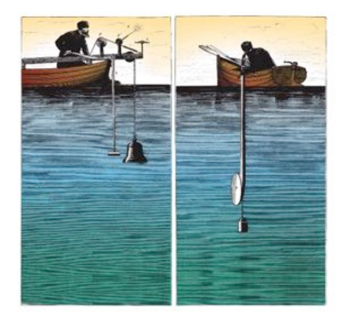
Basics of Underwater Acoustics

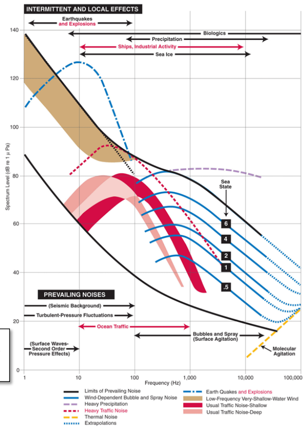


Nick Durofchalk ndurofchalk@gatech.edu
Dr. Karim Sabra karim.sabra@me.gatech.edu

Underwater Sound

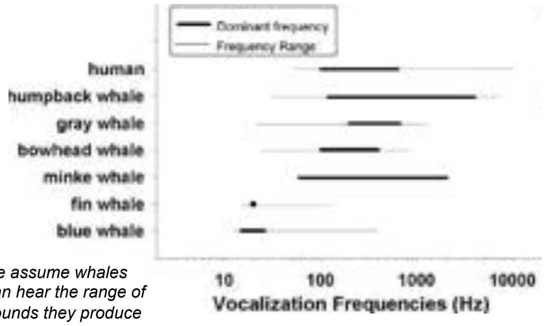
- Very low frequency (1-10 Hz)
  - Seismic activity
  - Explosions
- Low frequency (10 – 100 Hz)
  - Shipping traffic
  - Sea ice noise
- Mid frequency (100 – 1000 Hz)
  - Shipping traffic
  - Biological noise (whales, etc.)
  - Precipitation
- High frequency (1000 – 10,000 Hz)
  - Wind / spray noise
  - Biological noise (dolphins, etc.)

Sound in the ocean occupies a large frequency band



Wenz, Gordon M. "Acoustic ambient noise in the ocean: Spectra and sources." *The Journal of the Acoustical Society of America* 34.12 (1962): 1936-1956.

Underwater Sound



we assume whales can hear the range of sounds they produce

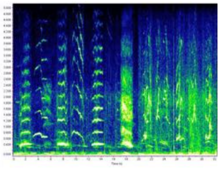
infrasonic (about 20 Hz) < human hearing < ultrasonic (about 20,000 Hz)

Underwater Sound

Spectrograms – biological sounds

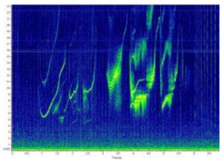
Humpback whale

Freq. band: 0 Hz – 5 kHz



Atlantic Spotted Dolphin

Freq. band: 0 Hz – 25 kHz



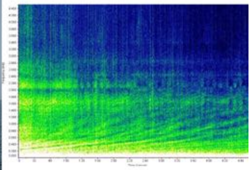
Noaa. "Sounds in the Ocean." *NOAA*, 31 Oct. 2019, www.fisheries.noaa.gov/national/science-data/sounds-ocean.

Underwater Sound

Spectrograms – man-made sounds

Shipping vessels

Freq. band: 0 Hz – 5 kHz



Utilizing noise from 'ships of opportunity' is an active research topic

Noaa. "Sounds in the Ocean." *NOAA*, 31 Oct. 2019, www.fisheries.noaa.gov/national/science-data/sounds-ocean.

Why Underwater Sound?

- Light and radio *(electromagnetic)* waves are **quickly attenuated** when propagating through the water
- Sound *(mechanical)* waves propagate very long distances underwater (global scales)

The speed of sound in water is approximately 1500 m/s while the speed of sound in air is approximately 340 m/s.

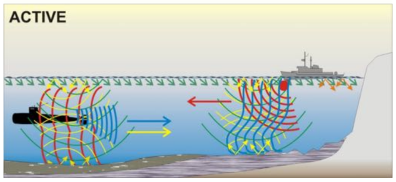
Uses of Underwater Sound

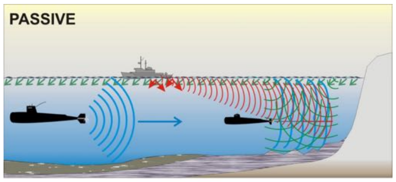
- SONAR (SOund NAvigation and Ranging)
- Detection, Classification, Localization, Identification
  - Passive: listening
    - Anti-submarine warfare, biological monitoring
  - Active: transmitting and listening (echolocation)
    - Anti-submarine warfare, mine detection, surveying (side-scan), depth sounding, imaging, fisheries
- Communication
- Monitoring global warming (Acoustic Thermometry of Ocean Climate (ATOC) project)

Uses of Underwater Sound

SONAR

SOund
NAvigation and
Ranging





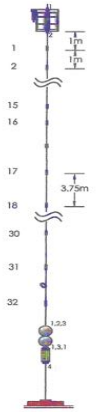
My current work involves passive sonar

- Detection, Classification, Localization, Identification, Imaging

My Current Research

Santa Barbara Channel Experiment (2016)

- Four VLAs deployed



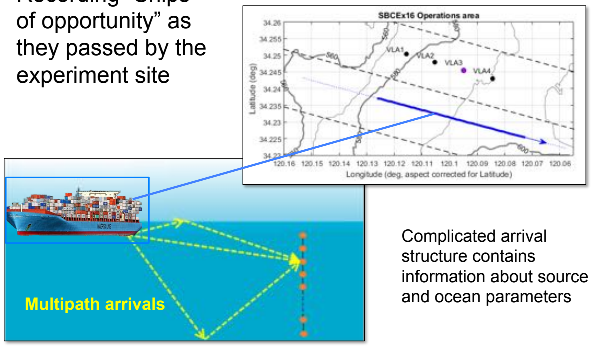
That's me!

Vertical Line Array (VLA)

My Current Research

Recording “Ships of opportunity” as they passed by the experiment site

Sept 16, 2016 *Anna Maersk* passes the VLAs



Complicated arrival structure contains information about source and ocean parameters

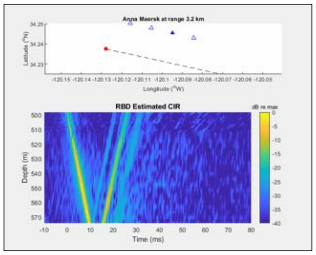
My Current Research

Through clever signal processing with can estimate the **Channel Impulse Response (CIR)**

Like a transfer function, the CIR maps an input signal to the received signal

Channel Impulse Response

- Function of **source position and ocean parameters**

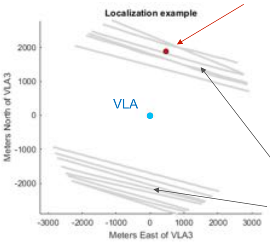


Throughout the experiment duration, we collect many CIR estimates

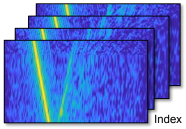
My Current Research

We can then use the CIR estimates to perform **source localization**

New target at unknown location



CIR library



Index N at range R_N

…

Index 1 at range R_1

Library ship tracks

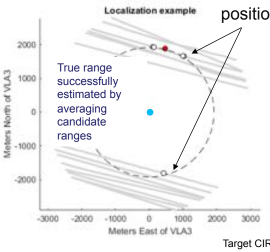
- Each location has a CIR and distance to VLA associated with it

Library: 14 ship-transit events
$N=2,114$ total snapshots in library

My Current Research

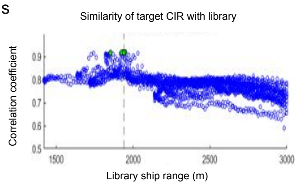
We can then use the CIR estimates to perform **source localization**

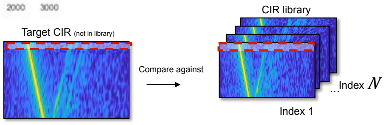
Candidate positions



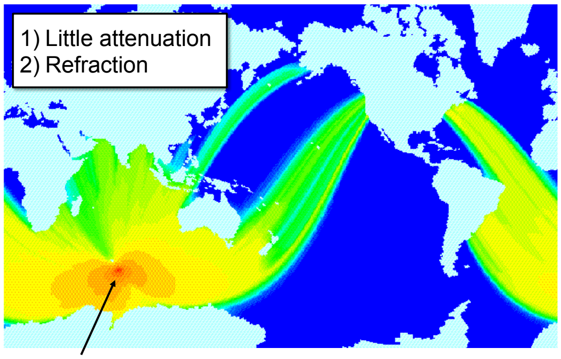
True range successfully estimated by averaging candidate ranges

Matched field processing





Sound Propagation on Global Scale



1) Little attenuation
2) Refraction

Earthquake epicenter

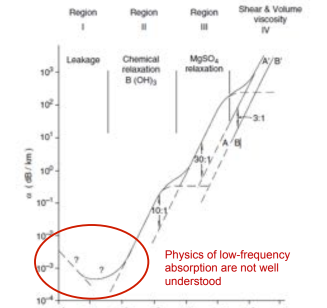
(Collins et al., JASA 97(3), p. 1567)

Sound Propagation on Global Scale

Attenuation

As sound propagates, some energy converted to heat (i.e. friction) or is scattered and dispersed.

Attenuation of low-frequency sound is **very small.**



Physics of low-frequency absorption are not well understood

Fig. 1.20 Regions of the different dominant processes of attenuation of sound in seawater (from Urick [25])

$$\alpha' = 3.3\times10^{-3} + \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 3\times10^{-4} f^2 \quad [dB/km]$$

Jensen, Finn B., et al. *Computational ocean acoustics.* Springer Science & Business Media, 2011.

Sound Propagation on Global Scale

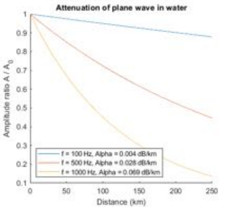
Attenuation - Example

Attenuation of plane-waves is defined from a decay-law-type equation.

$$A(x) = A_0 e^{-\alpha x}$$

The attenuation coefficient α is defined in units nepers/m, but in practice it is useful to discuss attenuation α' in units of dB/km

$$\alpha' \; [dB/m] \approx 8{,}686 \; \alpha \; [nepers/m]$$



Question: How much distance would a plane wave at 100 Hz have to travel in order to attenuate $\sim 10\ dB$? How would your answer change if the frequency was $1\ kHz$?

Frequency	α' (dB/km)	α(nepers/m)
100 Hz	0.0045	5.1802×10^{-7}
1,000 Hz	0.0693	7.9818×10^{-6}

$$\alpha' = 3.3\times10^{-3} + \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 3\times10^{-4} f^2 \quad [dB/km]$$

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Sound Propagation on Global Scale

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Solution:

α' at $100\ Hz$ is approximately 0.0045 dB/km
The plane wave must attenuate $\sim 40\ dB$ to be at the noise floor

$$10\ dB = 0.045\, dB/km \times x\ [km] \quad \rightarrow \quad x \approx 2200\ km$$

Similarly, if the frequency of the wave is $1000\ Hz$, $x \approx 144\ km$

Jensen, Finn B., et al. *Computational ocean acoustics.* Springer Science & Business Media, 2011.

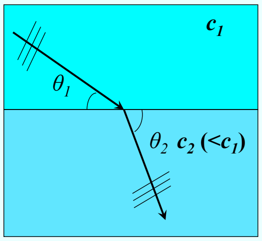
Sound Propagation on Global Scale

Refraction

"SOUND LIKES LOW SPEEDS" !

Snell's Law

$$\frac{\cos(\theta_1)}{c_1} = \frac{\cos(\theta_2)}{c_2}$$



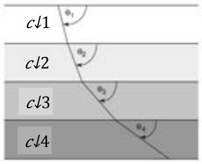
Direct application: **Ray Tracing**

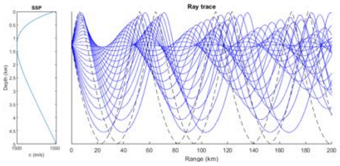
- High frequency (small wavelength) approximation
- Describes where in the water column sound emanating from a source is being sent: Good for rapid visualization & prediction
- Easier to compute for linear sound speed profiles

Historical insert > Ray Tracing

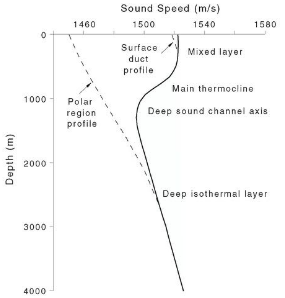
Ray Tracing

- Ray behavior long understood before mathematically formalized
- Law of refraction dates back to 1626.
- Lichte (1919) *On the influence of horizontal temperature layers in seawater on the range of underwater sound signals*
  - "There is a general opinion that water is significantly better for the transmission of sound signals than air because it is more homogeneous. This however, is not the case. On the contrary, for a variety of reasons, water is acoustically inhomogeneous in horizontal layers. As a result, a deviation of sound rays from straight lines, i.e., a bending of the sound rays takes place."





Generic Sound Speed Structure



- Speed of sound increases with:
  - Temperature, (T)
  - Salinity, (S)
  - Depth, (z) ambient pressure
- Exact relationship is complicated
- Dominating parameters vary diurnally, seasonally and geographically

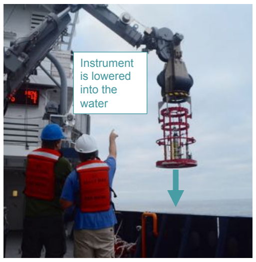
Empirical formula for sound speed

$c(T,S,z)=1449.2+4.6T-0.055T^2 + 0.00029T^3 +(1.34-0.01T)(S-35) + 0.016z$

Units: T (degrees centigrade), S (parts per thousand), z (meters)

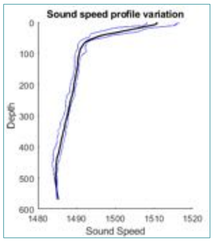
Measuring Sound Speed

CTD – Instrument used to measure **conductivity**, **temperature**, and **depth**.



Instrument is lowered into the water

Sound speed values are calculated from measurements



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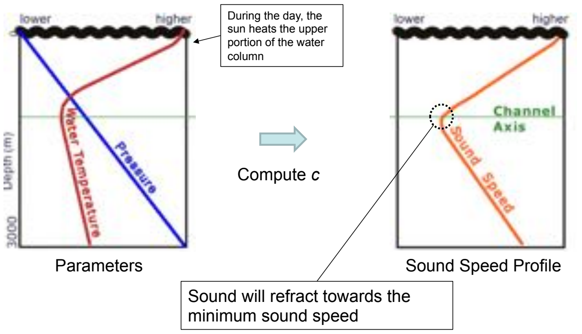

During the day, the sun heats the upper portion of the water column

Compute *c*

Parameters

Sound Speed Profile

Sound will refract towards the minimum sound speed

http://www.pmel.noaa.gov/vents/acoustics/tutorial/11-sofar.html

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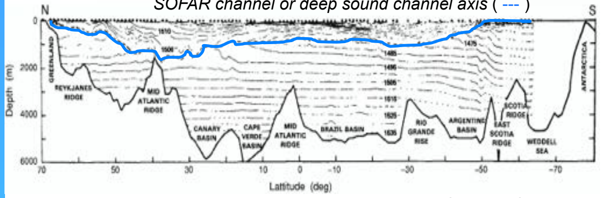
Global Sound Speed Structure

North-South Atlantic along 30.5°N

SOFAR channel or deep sound channel axis (---)



From Northrup and Colborn, JGR, 1974

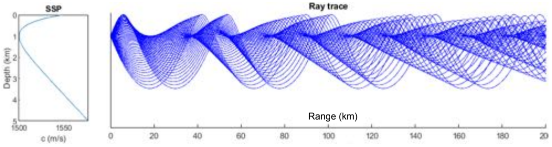
•Variability of the upper-ocean (<1km) sound speed structure.

•Stability of the deep isothermal layer.

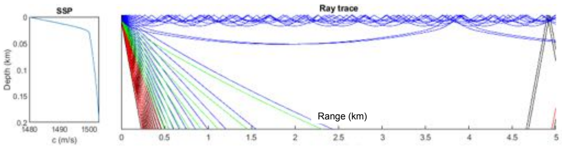
•Axis of the deep sound channel becomes shallower towards both poles and eventually reaches the surface.

Global Sound Speed Structure

The Deep Sea Sound (or SOFAR) channel is an effective wave guide near the mid-latitudes (min c at depths ~1000 m)

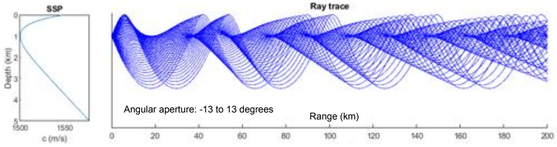


In polar regions, min sound speed is at the ocean surface. Propagation is heavily surface-interacting and lossy.

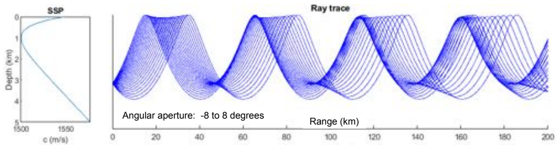


Global Sound Speed Structure

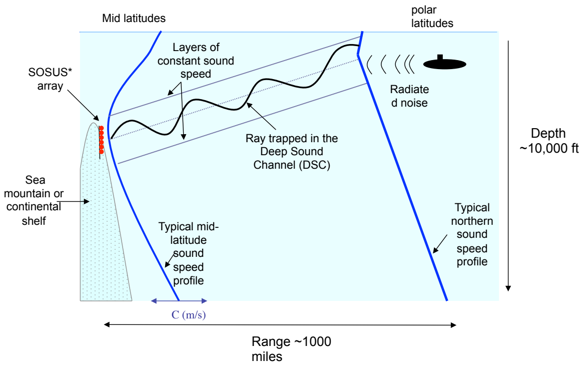
Portion of source power trapped in SOFAR waveguide is proportional to the aperture of internally refracted rays



Source off axis – less energy trapped in waveguide

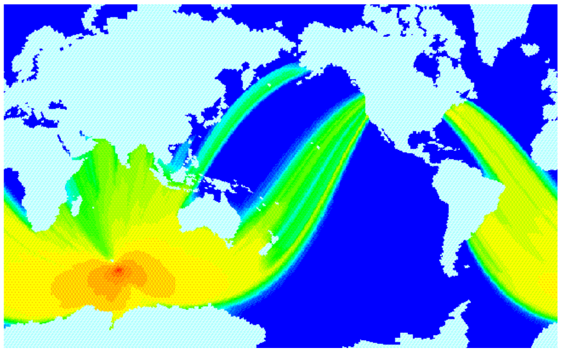


Historical Underwater Acoustics



*Sound Surveillance System (SOSUS).

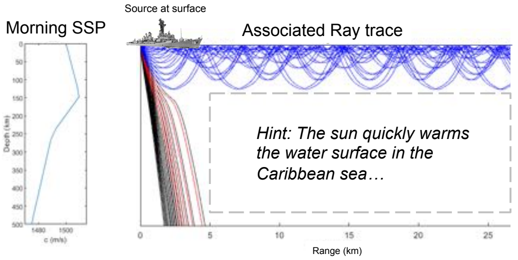
Sound Propagation Around the Globe



(Collins et al., JASA 97(3), p. 1567)

Trivia

In the summer of 1937, officers aboard the U.S.S. Semmes were at a loss to explain or correct the ship's sonar problems during exercises in the waters off Guantánamo Bay, Cuba. For some reason, the performance of the devices consistently deteriorated in the afternoon; they sometimes failed to return echoes at all. How would you explain this puzzling **"afternoon effect"** ?



Hint: The sun quickly warms the water surface in the Caribbean sea…

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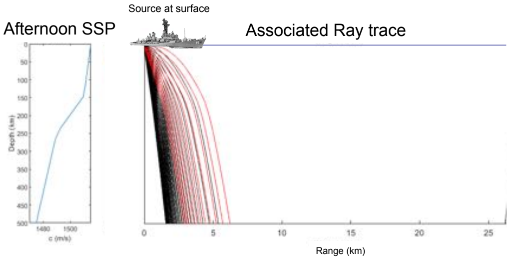
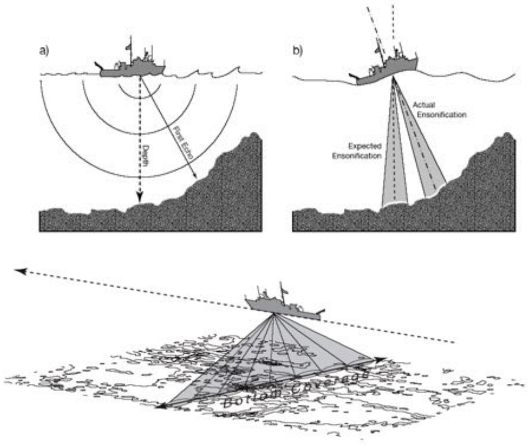
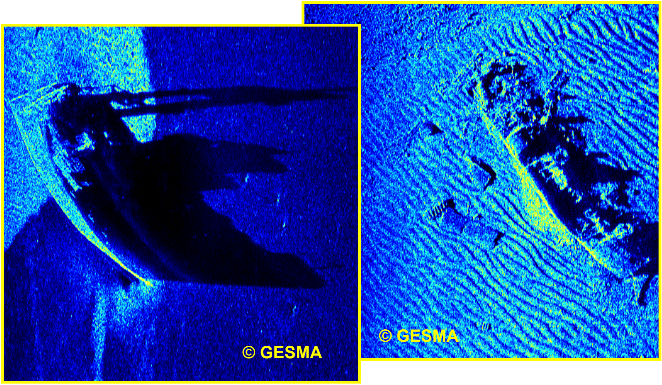


EXTRA SLIDES
Underwater Imaging

Underwater acoustic bottom mapping



Wrecks



Synthetic Aperture Sonar (SAS) Imaging

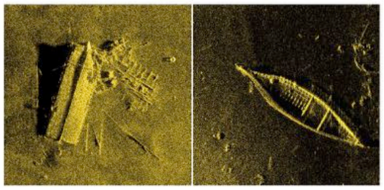


Fig. 6: SAS images of two different wrecks outside Bergen, Norway. The water depth is around 340 m. Courtesy of the Royal Norwegian Navy.