Signals and systems in Underwater Acoustics: listen through the ocean

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Outline

1. Generalities of sound propagation in the ocean

2. Sound speed in sea water
   - calculating the sound speed profile
   - typical profiles
   - ocean stratification

3. The deep ocean and coastal areas: transition zone

4. Transmission loss: border and frequency effects

5. Ambient noise

6. Sonar equation
7. Applications:
   - active and passive sonar
   - echosounding and fishing
   - geotechnical and oil exploration
   - ocean thermometry and tomography
   - marine mammal monitoring
   - underwater communications
   - localization and navigation
   - port and waterway protection

8. Examples of real signals

9. The ocean as an input - output model
Generalities of sound propagation in the ocean (1)

Sound attenuation in the ocean at high frequency with $T = 25^\circ C$ and $S = 35$ ppt.

Ambient noise power due to: sismic noise, thermic agitation, rain, surface noise, etc.

(Tolstoy & Clay, AIP, New York, 1987)
Generalities of sound propagation in the ocean (2)

- intermittent local effects
- permanent effects
- low frequency:
  - earthquake and explosions
  - wind in shallow water
- mid frequency
  - shipping noise
- high frequency
  - surface waves
  - surface noise
  - wind and waves
Generalities of sound propagation in the ocean (3)

Most important factors in ocean sound wave propagation

1. the (variation) of sound speed

2. water depth

3. media interface type

4. sound frequency $\lambda = \frac{c}{f}$
Sound speed in the ocean

- the speed of sound in the ocean was measured for the first time by Colladon and Sturm in 1827, in the lake of Geneva, Switzerland, having a value close to 1500 m/s, but varying with pressure (depth), with temperature and with salinity according to an empirical formula given by:

\[ c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016z \]

where

- \( c \) = sound speed (m/s)
- \( T \) = temperature (°C)
- \( S \) = salinity (ppt)
- \( z \) = depth (m)
Calculating the sound speed profile

Sound speed variability:
- latitude
- year season
- ocean agitation
- currents/fronts/topography
Typical sound speed profiles
Ocean stratification

- high variability of sound speed in the vertical but relatively constant in the horizontal
- forming a deep sound channel propagation (DSC = deep sound channel) associated with the minimum of the sound speed profile
- variation of the DSC with latitude
- disappearing of DSC in coastal areas with energy redistribution
Transition zone

- topography effect
- currents and tide
- internal tides
- energy concentration
The effect of water depth

- shallow water:
  ⇒ guided wave
  ⇒ strong interaction with the borders
  ⇒ border type (impedance)
  ⇒ frequency and wave length
  \[ \lambda = \frac{c}{f} \approx \frac{1500}{f} \]

- deep water:
  ⇒ refraction in the media
  ⇒ strong dependence from the water column
  ⇒ free space
Transmission loss

Transmission loss (TL) calculation is given by:

\[ TL_{dB} = 10 \log_{10} \frac{P_{source}}{P_{receiver}} \]

\( dB \) underwater = pressure re 1 \( \mu \)Pascal (in the air the reference is 20 \( \mu \)PA)

- in shallow water \( \Rightarrow \) by border interaction
- in deep water \( \Rightarrow \) by cylindrical attenuation with distance
Signal attenuation with distance

Model: C-Snap; F=50 Hz (seamount), F=25 Hz (upslope)
Sound signal attenuation with frequency

- 50 Hz
- 100 Hz
- 1 kHz
- 10 kHz

Signals and Systems in Underwater Acoustics
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Sound propagation (in short)

- depending on the wave equation with border conditions
- border reflections
- refraction in the media itself \((c(z) \text{ not constant})\)
- reverberation problem (media response to the acoustic signal)
- scattering effects in the surface or objects at high frequency (objects in movement)
Underwater acoustic noise

- **biological**: marine mammals, shrimps *(shrimp noise)*
- **sismic**: earthquakes, tectonic plate movement
- **human**: shipping noise, submarines, fishing
- **meteorological**: surface wind, waves *(bubble noise)*, tides, rain
Sonar equation (1)

SONAR *S*Oundy NAvigation and Ranging: the sonar equation has the objective to provide a simple method for determining the detection level of a given target in real conditions.

Active sonar in noise

\[ DT = SL + DIt + TS - 2TL - (NL-DI) \]

Active sonar in reverberating noise

\[ DT = SL + DIt + TS - 2TL - RL \]

Passive sonar

\[ DT = SL + DIs - TL - (NL-DI) \]

- **DT** = detection threshold
- **SL** = source level
- **DIt/s** = target/source directivity index
- **TS** = target strength
- **TL** = transmission loss
- **NL** = noise level
- **RL** = reverberation level
- **DI** = directivity index (receiver)
Sonar equation (2)

Example: we want to detect a target with an active sonar with a transmit power of $SL = 150 \text{ dB}$, a directivity index of the receiver $DI = 10 \text{ dB}$, a $TS = 10 \text{ dB}$, and a $DIt=25 \text{ dB}$ in an ambient noise $NL = 40 \text{ dB}$,

Active sonar in noise $DT = SL + DIt + TS - 2TL - (NL-DI)$
Applications

- active and passive sonar
- sidescan and multibeam sonar
- echosounding and fishing
- oil and geotechnical exploration
- ocean thermometry and tomography
- monitoring of marine mammals
- underwater communications
- target navigation and localization
- port and waterway protection
Sonar for military usage

LF sonar: 400 - 1000 Hz
- 10 - 50 km
- long range detection
- towed or hull mounted array

MF sonar: 3000 Hz
- < 5 km
- hull sonar (conformal)

HF sonar: > 100 kHz
- 100 - 250 m
- mine detection
- bottom exploration
Submarine detection

- **passive sonar:**
  extremely difficult

- **active sonar:**
  traditional, short range
  SURTASS - LFA, upto 10 km

- **sonobuoys:**
  (LOFAR)
  - active / passive
  - triangulation
  - mono and multisensor

USS Key West
Sidescan and multibeam sonar

multibeam sonar
- sweep beam
- two way travel time
- depends on depth

sidescan sonar
- towed
- records intensity
- difficult to navigate

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Sounding and fishing (1)

Hobby echosounding: 5 - 50 kHz, variable power; submerged objects and bottom type.

Hobby echosounding for fish detection: 20 - 200 kHz, angle and variable power.

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**swim bladder**
- resonant element
- density difference
- volume

**propagation conditions**
- thermocline
- muddy bottom, rock or algae
- water salinity
- dissolved particles
Sounding and fishing (2)

Objective
- to intimidate or attract fish schoals

Between species
- frequency: 0.1 - 60 kHz
- sensitivity: 100 - 160 dB (re 1µ P/Hz)

Studies
- comportamental
- *in situ*, invasive

Kastelein et al. “Startle response of captive North Sea fish species to underwater tones between 0.1 and 64 kHz”, Marine Environmental Research, Elsevier, No. 65, p.369-377, 2008
Geotechnical and oil exploration (1)

- anchored or towed systems
  - horizontal or vertical arrays
  - impulsive source (sparker/uniboom)
  - reflection analysis
  - *full-field* inversion
  - geological or sismic studies
  - sediment study
Geotechnical and oil exploration (2)

towed systems
• very long arrays (> 1 km)
• impulsive source / low freq
• reflection analysis
• geological studies
• bottom sampling
• (cores)

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Ocean thermometry and tomography

principle of medical TAC
- to "illuminate" an object from multiple points
- reconstruction of the object from the received signals (inversion)

global monitoring
- mean temperature in depth and range
- resolution: 0.01 °C
- scale: 3000 - 5000 km

initiatives
- HIFT: 1991
- ATOC: 1997-1999
- NPAL: 2002-
Ocean observation

Observation network NEPTUNE: Canada & U.S.A.

- deep water observation stations
  - biology, geophysics, oceanography
  - T wave observation
  - communications

ESONET observation network: european network (2007 - 2011)

- stations in 10 countries from Norway to Turkey
- 35 partners (in Portugal: UAc, FCUL, CINTAL, UALg)
- Azores: geothermal sources
Monitoring of marine mammals

- **frequency band**
  100 Hz - 200 kHz
- **sound level**
  from 140 to 230 dB re μPA
- **localization**
  passive, active and visual
- **sensitivity**
  frequency range and acoustic power
- **impact**
  tomography (ATOC)
  navy sonar (SURTASS-LF)

solmar.saclantc.nato.int

Orca
Pilot whale
Humpback whale
Underwater communications

- communication between subs
- communication sub-surface
- shallow water:
  \[ \Rightarrow < 5 \text{ km}, < 8 \text{ kbits/s} \]
- or deep water
  \[ \Rightarrow < 20 \text{ km}, < 15 \text{ kbits/s} \]
- control and command of autonomous vehicles
Navigation and localization

Tracking and navigation of cooperative underwater targets: AUVs
Port and waterway protection

- detection of an underwater vehicle of small dimension (AUV)
- diver detection
- shallow water
- network based sensor system

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Examples of acoustic signals (1)
MakaiEx Sea Trial - Kauai I., Hawai (EUA), September 2005.
Examples of acoustic signals (2)

Source: Testbed / Lubell 1424 (Spawar, USA) - Receiver: AOB2 (SiPLAB, Portugal)

HF: 8 - 14 kHz

BF: 1 - 8 kHz

SiPLAB acoustic array: 8 hydrophones,
10 - 75 m, Band: 50 Hz - 16 kHz
Examples of acoustic signals (3)
Modeling

**Source:**

\[ s(t) \]

**Ocean Model:**

\[ h(t) \]

**Receiver:**

\[ y(t) = x(t) + n(t) \]

**Parameters:**

- Water column, ocean bottom, geometrical; varying in time and/or in space; known, unknown or to be estimated

**Model:**

- Physical or generic

**Source:**

- Single or multiple; deterministic or random (noise)

**Receiver:**

- Single or multiple; known or unknown position

**Parameters:**

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Outline of Signals and Systems

- SS1 - Introduction and the generalized Matched Filter
- SS2 - Detection problems
- SS3 - Estimation problems
- SS4 - Spatial array processing
- SS5 - Underwater Communications Basics
- SS6 - Underwater Communication Channels and Equalizers
References

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