical models of natural waters to solve and provides results from a variety of models and approaches

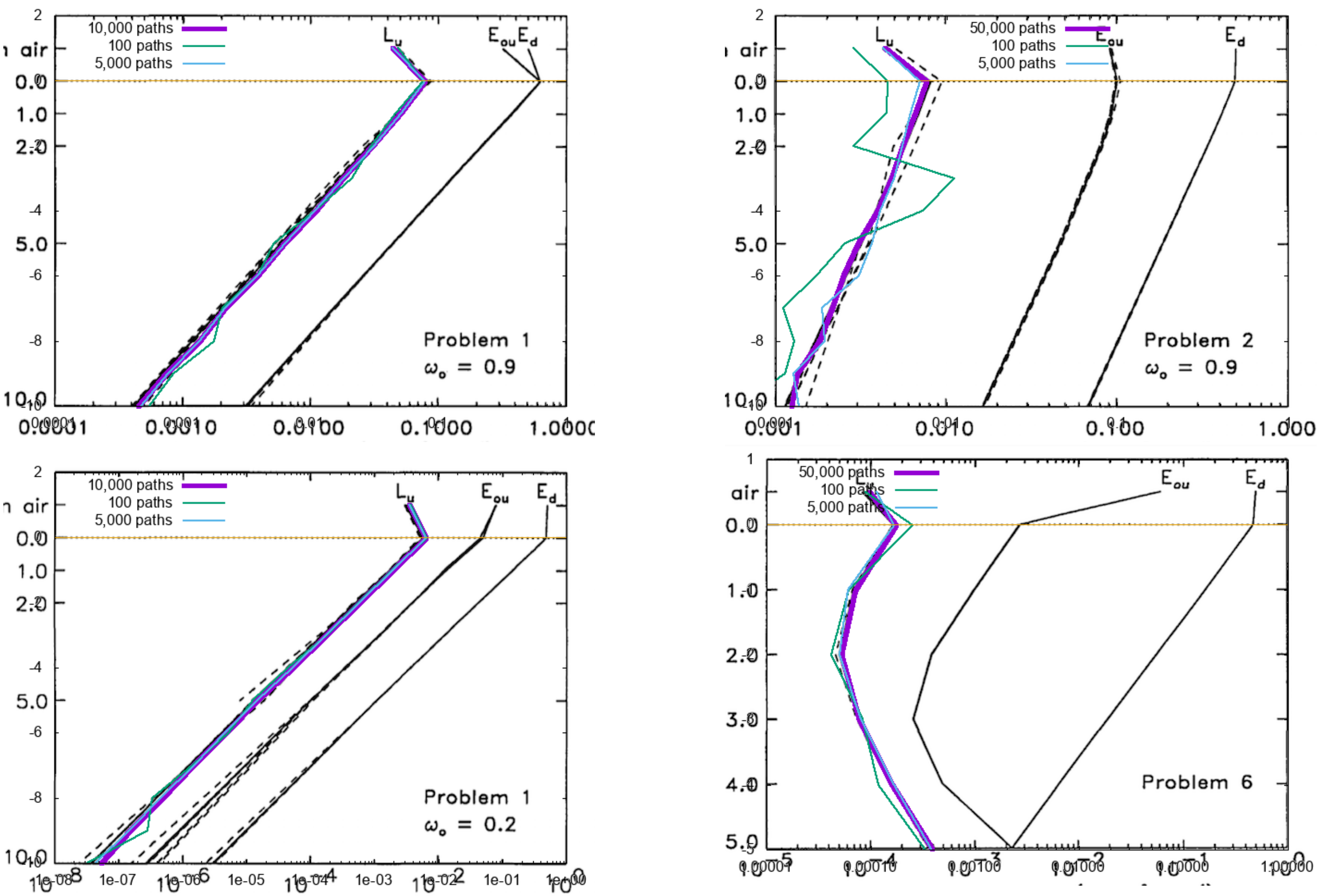
Matching the results from these problems is considered a first step verification that the DIRSIG5 radiometry is correct



example results including variation in participating models

Radiance results

- *Limited data available from paper so results are over-plotted onto paper figures*
- *Tests are run using a specialized sensor plugin that defines an array of sensors in/out of the water*



- Conclusions and Discussion…
  - We’ve taken the radiative transfer equation and broken it into three components
    1. Beam-based, direct solar scattering contribution
    2. Path-tracing for diffuse sources and multiple scattering
    3. *Forward scattering cone extraction and direct solution*
  - Path-traced solution exploits overlapping paths
  - Approach can be scaled up to large, tiled scenes
  - A plugin interface allows the user to define arbitrary surface structure and medium properties