Discovery of Sound in the Sea 2022 Webinar Series **Acoustic Propagation** Modeling

THE UNIVERSITY OF RHODE ISLAND









Who is this for?

- People trying to understand a report or talk that contains modeling.
- Decision maker trying to evaluate and interpret modeling results.
- Those seeking general introduction and resources for learning more.



It's better to be bored than lost

- Preliminaries: review of wavelength and Fourier synthesis.
- Spherical, cylindrical, and "practical" spreading.
- Water and bottom attenuation.
 - Damped cylindrical spreading model for pile driving.
- Information required for more detailed numerical models.
- Three most common "complex" models:
 - Ray tracing
 - Normal Modes
 - Parabolic Equation (PE)
- Source directionality

Review: acoustic wavelength



Compression

+Dansion

ompression

- Wavelength=sound speed / frequency=1500/f
- As frequency increases, wavelength shrinks.
- 1.5 kHz sound has 1 m wavelength in water.
- 150 Hz sound has 10 m wavelength
- 15 kHz has 10 cm (0.1 m) wavelength.

Wavelength relative to ocean depth determines whether "shallow" or "deep" ocean



- How many acoustic wavelengths fit in your local ocean?
- 10 wavelengths is a good rule of thumb:

$$D' = 10 * c/f$$

- If D'>D, "deep water," then then frequency and wavelength have less impact on modeling.
- If *D'<D, "shallow water,"* then then frequency and wavelength cannot be ignored, and modeling results strongly depend on frequency.
- Example: for 1.5 kHz, water depth needs to be >10 m in order to discount frequency effects.
- Note: source depth and sound speed profile scale may also cause strong dependence on frequency.

Fourier Synthesis

- Fourier Synthesis allows us to restrict our modeling to *tones* (sine waves)
- Right: as more tones are added to a time series, we can "build" a square wave.
- Any sound, no matter how complicated in time, can be broken down into a sum of tones of different amplitudes and time delays (phase).
 - Modeled seismic airgun source signal and spectrum (right)
- Therefore, acoustic models only need to model tones.
 - Run the model over a bunch of frequencies, and then conduct a Fourier synthesis.







Simple models of sound propagation can be very useful

- Simple models can accurately represent sound propagation in deep water when far from a boundary (surface, seafloor).
 - Appropriate when water depth *and* source depth greater than 10 wavelengths.
- A valuable "common sense" check for more complicated models.
- Spherical spreading: sound spreads as a sphere in open water.



Spherical spreading model is simplest propagation model



$$Intensity = \frac{Source\ Power}{4\pi r^2}$$

- The intensity of a sound falls off quickly with increasing range.
- Since acoustic power often can't be measured directly, we define a "reference range" to characterize the power:

Intensity =
$$\left(\frac{Source Power}{4\pi r_0^2}\right) \left(\frac{r_0^2}{r^2}\right)$$
 $r_0 = 1 m$

Decibel notation and transmission loss

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Spherical spreading TL= 20log(r)

2x distance-> 6 dB loss-> 4x smaller

3x distance -> 10 dB loss ->10x smaller

10x distance-> 20 dB loss-> 100x smaller

• Intensity = $\left(\frac{Source\ Power}{4\pi r_0^2}\right) \left(\frac{r_0^2}{r^2}\right)$

Source term Propagation term

• Convention is to use *decibels*:

10/og(Intensity) = $10\log\left(\frac{Source\ Power}{4\pi r_0^2}\right) + 10\log\left(\frac{r_0^2}{r^2}\right)$

RL = SL - 20log(r)

Received Level (dB) = Source Level (dB) - Transmission loss (TL)

- Transmission Loss (TL; aka propagation loss) is a positive number.
- The bigger the number, the greater the reduction in source level (attenuation).
- Allows us to model propagation without knowing the source level.

Cylindrical spreading: sound energy spread across a cylinder, not a sphere

 $RL = SL - \left[20\log(r_s) + 10\log(r/r_s)\right]$

TL



Example of simple models for a pile driving scenario in 10 m water



- Cylindrical spreading most conservative (yields highest cutoff range)
- True transmission loss typically lies between cylindrical and spherical spreading (see data points).
 - Exception: shallow low frequency source in "deep water".
- 15log(r) often used as a "practical spreading" guide if no information is available besides water depth.
 - Can fit your own coefficient by finding a straight-line least-squares fit to semilog-plotted data.

Seawater attenuates sound at various rates, depending on frequency



- Arises from seawater chemistry
 - Magnesium and boron salts.
- Below 1 kHz: no effect at all.
- 10 kHz and above: essential effect.
 - For beaked whales (25 -75 kHz), can ignore ocean bottom.

TL=20log(r)+a*r

Bottom loss key factor in shallow water propagation



Table 1.3 Geoacoustic properties of continental shelf and slope	e environments
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Bottom type	р (%)	ρ_b/ρ_w	$\frac{c_p/c_w}{-}$	с _р (m/s)	cs (m/s)	(dB/λ_p)	$lpha_{s}$ (dB/ λ_{s})
Clay	70	1.5	1.00	1500	< 100	0.2	1.0
Silt	55	1.7	1.05	1575	$c_{s}^{(1)}$	1.0	1.5
Sand	45	1.9	1.1	1650	$c_{s}^{(2)}$	0.8	2.5
Gravel	35	2.0	1.2	1800	$c_{s}^{(3)}$	0.6	1.5
Moraine	25	2.1	1.3	1950	600	0.4	1.0
Chalk	-	2.2	1.6	2400	1000	0.2	0.5
Limestone	-	2.4	2.0	3000	1500	0.1	0.2
Basalt	-	2.7	3.5	5250	2500	0.1	0.2
$c_s^{(1)} = 80 \tilde{z}^{0.3} \qquad c_w = 1500 \text{ m/s}, \ \rho_w = 1000 \text{ kg/m}^3$ $c_s^{(2)} = 110 \tilde{z}^{0.3} \qquad c_w^{(3)} = 180 \tilde{z}^{0.3}$							

- Material parameters include bottom density, compressional and shear sound speed, and material attenuation.
 - Grain size often allows prediction of other parameters.
 - Combine to specify a *reflection coefficient* that shows effects of incident angle, frequency.
- May have multiple layers of sediments, each with own set of parameters.
- The lower the frequency, the deeper the sound will penetrate into the sediment.
- Scattering from rough surfaces can also add to transmission loss, especially when roughness scale~ wavelength.

Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient



Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient





FIG. 3. Comparison of COMPILE results and analytical estimates of damped cylindrical spreading approaches and $15\log(r)$ -approach scaled at r = 11 m (depth-averaged/The vertical bars are not error bars, but indicate the minimum/maximum sound exposure occurring in the water column).

Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient





FIG. 4. Comparison of BR1 measurements and analytical estimates of damped cylindrical spreading approaches and $15\log(r)$ -approach scaled at r = 234 m in a depth of z = 25 m. Dotted lines indicate limiting cases of a fine sand and a coarse sand half-space, respectively, see Sec. V.

What information is needed for detailed model?

Frequency
Water depth
Source depth
Receiver location (depth)
Bottom composition (important for low frequency)
Bathymetric profiles (range independent vs. range dependent)
Sound speed profile, including range dependence. (high frequency)
Surface roughness/ice cover and bottom roughness. (high frequency)
Scatterers in water column (fish): objects the same wavelength

How do I get this environmental information?



• Pro tip: A great way to appear intelligent when questioning an acoustic modeler!

Examples of online databases



Project Home Overview Main Topics Vupdates References Contacts MAIN TOPICS RELATED USGS DATASETS Data Catalog Surficial Sediment Data from the Gulf of Maine. Georges Bank, and Vicinity (Poppe and others, 2003) Sediment data, an overview of the sediment distribution off the US east coast, and basemaps are provided with geographic coordinates to allow the data to be integrated into a Geographic Information usSEABED: Atlantic Coast Offshore Surficial Sediment Data Release (Reid and others, 2005) System (GIS usSEABED: Gulf of Mexico and Caribbean (Puerto Rico and U.S. Virgin Islands) Offshore Surficial Sediment Data Release (Buczkowski and others, 2006) USGS East-Coast Sediment Analysis:Procedures. Database, and GIS Data **Database Visualization** Overview maps of the sediment classes for samples CITATION in the U.S. Geological Survey East-Coast Sediment Please cite the following database documentation and URL when information in this database is published: Texture Database are available for several selected U.S. Atlantic East Coast regions. Maps are provided in both JPEG image and Adobe PDF formats. McMulleri, K.T., Yakawaki, K.Y., and Poppe, L.J., 2014, GIS data catalog (ver. 30, November 2014), in Poppe, L.J., McMullen, K.Y., Williams, S.J., and Paskevich, V.F., eds., USGS east-coast sediment analysis: Procedures, database, and GIS data, U.S. Geological Survey Open-File Report 2005-1001, available online at Field methods and laboratory procedures used in the sedimentation laboratory at the Woods Hole Coastal and Marine Science Center (Poppe and others, 2014) are described in this overview. The U.S. Geological Survey East-Coast Sediment http://pubs.usgs.gov/of/2005/1001

Software used in the sedimentation laboratory at

he Woods Hole Coastal and Marine Science Center available as downloadable zipped files. These mpressed files contain compiled and uncompiled rsions of the software, helpful readme files, test files, and detailed documentation

Texture Database contains information on the collection, location, description, and texture of samples taken by marine sampling programs at the Woods Hole Coastal and Marine Science Center. Most of the samples are from the Atlantic Continental Margin of the United States, a small number of samples have been collected from a variety of other locations such as Lake Baikal, Russia, the Hawaiian Islands region, Puerto Rico, and Lake Michigan.

U.S. Department of the Interior | U.S. Geological Survey URL: http://woodshole.er.usgs.gov/project-pages/sediment/index.html Page Contact Information: <u>Feedback</u> Page Last Modified: Tuesday, 30-Dec-2014 09:28:37 EST (GW)

McMullen, K.Y., Paskevich, V.F., and Poppe, L.J., 2014,

U.S. Geological Survey East-Coast Sediment Texture Database online at URI http://woodshole.er.usgs.gov/project-pages/sediment/ National Centers for Environmental Information

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World Ocean Atlas

The World Ocean Atlas (WOA) is a collection of objectively analyzed, quality controlled temperature, salinity, oxygen, phosphate, silicate, and nitrate means based on profile data from the World Ocean Database (WOD). It can be used to create boundary and/or initial conditions for a variety of ocean models, verify numerical simulations of the ocean, and corroborate satellite data.

Data Access Help

Home / Products / World Ocean Atlas

Access Methods

Use WOASelect 2018 to search data from the most recent quarterly update by specific parameters (date, geographic area, probe type, etc.) and measured variables. View a dataset distribution map and cast count of your search criteria, and download a custom dataset in WOD native, csv, or netCDF.





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Current WOA Citation

Boyer, Tim P.; Garcia, Hernan E.; Locarnini, Ricardo A.; Zweng, Melissa M.; Mishonov, Alexey V.; Reagan, James R.; Weathers, Katharine A.; Baranova, Olga K.; Seidov, Dan; Smolyar, Igor V. (2018), World Ocean Atlas 2018. [indicate subset used]. NOAA National Centers for Environmental Information. Dataset. https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18. Accessed [date].





Three popular types of detailed models

- Each model makes assumptions about acoustic field to speed up computation.
- Ray tracing
 - BELLHOP
- Normal mode propagation
 - KRAKEN
- Parabolic Equation (PE)
 - RAM-GEO
- Not covered:
 - Wavenumber integration
 - best for ice, complex elastic boundaries, exact near field
 - Finite difference or finite element modeling.
 - Exact solution to wave equation
- Ocean Acoustics Library clearinghouse:
 - oalib-acoustics.org

Ray tracing

- "Shoot" rays that measure travel time, amplitude
 - "Denser" clusters of rays=more accurate results.
- Eigenrays
 - Rays that connect source and receiver.
- Key assumption: wavelength << ocean depth or features.
- Biggest advantages
 - deep water with little bottom interaction. (in terms of wavelengths)
 - Range-dependent bathymetry or environment.
- Disadvantages
 - Bottom interactions
 - More robust for measuring travel times than transmission loss.
- Common program: BELLHOP (Mike Porter)



Ray tracing visualizes refraction well, but all advanced models effectively include it



- "Snell's Law": A ray bends toward slower regions.
- Ray tracing codes basically evaluate Snell's law at every step.



Two ways of representing ray outputs

Ray tracing of deep water channel

• TL of shallow duct near Hawaii for FKW depredation study (inverted color)



Two ways of representing ray outputs

Ray tracing of deep water channel



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Normal mode model

- For shallow water where ray paths become "quantized"
- Key assumption: wavelength large vs. ocean bottom or sound speed profile features.



Normal mode model

- For shallow water where ray paths become "quantized"
- Key assumption: wavelength large vs. ocean bottom or sound speed profile features.
- Biggest advantages
 - Extremely fast
 - Can compute multiple receivers simultaneously.
- Disadvantages
 - Must be a few water depths away.
 - Awkward to implement range dependence.
 - Very shallow water has no modes (cutoff frequency)
- Common program: KRAKEN (Mike Porter)

Parabolic equation

- March a full-wave solution out in range in complex environment.
- Key assumptions:
 - wavelength large compared to ocean depth or ssp features.
 - Direction of propagation is mostly horizontal (small-angle approximation).
 - Getting less restrictive with newer formulations (Pade formulation)
 - No backpropagating (backwards-reflected) energy
- Biggest advantages
 - Fast TL computation in complex range-dependent environments. (See famous "wedge" example on right)
- Disadvantages
 - Propagation of large vertical angles still problematic (Pade approximation best).
- Common programs:
 - RAM-GEO (Mike Collins), wide-angle, navy certified
 - FWRAM (JASCO)
 - Good question to ask: what range of vertical angles is possible?



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Summary of models

Advanced Applications for Underwater Acoustic Modeling, Paul C. Etter

	Applications								
Model type		Shallo	w water		Deep water				
	Low frequency		High frequency		Low frequency		High frequency		
	RI	RD	RI	RD	RI	RD	RI	RD	
Ray theory	0	0	•	•	•	•	•	•	
Normal mode	•	0	•	•	•	0	•	0	
Multipath expansion	0	0	0	•	•	0	•	0	
Fast field	•	0	•	•	•	0	•	0	
Parabolic equation	0	•	0	0	•	•	•	0	
Low frequency (<500 Hz) High frequency (>500 Hz)					RI: range-independent environment RD: range-dependent environment				

Modeling approach is both applicable (physically) and practical (computationally)

Limitations in accuracy or in speed of execution

Neither applicable or practical

Computational Ocean Acoustics



- Range independent:
 - Normal mode if shallow water (low frequency).
 - Ray tracing if deep water.
- Range dependent:
 - PE if shallow water
 - Ray tracing if deep water

A comment on directional sources

- Ray tracing: can be weighted by launch angle.
- PE: Directional "starter" or multiple distributed sources
- Normal mode: distributed sources to reproduce source beampattern
- Pro tip: ask how directional sources are modeled!



Figure 5. Vertical radiation pattern of typical array. dB levels re 1μ Pa-m; rms peak-to-peak maximum of 13.4 bars (absolute P-to-P maximum of 19 bars).

Caldwell, Leading Edge, 2000

Conclusion

- Simple spreading models
 - Transmission loss, DCSM for pile driving
- Input requirements for models
- Ray, Normal Mode, and PE models
- Evidence of good modeling technique
 - Frequency and water depth match the technique.
 - Sources of environmental parameters clearly identified.
 - If environment not known, a range of values are tested.
 - Strategy for directional sources explained.
- Not covered-full 3-D modeling
- Further resources:
 - oalib-acoustics.org
 - P.C. Etter, Underwater Acoustic Modeling (E & FN Spon, London, UK, 1996).
 - Jensen, Kuperman, Porter, Schmidt, Computational Ocean Acoustics

Examples of other numerical codes

Technique		Range independent		Range dependent						
	CAPARAY	PLRAY		ACCURAY	GRAB	LYCH	Pedersen	RAYWAVE		
	FACT	RANGER		BELLHOP	GRASS	MEDUSA	PlaneRay ^b	RP-70		
Ray theory	FLIRT			Coherent DELTA	HARORAY	MIMIC	PWRC ^c	SHALFACT		
Ray theory	GAMARAY			FACTEX	HARPO	MPC	Ray5 ^d	TRIMAIN		
	ICERAY			FeyRay ^a	HARVEST	MPP	RAYSON ^e	XRAY ^f		
	AP-2/5	MODELAB	ORCA	ADIAB	COUPLE	KRAKEN	PROSIM	WKBZ		
	BDRM	NEMESIS	POPP ^g	ASERT	CPMS	MOATL	SHAZAM	WRAP		
Normal mode	COMODE	NLNM	PROTEUS	ASTRAL	FELMODE	MOCTESUMA	SNAP/C-SNAP	3D ocean		
	DODGE	NORMOD3	SHEAR2	CENTRO	IECM ^h	NAUTILUS	SWAMP ⁱ			
	FNMSS	NORM2L	Stickler	CMM3D	Kanabis	PROLOS	WEDGE			
Multipath	FAME	NEPBR				Integrated mode ^j				
Expansion	MULE	RAYMODE								
Fast field or	FFP	OASES	SAFARI	CORE	RD-OASES	SAFRAN				
wavenumber	Kutschale FFP	pulse FFP	SCOOTER	OASES-3D ^k	RDOASP					
integration	MSPFFP	RPRESS	SPARC	RDFFP	RDOAST					
				AMPE/CMPE	FEPES	MONM3D ^m	PE-FFRAME	Two-WayPE		
Parabolic Use equation				Cartesian 3DPE ¹	FOR3D	MOREPE	PESOGEN	ULETA		
				CCUB/SPLN/CNP1	HAPE	NSPE ⁿ	PE-SSF (UMPE/MMPE)	UNIMOD		
	Use single	e environmental spe	cification	corrected PE	HYPER	OS2IFD	RAM/RAMS/RAMGEO ^p	3DPE (NRL-1)		
				DREP	IFD wide-angle	OWWE ^o	RMPE ^q	3DPE (NRL-2)		
				FDHB3D	IMP3D	PAREQ	SNUPE	3DTDPA		
				FEPE	LOGPE	PDPE	Spectral PE	3DWAPE ^r		
				FEPE-CM	MaCh1	PECan	TDPE			

TABLE 1: Summary of underwater acoustic propagation models. Superscript letters identify those models that have been added to the inventory since 2003.

Advances in Acoustics and Vibration

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