SEVENTH FRAMEWORK PROGRAMME
Marie Curie Actions-People
International Research Staff Exchange Scheme

Ocean Acoustic Exploration (OAEx)

OAEx’10 EXPERIMENT
DATA REPORT and PROCESSING
Workshop
Centro de Investigação Tecnológica do Algarve (CINTAL)
Universidade do Algarve
Campus de Gambelas, Faro, Portugal
June 2011
Abstract

This report includes the presentations of the OAEx’10 Experiment Data Report and Processing Workshop held 27-28th June 2011 at the University of Algarve. The objectives of this workshop were to finalize the OAEx’10 Experiment data report lead by IEAPM, present preliminary results from the different groups and discuss the next steps on data processing and data dissemination. The workshop occurred in a period were a large number of researchers from IEAPM, COPPE/UFRJ and UVic visited University of Algarve/Cintal in the framework of the OAEx programme, thus allowing to a broaden exchange of ideas within the group and synchronize the efforts of the different researchers involved.
Contents

Programme .................................................. 2
Attendance list .............................................. 6
Presentations ................................................ 8
Programme

OAEx’10 EXPERIMENT DATA REPORT AND PROCESSING WORKSHOP

27-28th June 2011
University of Algarve
Meeting room 3.18, FCT Building

June 27th

14:00-14:15 OPENING

14:15-14:45 GEOACOUSTICS PARAMETERS OF SEAFLOOR ON OAEX’S RESEARCH AREA - A CONTRIBUTION TO ACOUSTIC EXPERIMENTS

Simões, I. C. V. P. (1) Macedo, H. C. (1); Artusi, L. (1); Hermand, J. -P. (2); Abuchacra, R. C. (3); Figueiredo Jr., A. G. (3) , Alvarez, Y. G.(1); Romano, R.C.G. (1); Plouvier, L.(1),

(1)Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM,
(2)Université libre de Bruxelles (ULB) – Environmental Hydroacoustics Laboratory,
(3)Departamento de Geologia – LAGEMAR - Universidade Federal Fluminense – UFF

14:45-15:15 OAEx’10 Experiment : CONTRIBUTIONS FROM PHYSICAL OCEANOGRAPHY

Ana Cláudia de Paula, Leandro Calado, Wandrey de Bortoli Watanabe, Ricardo Marques Domingues, Eduardo Negri de Oliveira, Fernando de Oliveira Marin

Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM

15:15-15:30 Coffee Break

15:30-16:00 LFMs ARRIVAL PATTERNS at OAEx’10

Leonardo Martins Barreira, Fábio Contrera Xavier, Marcus Vinícius da Silva Simões, Celso Marino Diniz

Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM
16:00-16:30 SOME PRELIMINARY OBSERVATIONS OF OAEx SEA TRIAL AND GUIDELINES FOR FUTURE WORK
Salman Ijaz, António J. Silva, Sérgio M. Jesus
SiPLAB, ISR-Lisbon, University of Algarve

JUNE 28th
09:30-10:00 GEOACOUSTIC MODELING IN SHALLOW WATER SEDIMENT ENVIRONMENTS
Ross Chapman
University of Victoria

10:00-10:30 ACOUSTIC INVERSION WITH MFP FOR SEABED CHARACTERIZATION IN OAEx’10 EXPERIMENT
Lussac P. Maia(1), Lucia Artusi(2), Carlos E. Parente R.(1), Jean-Pierre Hermand (3)
(1)Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE)/Federal University of Rio de Janeiro (UFRJ),
(2)Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM,
(3)Université libre de Bruxelles (ULB) – Environmental Hydroacoustics Laboratory

10:30-10:45 Coffee Break

10:45-11:15 PROPAGATION EXPERIMENTS WITH CAVITATION NOISE
Hugo Chaves, Benavides Xavier, Kleber Pessek, Luis Guimarães, Carlos Parente
Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE)/Federal University of Rio de Janeiro (UFRJ)

11:15-11:45 BELLHOP TRANSMISSION LOSS PERFORMANCE EVALUATION FROM FIELD DATA OF OAEx’10 EXPERIMENT
Celso Marino Diniz, Marcus Vinicius da Silva Simões, Leonardo Martins Barreira, Fábio Contrera Xavier
Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM
11:45-12:15 NUMERICAL MODELING OF SIGNAL PROPAGATION IN THE CONDITIONS OF THE OAEEx’10 EXPERIMENT

Orlando Rodriguez(1), Fábio Contrera Xavier(2)

(1) SiPLAB, ISR-Lisbon, University of Algarve,
(2) Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM

12:15-14:00 Lunch

14:00-14:30 BAYESIAN SONAR PERFORMANCE PERSPECTIVES FOR CABO FRIO

Nélson Martins(1), Leandro Calado(2)

(1) SiPLAB, ISR-Lisbon, University of Algarve,
(2) Marinha do Brasil - Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM

14:30-15:30 FUTURE WORK PLANNING
Attendance list

- **UALG /PT**
  - Sérgio Jesus (sjesus@ualg.pt)
  - Nélio Martins (nmartins@ualg.pt)
  - Paulo Felisberto (pfelis@ualg.pt)
  - Orlando Rodríguez (orodrig@ualg.pt)
  - António Silva (asilva@ualg.pt)
  - Salman Ijaz (ssiddiqui@ualg.pt)
  - Fábio Lopes (flsantos@ualg.pt)
  - Usa Vilaipornsawai (usa.vilaipornsawai@mail.mcgill.ca)
  - Paulo Santos (pjsantos@ualg.pt)
  - Ana Bela Santos (absantos@ualg.pt)
  - Emanuel Ey (emanuel.ey@gmail.com)
  - Cristiano Soares (csoares@ualg.pt)

- **IEAPM / BR**
  - Marcus Vinicius Simões (simoes@ieapm.mar.mil.br)
  - Ana Cláudia de Paula (ana.claudia@ieapm.mar.mil.br)
  - Lúcia Artusi (lucia@ieapm.mar.mil.br)
  - Isabel Peres Simões (isabel@ieapm.mar.mil.br)
  - Leonardo Barreira (barreira@ieapm.mar.mil.br)
  - Celso Diniz (celso@ieapm.mar.mil.br)
  - Wandrey Watanabe (wandrey@ieapm.mar.mil.br)

- **COPPE / BR**
  - Kléber Pessek (kpessek@uol.com.br)
  - Hugo Chaves (hugochaves1@gmail.com)
  - Benevides Xavier (bcbxavier@yahoo.com)
  - Lussac Maia (lussacmaia@gmail.com)

- **UVic / CA**
  - Ross Chapman (chapman@uvic.ca)
Presentations

GEOACOUSTICS PARAMETERS OF SEAFLOOR ON OAEX’S RESEARCH AREA
- A CONTRIBUTION TO ACOUSTIC EXPERIMENTS 9

OAEx’10 EXPERIMENT:
CONTRIBUTIONS FROM PHYSICAL OCEANOGRAPHY 16

LFMs ARRIVAL PATTERNS at OAEx’10 24

SOME PRELIMINARY OBSERVATIONS OF OAEx SEA TRIAL
AND GUIDELINES FOR FUTURE WORK 31

GEOACOUSTIC MODELING IN SHALLOW WATER
SEDIMENT ENVIRONMENTS 35

ACOUSTIC INVERSION WITH MFP
FOR SEABED CHARACTERIZATION IN OAEx’10 EXPERIMENT 42

PROPAGATION EXPERIMENTS WITH CAVITATION NOISE 53

BELLHOP TRANSMISSION LOSS
PERFORMANCE EVALUATION
FROM FIELD DATA OF OAEx’10 EXPERIMENT 59

NUMERICAL MODELING OF SIGNAL PROPAGATION
IN THE CONDITIONS OF THE OAEx 10 EXPERIMENT 67

BAYESIAN SONAR PERFORMANCE PERSPECTIVES FOR CABO FRIO 76
GEOACOUSTICS PARAMETERS OF SEA FLOOR AT OAEx RESEARCH AREA

CONTRIBUTIONS TO ACOUSTIC EXPERIMENTS
INTRODUCTION

• Shallow water acoustic propagation is strongly influenced by interaction with the seabed

• Geoaoustic models are based on measured, extrapolated and predicted values

• Although the recent acoustical development, in Brazil we are still taking the first steps in geoaoustic research

• Information gathered will be useful on planning acoustic experiments, improve better models of submarine propagation and increase the accuracy of predictive sonar range.

GOAL

• To know the geological/geoaoustic settings

• Data presented: multibeam data, surface sediments analyses, side scan data, high resolution seismic data and geological cores.

• To present average values and statistical analyses of laboratory determined properties of the various sediment types as compressional wave velocity (Vp), density, acoustic impedance and porosity; the relations between these parameters and grain size of sediments and the influence of time, orientation and composition of subbottom layers.
Sea floor

- **Bathymetry**
  - multibeam echosounder – 95 kHz
  - nautical charts (1503, 1505 e 1508)
  - TAURUS hydrographic ship
- **Surface geological samples**
  - samples on Banco Nacional de Dados Oceanográficos da Diretoria de Hidrografia e Navegação (BNDO/DHN)
  - Van-Veen and Gibbs
- **Sidescan sonar**
  - Sonar Klein Serie 5000 - 100/500 kHz
  - Ocean Surveyor ship SonarWiz5

Sub Sea floor

- **Seismic**
  - Geopulse 3,5 kHz (Geoacoustics)
  - SonarWiz5
  - Ocean Surveyor ship
- **Geological Cores**
  - Piston core
  - DIADORIM ship
  - Multi-Sensor Core Logger
  - granulometric analyses and CaCO3 contents

Bathymetry

Seafloor sediments
Cores

GEOTEK Multi-Sensor Core Logger (MSCL)

compressional wave velocity (Vp), bulk density and porosity acoustic impedance
### Sediment Average Vp (m/s)

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Average Vp (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium sand (1 to 2 Φ)</td>
<td>1671</td>
</tr>
<tr>
<td>Fine sand (2 to 3 Φ)</td>
<td>1684</td>
</tr>
<tr>
<td>Very fine sand (3 to 4 Φ)</td>
<td>1606</td>
</tr>
<tr>
<td>Coarse silt (4 to 5 Φ)</td>
<td>1551</td>
</tr>
<tr>
<td>Medium silt (5 to 6 Φ)</td>
<td>1544</td>
</tr>
</tbody>
</table>

### Sediment Average Density (g/cm³)

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Average Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium sand (1 to 2 Φ)</td>
<td>2,191</td>
</tr>
<tr>
<td>Fine sand (2 to 3 Φ)</td>
<td>1,996</td>
</tr>
<tr>
<td>Very fine sand (3 to 4 Φ)</td>
<td>1,869</td>
</tr>
<tr>
<td>Coarse silt (4 to 5 Φ)</td>
<td>1,770</td>
</tr>
<tr>
<td>Medium silt (5 to 6 Φ)</td>
<td>1,674</td>
</tr>
</tbody>
</table>

### Sediment Acoustic Impedance

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Acoustic Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium sand (1 to 2 Φ)</td>
<td>3755,41</td>
</tr>
<tr>
<td>Fine sand (2 to 3 Φ)</td>
<td>3312,24</td>
</tr>
<tr>
<td>Very fine sand (3 to 4 Φ)</td>
<td>2948,03</td>
</tr>
<tr>
<td>Coarse silt (4 to 5 Φ)</td>
<td>2709,76</td>
</tr>
<tr>
<td>Medium silt (5 to 6 Φ)</td>
<td>2732,54</td>
</tr>
</tbody>
</table>

### Sediment Porosity (%)

<table>
<thead>
<tr>
<th>Sediment</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium sand (1 to 2 Φ)</td>
<td>32,4</td>
</tr>
<tr>
<td>Fine sand (2 to 3 Φ)</td>
<td>43,7</td>
</tr>
<tr>
<td>Very fine sand (3 to 4 Φ)</td>
<td>51,1</td>
</tr>
<tr>
<td>Coarse silt (4 to 5 Φ)</td>
<td>56,2</td>
</tr>
<tr>
<td>Medium silt (5 to 6 Φ)</td>
<td>56,7</td>
</tr>
</tbody>
</table>
Conclusions

Physical and acoustic properties coincide well with bathymetry

Compressional wave velocity decreases seaward where porosity and clay content increase

The sediment texture governs the physical and acoustic properties

Geoacoustic behavior coincides relatively well with Hamilton and Bachman (1982) and Kim et al (2001)

These data were tested with Bellhop model with good results

Future acoustic experiments should consider these results.

Thank you.
PHYSICAL OCEANOGRAPHY GROUP
CONTRIBUTIONS TO OAEx PROJECT

A.C. de PAULA
W.B. WATANABE
L. CALADO

OAEx – Workshop – June 2011
PARTICIPANTS

Permanents, but not exclusive:

Ana Cláudia de Paula
Leandro Calado
Wandrey de Bortoli Watanabe
Eduardo de Negri Oliveira

Undergraduate Students, not exclusive:

Carolina Mayumi Sato
Arthur Ramos
Gabriel Serrato
Gabriel Codato (BSc Thesis, in prep)
PARTICIPANTS

Previous collaborators
- Fernando de Oliveira Marin
- Felipe Sarquis Aiex Maneschy
- Ricardo Marques Domingues

External collaborators
- Ilson Carlos Almeida da Silveira
- Leandro Ponsoni - Brazilian PhD student at ULB

SECONDMENTS

Brazilians abroad
- Marin: UAIG (Sep 2009)
- Ana Cláudia: ULB (Nov 2009)
- Leandro: ULB (Oct 2010)
- Ana Cláudia: UAIG (Jan 2011)

Portugueses at IEAPM
- Nélson (twice)
- Orlando

Belgian at IEAPM
- Olivier (twice)
SCIENTIFIC AND TECHNICAL CONTRIBUTIONS

Regional Ocean Dynamics
Multi-scale Objective Analysis
Use of oceanographic circulation models
Oceanographic Feature Models
Collecting oceanographic data in the OAEx cruise

Regional Ocean Dynamics

Multi-scale Objective Analysis (MSOA)

Ocean Circulation Modeling
Regional Ocean Modeling System (ROMS)
3D ocean parameters modeling
Wind forcing (scaterometter data)
Tidal forcing (altimetry based model)
Initial conditions: SST+Upwelling Feature Model
Output can be used as input for acoustic models
Ocean Circulation Modeling

Oceanographic Feature Models

$T_i(x, z) = [T_{ic}(x) - T_{ib}(x)]\Phi(x, z) + T_{ib}(x)$;
Feature Model for BC eddies

\[ T(r, z, \theta) = T_k(z, \theta)(1 - e^{-r/k}) + T_o(z)e^{-r/R}, \]

\[ T_k(z, \theta) = [T(z) + \frac{(T_o(z) - T_l(z))}{2}e^{\theta/\gamma(1 + \cos \theta)}]. \]
Collecting oceanographic data in the OAEx cruise

RESULTING PUBLICATIONS


RESULTING PUBLICATIONS


ACKNOWLEDGEMENTS

Marinha do Brasil
EU - Marie Curie Actions
ULB
UAIlg
Summary

- Signal Received at each hydrophone
- Signal Received at the array
- Transects analyzed
- Comparison: Field Data x Bellhop
- Conclusion

Signal Received at Each Hydrophone

10 LFMs 500-1000Hz (1s + 0.5s pause)
20 LFMs 1000-2000Hz (0.5s + 0.25s pause)
Signal Received at the Array

Transects Analyzed

Comparison: Field Data x Bellhop

TX9 (distance 700m)
Comparison: Field Data x Bellhop

TX17 (distance 4000m)

Transects Analyzed

TX15 (distance 3200m)

Comparison: Field Data x Bellhop
Conclusion

- LFM arrival pattern well defined from the vertical array for distances up to 4000m.
- Observed signal dilation of about 70ms in both bands.
- Bellhop with good agreement for short distances (<1000m).
- For longer distances model should be adjusted.
- Time-varying nature of the channel cannot be properly handled by the model.
- SSP and bottom properties considered range independent.
- Inversion can yield SSP and bottom properties effective fields.

Thanks!
OAEx sea trial Communications signals:
Some Preliminary Observations and guidelines for future Work

Salman Ijaz Siddiqui, António J. Silva, Sérgio M. Jesus.
SIPLAB, ISR-Lisbon, University of Algarve, Portugal
Outline

- Transmitted Signals Waveforms
- Received Signals Waveforms
- Preliminary Results
- Simulations
- Guidelines for future Work in Brazil

Transmitted Signals Waveforms

<table>
<thead>
<tr>
<th>Code</th>
<th>Type</th>
<th>Duration (sec)</th>
<th>Band Separation (Hz)</th>
<th>Start Stop Frequency (KHz)</th>
<th>Silence at the end (sec)</th>
<th>Repetition rate (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFM</td>
<td>LFM</td>
<td>0.1</td>
<td>-</td>
<td>2.64-3.75</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Code_A</td>
<td>FSK</td>
<td>0.05</td>
<td>50</td>
<td>3.0-4.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Code_B</td>
<td>FSK</td>
<td>0.01</td>
<td>20</td>
<td>3.0-5.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Transmitted Signals Waveforms Code A
Received Signals

- Two Transmissions on first day (19-11-2010)
- Two Transmissions on second day (20-11-2010)
- Low Amplitude of the received signals
- High source receiver range at the start

Impulse Responses

11:44 AM, 19-11-2010
Received FSK signals

Doppler Analysis

Guidelines for future work

- Use Passive time Reversal to exploit the spatial diversity in FSK signals.
- Use FSK signals to update the channel estimates.

Thank You!
Low frequency Geoacoustic Modelling in Shallow Water Sediment Environments

Ross Chapman

University of Victoria, BC, Canada

Work supported by ONR Ocean Acoustics
**Outline**

- Background of geoacoustic inversion
  - what is an inverse method?
  - what are the objectives?
  - what type of data are used in inversions?
  - how does geology interact with acoustics in present day inverse methods?
- Example applied to shallow water acoustics
  - SW06 experiment on New Jersey Shelf

**Geoacoustic Modelling:**

- Characterize the structure and properties of the ocean bottom from measurements of the *acoustic field* in the water
- This is an inverse problem….field → bottom properties

- Why is this important?
  - what is the impact of the ocean bottom on TL in the ocean?
  - what properties of the bottom are important?

**Inversion: where did it come from?**

- Roots go back to Neil Frazer (Science, 1990)
  (with honourable mention to George Frisk (1988))
  - MFP: field measurements and accurate propagation models
  - Efficient search algorithm….simulated annealing
  - Geoacoustic ‘Perfect Storm’: combined physics of sound propagation with signal processing
- 1990’s: geoacoustic inversion as an optimization problem
  - prior geophysical model of the bottom
  - comparison modelled response with field data
  - efficient search algorithm
  - Many efficient methods developed, tested and implemented:
    - Gerstoft (Saga); Knobles and Westwood;…..
    - Benchmark workshops (1997)……

**20 years later:**

- Inversion is an *Estimation process*:
  - infer parameters of a physical model of the ocean bottom from the information about the model in the data
- Fundamental paradigm shift:
  - inversion involves providing the user with:
    - model parameter estimate (mean; most probable)
    + estimate of uncertainty (confidence limits)
Acoustic data: what type of data are used?

- Pressure field: primary observable
  - CW; Broadband (LFM; shots; airgun…
  - Noise (Siderius; Gerstoft…..
- Observables derived from the acoustic pressure
  - Reflection coefficient (Holland…
  - Horizontal wavenumber (Frisk, Becker…
  - Time-frequency: modal dispersion (Miller, Potty, Zhou..
  - Acoustic travel time (Jiang….
- Others…all involve some type of signal processing on the pressure field data

Inversion approaches

- Linear or linearized:
  - Perturbative methods (Frisk; Rajan; Lynch; Becker…
  - Provide measure of error
  - Apply well to some types of data
    - E.g. travel time, horizontal wavenumber
- Non-linear methods:
  - Assess a multi-dimensional model parameter space
    - Prior model from ‘ground truth’ information
  - Require an efficient ‘navigation’ method
  - Provide measure of error
  - Not sensitive to starting model

Implementation

- Bayesian approach: (formalized by Dosso (2002))
  - Allows input of local geology (prior knowledge of model)
  - Results are provided as probability of models in the search space: 1-d or 2-d marginal distributions
  - Inversion tells whether data has any information about prior model
  - Bayesian approach applies to all types of data

Warning: Data errors in geoacoustic inversions

- Bayesian inversion compares measurement and model in terms of a likelihood function:
  \[ L = \exp[-E(m, d)] \]
  \[ E(m, d) = \frac{1}{2}(d - d(m))^T C_d^{-1} (d - d(m)) \]

- \( d - d(m) \) is interpreted as ‘noise in the inversion’ i.e. experimental and ‘theory’ errors
- Distribution is not known
- Data error Covariance \( C \) may not be diagonal
Example of geoacoustic inversion

- Data from ONR Shallow Water '06 experiment
  - two sites of different sediment geology
  - short range experiments at each site
  - mid-frequency 1.5 – 4.5 kHz sweeps
  - use acoustic travel time data at vertical and horizontal arrays
  - estimate local geoacoustic properties

- Develop prior geoacoustic model from
  - local knowledge of environment (ground truth)
  - the experimental data itself

Prior Geological knowledge of NJ Shelf

- Many investigations:
  - Mayer; Kraft; Goff; Austin; Turgut; AMCOR; Geoclutter……

- Methods:
  - Physical samples:
    - Sediment grab samples
    - in situ probes
    - Sediment cores
  - Remote sensing
    - Chirp sonar profiles

Chirp sonar travel time sections

Sand ridge - medium course to coarse sand
1. Grain sizes ~ 0.8-1.5 phi
2. Low-frequency sound speed ratio ~ 1.11-1.14, sound speeds 1650-1710

Outer shelf wedge (Medium sand - clay mixture)
1. Grain sizes ~3+ phi
2. Sound speed ratio ~ 1.06-1.08, sound speeds 1580-1610 m/s

Sea floor sound speed map

<table>
<thead>
<tr>
<th>Sound speed (m/s)</th>
<th>72.4</th>
<th>72.6</th>
<th>72.8</th>
<th>73.0</th>
<th>73.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1620</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1670</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1720</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1770</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Latitude (deg N) 39.0 39.2 39.4 39.6
Longitude (deg W) 72.4 72.6 72.8 73.0 73.2
map of R reflector (2-way travel time)

Sediment cores: outer shelf

Outer shelf wedge site (Moray)

Broadband acoustic data: 1.5 – 4.5 kHz
Sand wedge site (SWAMI32)

SWAMI32 site:
- ARL’s L-shape array
- VLA – 10 hydrophones
- HLA – 20 hydrophones

Bayesian travel time inversion:
Bayes’ rule:
\[ P(m|d) = \frac{P(d|m)P(m)}{P(d)} \]
\[ L(m) \propto \prod_{L} \exp \left[ -\frac{1}{2} (\Delta t_{L} - \Delta T_{L}(m))^{T} C_{L}^{-1} (\Delta t_{L} - \Delta T_{L}(m)) \right] \]

Relative travel times:
- time difference between sea floor and sub-bottom paths
- invert single layer geoacoustic model
  - sediment layer thickness and sound speed

Data error covariance matrix estimation:
- from multiple pings

Sampling algorithm:
- MCMC of Metropolis Gibbs sampling

Inversion results for SWAMI32 site:
Layer thickness:
\[ [3.92 \ 5.10 \ 5.98] \ m \]

Recall from ‘Ground truth’:
- medium course to coarse sand
- Grain sizes ~ 0.8-1.5 phi
- sound speeds 1650-1710

Sound speed:
\[ [1623 \ 1652 \ 1681] \ m/s \]
Short range geoacoustic inversions:

- Travel time inversions
  - Outer shelf wedge site:
    - sound speed 1600 m/s ± 30 m/s
    - average over 20-m depth to R-reflector
  - Sand wedge site
    - sound speed 1650 m/s ± 30 m/s
    - average over 5 m sand layer

Summary:

- Geoacoustic modelling is an inverse problem
- Geoacoustic inversion is an estimation process
  - provide model parameter estimate and its uncertainty
  - Bayesian approach applies to any type of acoustic data
- What's in the future?
  - Model selection: can this be done in the inversion?
  - What other types of data are useful?
    - particle velocity
    - applications of inverse methods at higher frequencies
  - Is Bayesian approach the only way?

Acknowledgements

- Just about everyone in the room who has contributed to the development of geoacoustic inversion
- Special thanks to Neil, Evan, David, Mae, Stan and Alex, and
- all my graduate students who took my simple suggestions to higher levels

Thanks!
Acoustic inversion with broadband MFP for seabed characterization in OAEx’10 experiment

Lussac P. Maia(1), Lucia Artusi(2), Carlos E. Parente(3), Jean-Pierre Hermand(4)

(1) Centro de Apoio a Sistemas Operativos (CASOP), Ilha de Mocanguê, s/n, Niterói/RJ, Brazil
(2) Instituto de Estudos do Mar Almirante Paulo Moreira (IEAPM), r. Kioto, 253, Arraial do Cabo/RJ, Brazil
(3) Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE)/ Federal University of Rio de Janeiro (UFRJ), Technology Centre, Ilha do Fundão, Rio de Janeiro/RJ, Brazil
(4) Université libre de Bruxelles (U.L.B.), Av. Franklin D. Roosevelt, 50 CP 194/5, 1050 Brussels, Belgium

2nd Ocean Acoustic Exploration Meeting
Faro, Portugal – June, 2011

Acoustic inversion with broadband MFP for seabed characterization in OAEx’10 experiment

Lussac P. Maia(1), Lucia Artusi(2), Carlos E. Parente(3), Jean-Pierre Hermand(4)

(1) Centro de Apoio a Sistemas Operativos (CASOP), Ilha de Mocangaú, s/n, Niterói/RJ, Brazil
(2) Instituto de Estudos do Mar Almirante Paulo Moreira (IEAPM), r. Kioto, 253, Arraial do Cabo/RJ, Brazil
(3) Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE)/ Federal University of Rio de Janeiro (UFRJ), Technology Centre, Ilha do Fundão, Rio de Janeiro/RJ, Brazil
(4) Université libre de Bruxelles (U.L.B.), Av. Franklin D. Roosevelt, 50 CP 194/5, 1050 Brussels, Belgium

2nd Ocean Acoustic Exploration Meeting
Faro, Portugal – June, 2011


Lussac P. Maia, L. Artusi, C. E. Parente, J.-P. Hermand
Acoustic inversion with broadband MFP in OAEx’10

Outline

Introduction
Objectives
OAEx’10 Experiment
Processor
Results
Conclusions
Introduction

- Acoustic inversion techniques: characterization of the seabed or the marine environment;

- Several methods, e.g.: Bartlett MFP, MBMF, FD-MBMF, MMP, ... -(domain, objective function, sampling/type of signal);

- This work: results of broadband MFP inversion – incoherent-in-frequency linear processor;

- Data: Ocean Acoustic Exploration 2010 experiment (OAEx’10), off the south-east coast of Brazil;

Objectives

- Show the general characteristics of the OAEx’10 experiment;

- Review briefly some theory: show the processing applied in this work;

- Present the results & conclusions of the broadband MFP inversion with those acoustical pressure data.

(For Run #1 – Core9 site)
AOEx’10 Experiment

- November 19-22, 2010 - off the coast of Arraial do Cabo/RJ, continental shelf in southeast of Brazil;
- Others data collected: CTD, pressure gauge, GPS, echo sounding (source ship), early seismic profiles and core samples;
- Acoustic measurements: near core number 9, short S-R transect (700-m), sparse 8-hydrophones array;
- Source: set to max. range cable (10-m depth), multitone signals, sequences repeated every minute during 10 minutes;

OAEx’10 Experiment – Site & ground truth

- Red triangles: core positions (number 9 is over the 40-m isobath);
- Blue line: acoustic run transect.
Information from previous seabed assessment: Sand, C-sed near to 1750m/s, \( \rho = 1.6 \, \text{g/cm}^3 \), sediments layer between 10 and 40m.

Sediment & bottom ssp model:
- Search of \textit{a priori} sound speed profile in sediments over isovelocity bottom halfspace;
- Aspect kept;
- Lower point in sediment – 1720 to 1780 m/s;
- Isovelocity in bottom – 1730 to 1790 m/s;

Sequences: each full sequence is composed by one CW multitone signal (250 Hz to 1000 Hz) followed by one LFM signal (250 Hz to 2000 Hz):

Sequence of CW and LFM signals emitted every minute, during 10 minutes. Spectrogram of the acoustic data recorded on the deepest hydrophone during the 6th sequence.
Multitone signal: emitted by the source (left) and received in the deepest hydrophone (right).

**OAEx’10 Experiment – Geometries**

- Receivers: Acoustic Array consisting of eight hydrophones 3-m equally and vertically spaced;
- Top array element was set to 4-m depth;
- Environment between the source and receivers: approx. 47–48-m depth, 700-m, range-independent;
- Sediment layer (10–40m) over bottom halfspace.

**OAEx’10 Experiment – Support data**

Water sound speed profile collected from CTD just before the acoustic measurements on core#9 site (left). Histogram of the hydrostatic pressure data collected from pressure gauge positioned joint to the source (*one day before) in November 19, 2010 (right).
### Processor – Forward models and optimizations

- Bartlett MFP coherent-in-space and incoherent-in-frequency processor applied to sparse CW signals;

- Range-independent shallow water waveguide – normal modes model for solution of the wave equation with those boundary conditions for create the predict fields;


### Processor – Bartlett MFP

Considering a shallow water environment parameterized by a model vector \( \mathbf{m} \), the processor used is:

\[
\phi(\mathbf{m}) = \sum_{i=1}^{F} \sum_{j=1}^{H} \left( R_{ij} - d_{ij}(\mathbf{m}) \right) \sum_{l=1}^{H} R_{jl} d_{jl}(\mathbf{m})
\]

Where:

- \( d_{ij}(\mathbf{m}) \) – [predicted data for the \( i^{th} \) frequency and \( j^{th} \) hydrophone];
- \( R_{ij} = p_{ij} p_{ij}^{\dagger} \) – [Estimated correlation matrix of the observed acoustic data];
- \( p_{ij} \) – [observed data for the \( i^{th} \) frequency and \( j^{th} \) hydrophone];

The \( \dagger \) symbol stands for the conjugate transpose.

**Huge search space: strong statistics – G.A. 4500 calls for 40 populations**

\[SNAP, SAGA, 8cores, compiled in Hydra U.L.B. cluster.\]
• Bayesian inference: results in terms of probability distributions;

• Environmental a priori information and S-R geometry reflects in the a priori distribution $\rho(m)$ – The results of the inversion procedure reflects in the a posteriori distribution $\sigma(m;d)$;

• Relation: $\sigma(m;p) = \Lambda(m;p)\rho(m)$

Where the $\Lambda(m;p)$ is the likelihood function.

Results reached in this acoustic run of the experiment

Results - e.g. for ping # 5:
One-dimensional marginal a posteriori probability distributions (PPD) for each inverted parameter (blue surface);

Maximum a posteriori (red solid line) – maximum likelihood (red dashed line) – mean and standard deviation of the distributions (green cross and line,resp.).
Results – Analysis of stability

Evolution of the mean marginal PPD results for the 9 processed multitone signals.

The vertical axis limits correspond to the search ranges in the optimization algorithm.

Figure: From 1 to 6: Source depth (m), Receiver depth (m), S-R range (m), Water depth (m), C-sediments (m/s), Rho-sediments (g/cm$^3$).

Figure: From 7 to 12: Att-sediments (dB/λ), C-bottom (m/s), Rho-bottom (g/cm$^3$), Att-bottom (dB/λ), Thickness sed-layer (m), Array tilt (m).
Results – Comparison with ground truth & support data

Figure: From 1 to 4: Source depth (m), Receiver depth (m), S-R range (m), Water depth (m).

Figure: From 5 to 8: C-sediments (m/s), Rho-sediments (g/cm³), Att-sediments (dB/λ), C-bottom (m/s).

Figure: From 9 to 12: Rho-bottom (g/cm³), Att-bottom (dB/λ), Thickness sed-layer (m), Array tilt (m).
In general, the inverted geoacoustic parameters showed higher instability with respect to the geometric parameters; 
- short propagation range;
- a weaker interaction with the seabottom;
- greater complexity involved in the resolution of seabed characterization problem.

Results consistent with the earlier seismic and core assessment;

Some interference can be seen in the instant of the ping number 6;

In spite of this, the inversion still provides a reasonable estimation of the physical parameters in the area of the experiment;

It confirms the ability of the broadband Bartlett MFP approach to invert efficiently multitone signals recorded on hydrophone array using a coherent-in-space processor.

Thanks!
OAEx

Noise Cavitation Experiments

Carlos Eduardo Parente
Luiz Gallisa
Kleber Pessek
Benevides Colella Xavier
Antonio Hugo S Chaves
INTRODUCTION

• MAIN PROBLEM – ESTIMATE SOURCE DISTANCE IN PASSIVE MODE
• IMPROVE THE DETECTION DISTANCE
• SIMPLIFIED CALCULUS
• Database – shallow waters – below frequency 1Khz
  (cavitation noise).
• 1978_ first images
• BETA INVARIANT – CHUPROV

AIMS

• Understand how beta invariant affect the modal propagation in one area.
• Estimate distances
• Improve detection distance for nowadays systems
• Allow a rapid and precise calculus of detection limit
• Cavitation broadband noise model
EXPERIMENTS

OAEx 10

PESQUISEX 11

Pesquisex 11

PESQUISEX 11
RESULTS

\[ \beta = \frac{r}{\omega} \frac{d\omega}{dr} \]
CONCLUSION AND FUTURE WORKS

• Inicial estimation of Beta in different areas and experiments
• Find a simplified calculus to execute instead a graphic solution
• Search to solve Operational Condition in Shallow Waters for the Submarine.

OAEX11
Oaex 10 – calculo IR semelhante ao feito em 09, data check and simplified inversion
Signal processing - noise cavitation experiments
END
BELLHOP TRANSMISSION LOSS PERFORMANCE EVALUATION FROM FIELD DATA OF OAEx’10 EXPERIMENT
Objective

Evaluate the Bellhop Transmission Loss model using data from the OAE '10 sea trial.

Summary

• Objective
• Methodology
• Results
• Conclusions
• Future Work

Methodology

[Diagram showing setup details]
Methodology

Legend

WHT - SISPRES1
CYAN - SISPRES2
YLW - SISPRES3
GRN - SISPRES4
RED - SISPRES5
MGT - SISPRES6
BLK - SISPRES9
YLW/RED - SISPRES12
GRN/YLW - SISPRES13
RED/BLK - SISPRES14
MGT/YLW - SISPRES16
BLK/YLW - SISPRES17

\[ SL_{dB} = 184.61 \text{db} \]
Methodology

Hidrofones' Sensitivity

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Sensitivity [re 1V/uPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>-170</td>
</tr>
<tr>
<td>500</td>
<td>-165</td>
</tr>
<tr>
<td>1000</td>
<td>-160</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>2500</td>
<td>500</td>
</tr>
<tr>
<td>3000</td>
<td>1000</td>
</tr>
<tr>
<td>3500</td>
<td>1500</td>
</tr>
<tr>
<td>4000</td>
<td>2000</td>
</tr>
<tr>
<td>4500</td>
<td>2500</td>
</tr>
<tr>
<td>5000</td>
<td>3000</td>
</tr>
<tr>
<td>5500</td>
<td>3500</td>
</tr>
<tr>
<td>6000</td>
<td>4000</td>
</tr>
<tr>
<td>6500</td>
<td>4500</td>
</tr>
<tr>
<td>7000</td>
<td>5000</td>
</tr>
<tr>
<td>8000</td>
<td>5500</td>
</tr>
<tr>
<td>9000</td>
<td>6000</td>
</tr>
</tbody>
</table>

Methodology

Received Signal - After Filtering

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Amplitude [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>250</td>
<td>2.5</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td>350</td>
<td>3.5</td>
</tr>
<tr>
<td>400</td>
<td>4</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
</tbody>
</table>

Summary

- Objective
- Methodology
- Results
- Conclusions
- Future Work
Results - Hydrophone 1

• Possuímos um equipamento de baixo custo e operando;
• Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
• Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
• O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 2

• Possuímos um equipamento de baixo custo e operando;
• Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
• Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
• O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 3

• Possuímos um equipamento de baixo custo e operando;
• Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
• Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
• O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 4

• Possuímos um equipamento de baixo custo e operando;
• Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
• Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
• O sistema é flexível e se mostra apto a futuras melhorias.
Results - Hydrophone 5

- Possuímos um equipamento de baixo custo e operando;
- Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
- Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
- O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 6

- Possuímos um equipamento de baixo custo e operando;
- Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
- Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
- O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 7

- Possuímos um equipamento de baixo custo e operando;
- Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
- Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
- O sistema é flexível e se mostra apto a futuras melhorias.

Results - Hydrophone 8

- Possuímos um equipamento de baixo custo e operando;
- Possuímos um sistema de software que controla o sistema e é mais preciso do que a operação manual de análise de posição e sincronismo;
- Foi desenvolvido um algoritmo que processa os arquivos GPS e calcula a distância entre a fonte e o receptor;
- O sistema é flexível e se mostra apto a futuras melhorias.
Conclusions

• Array’s hydrophones successfully calibrated;
• Good agreement between the experimental and Bellhop modeled data, considering the low distance variation and high frequency issues.

Future Works

• Enhance experimental data with more distance variation;
• Evaluation of the transmission loss from field data using wavelets;
• Advance in the use of Bellhop model by adjusting its parameters based on the TL experimental data;
• Implement other models such as Parabolic Equation.
QUESTIONS?
NUMERICAL MODELING OF SIGNAL PROPAGATION IN THE CONDITIONS OF THE OAEx’10 EXPERIMENT
Modeling signal propagation in the OAEx'10 experiment

General Overview
- The OAEx'10 experiment
  - Site bathymetry
    - Acoustic source and array
    - Mean sound speed profile
  - KRAKEN calculations
    - Normal modes
    - Transmission loss calculations
  - Bellhop calculations
    - Ray spreading for different source depths
    - Eigenrays and arrivals
    - Transmission loss for different source apertures
    - Impulse response
  - Conclusions

Conclusions

Orlando C. Rodríguez & Fábio C. Xavier
OAEx Workshop 2011
Modeling signal propagation in the OAEx'10 experiment

General Overview
- The OAEx'10 experiment
  - Site bathymetry
  - Acoustic source and array
  - Mean sound speed profile
- KRAKEN calculations
  - Normal modes
  - Transmissions loss calculations
- Bellhop calculations
  - Ray spreading for different source depths
  - Eigenrays and arrivals
  - Transmission loss for different source apertures
  - Impulse response
- Conclusions
OAEx'10 bathymetry

Range ≈ 1500 m

Orlando C. Rodríguez & Fábio C. Xavier

Characteristics (IEAPM):

\[ \rho \approx 1.9 \] (g/cm³)

\[ c_p \approx 1626 \] (m/s)

\[ \alpha_p \approx 0.8 \] (dB/λ)

OAEx'10 acoustic source and array

Lubel source Hydrophone array

OAEx'10 mean sound speed profile
Normal mode expansion of acoustic pressure

\[ P(r, z) = S(\omega) \frac{e^{i\pi/4}}{\rho(z_s)\sqrt{8\pi r}} \sum_{m=1}^{M} u_m(z_s) u_m(z) e^{i k_m r} \sqrt{k_m} \]

where \( u_m(z) \) are the acoustic modes and \( z_s \) is the source position.

Transmission loss @ 500 Hz

Gaussian beams

Acoustic pressure along a ray:

\[ P(s, n) = \frac{1}{4\pi} \sqrt{\frac{c(s)}{c(0)} q(0)} \frac{\cos \theta(0)}{q(s)} \exp \left[ -i\omega \left( \tau(s) + \frac{1}{2} \frac{p(s)}{q(s)} n^2 \right) \right] \]

where \( s \) is the ray arclenght and \( n \) is the ray normal.
Eikonal equations ("Kinematics" of ray tracing):

The trajectories that minimize $\tau(s)$ can be obtained solving the system

\[
\frac{dr}{ds} = c(s)\sigma_r(s), \quad \frac{d\sigma_r}{ds} = -\frac{1}{c^2} \frac{\partial c}{\partial r},
\]
\[
\frac{dz}{ds} = c(s)\sigma_z(s), \quad \frac{d\sigma_z}{ds} = -\frac{1}{c^2} \frac{\partial c}{\partial z}.
\]

"Dynamic" equations:

The beam influence depends on the parameters $p$ and $q$, which are solutions of the system

\[
\frac{dq}{ds} = c(s)p(s), \quad \frac{dp}{ds} = -\frac{c_{nn}}{c^2} q(s).
\]

where

\[
c_{nn} = \left(\frac{dr}{dn}\right)^2 c_{rr} + 2\left(\frac{dr}{dn}\right)\left(\frac{dz}{dn}\right) c_{rt} + \left(\frac{dz}{dn}\right)^2 c_{zz}.
\]
Conclusions

There is a remarkable good agreement between real data and model predictions despite the improvised nature of assumptions regarding waveguide geometry.

- Acoustic models complement perfectly each other pointing to particularities of signal propagation (like the excitation of higher order modes) that could be missed by relying on a single model.
- A further review of environmental data is highly recommended in order to improve model accuracy.
- The environmental complexity of the waveguide deserves the development of further predictions using models, which rely on different approximations (like, for instance, the parabolic equation).

There is a remarkable good agreement between real data and model predictions despite the improvised nature of assumptions regarding waveguide geometry.

- Acoustic models complement perfectly each other pointing to particularities of signal propagation (like the excitation of higher order modes) that could be missed by relying on a single model.
- A further review of environmental data is highly recommended in order to improve model accuracy.
- The environmental complexity of the waveguide deserves the development of further predictions using models, which rely on different approximations (like, for instance, the parabolic equation).
OBRIGADO PELA VOSSA ATENÇÃO
Bayesian sonar performance prediction perspectives for Cabo Frio

N. Martins\textsuperscript{1} and L. Calado\textsuperscript{2}

\textsuperscript{1}Institute for Systems and Robotics
University of Algarve, SiPLAB
Portugal

\textsuperscript{2}Brazilian Navy
Instituto de Estudos do Mar Almirante Paulo Moreira
Brazil

II OAEx Workshop, June 2011
Sonar — passive sonar equation

\[ SL - TL - NL + DI = DT \]

Source level - Transmission loss - Noise level + Directivity index = Detection threshold

Acoustic prediction

At present time \( t_P \), determine the acoustic field at future time \( t_F \), in a given area

\[ \text{Transmission loss in transect } k \]

\[ \text{Acoustic field} = ? \]

Physics, data and models

- **Physics**
  - Environment evolves with time
  - Acoustic propagation = function(environmental properties)

- **Data**
  - Oceanographic: water column temperature, ocean floor samples, nautical charts, etc.
  - Acoustic: hydrophone array system(s)

- **Models**
  - Environmental: oceanographic prediction system
  - Acoustic: ray tracing, normal-mode, parabolic equation, etc.

Standard acoustic prediction cell

```
Water column properties at \( t_P \) ➔ Oceanographic model ➔ Water column properties at \( t_F \) ➔ Acoustic model ➔ Predicted acoustic field at \( t_F \)
```

**Strong point:** computational speed
Real forward and inverse acoustic modeling

Modeling is just an approximation!

Fine environmental detail

Long computational times

Environmental mismatch

Motivation

Future time

Shifted environment

Modeled propagation

Slightly shifted acoustic signals

Learn shifts from forecasts/measures, w/ past data

An ocean of information

Forecasts

CTDs

Acoustics

Model parameters

Geoacoustics

Geographic coordinates

Time

β b F γ g F
I κ c F m F µ o F ω

β a F n ν

ψ I ω

w F o F

w F F g F F m F F b F c F F b F F c F F g F

[t0, tF]

[t0, tF]
Application example: MREA’03 data set
CTD casts in the MREA’03 sea trial -
Elba Island
( 142 × 87.9 km )

Acoustic field simulations: Julian
day (JD) 151–175
▶ Navy Coastal Ocean Model (NCOM)\(^1\)
▶ SACLANTCEN normal-mode acous. prop. model (SNAP)\(^2\) and
SNAP w/ adiabatic approximation (ground truth acoustics)

\(^1\) Martin P., “Description of the Navy Coastal Ocean Model version 1.0”, ...
\(^2\) F.B. Jensen and M.C. Ferla, “SNAP: The SACLANTCEN normal-mode
acoustic propagation model”, SM-121, SACLANT...

Acoustic propagation transect

Simulation parameters

Initialization survey

Acoustic prediction computation

Required prediction time

\( t_I \)

\( t_0 \)

\( t_1 \)

\( \ldots \)

\( t_P \)

\( t_F \)

Time

Regular acoustic-oceanographic sampling

Acoustic prediction time line
▶ Mismatch: EOF representation (3 EOFs (87% of the variance)
for 465 profiles)
▶ Frequencies: 10 tones in [540–900] Hz (1.7 < \( \lambda \) < 2.8 [m])
▶ 50 time samples in \([t_0, \ldots, t_F]\)
▶ Use the information up to time \( t_P = t_{25} \), to predict for the
posterior times
▶ Step: 12 h

Acoustic propagation model parameters

▶ Water column SSP 1\(^{st}\) EOF coefficient
▶ Water column SSP 2\(^{nd}\) EOF coefficient
▶ Water column SSP 3\(^{rd}\) EOF coefficient
▶ Sediment comp. speed at water-sediment interface
▶ Sediment comp. speed at sediment-subbottom interface
▶ Sediment thickness
▶ Subbottom comp. speed
PDF to estimate

\[ p(a_{Fn}|c, g, o_F) = (\cdot)\int p(a_{Fn}|m_F) \, p(m_F|c, g, o_F) \, dm_F \]

Information about the future acoustic field

Information about the future propagation model parameters

PDF approximations

- Vector to scalar: \( p(m_F|c, g, o_F) \approx \prod_{q=1}^{7} p(m_q|c, g, o_F) \)
- Homologous quantities:
  \( p(m_{w1}|c, g, o_F) \approx p(m_{w1}|o_1) \), the same for other EOFs
  \( p(m_p|c, g, o_F) \approx p(m_p|c) \), the same for other seafloor params.
- No acoustic model parameters realizations:
  \( p(m_{w1}|o_1) \approx p(m_{w1}|a_p) \), etc.

Water column measures vs. forecasts

Measure | Forecast

Acoustic inversion results
\( p(\text{future propagation model parameters | other}) \)

- Mean 1
- Mean 2
- Mean P
- Align + average
- Shape estimate

Polynomial fit of the means → mean estimate

Future environmental posterior densities estimates

- EOF coefficient # 1 [m/s]
- EOF coefficient # 2 [m/s]
- EOF coefficient # 3 [m/s]

Subbottom sound speed [m/s] Probability
- 1480 1500 1520 1540 1560
- 0.05 0.1 0.15 0.2 0.25 0.3 0.35

Sediment upper speed [m/s] Probability
- 1500 1550 1600
- 0.05 0.1 0.15 0.2 0.25 0.3 0.35

Sediment lower sound speed [m/s] Probability
- 1500 1550 1600
- 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

Sediment thickness [m] Probability
- 2 4 6
- 0.1 0.2 0.3

Acoustic field estimate error

- Time [JD] Average error
  - (a) Standard
  - (b) MAP
  - Mean
  - Median

Real part

Imaginary part

- 81
**Problem:** to determine instantaneous three-dimensional water column properties (sound speed or temperature field, etc.)

Water column properties = ?

Applications: oceanography, oceanic engineering, sonar performance prediction, biology, etc.

---

**3D EOF parametrization**

\[ c(x, y, z) = \bar{c}(x, y, z) + \sum_{k=1}^{K} \alpha_k \hat{E} OF_k(x, y, z), \]

\( \bar{c}(x, y, z) \): average 3D sound speed field

\( \alpha_k \): coefficients

\( \hat{E} OF_k(x, y, z) \): 3D \( k \)-th EOF estimate (Latitude-, longitude-, and depth-dependent) \( \alpha_k \) is representative of the full 3D space. \( \Rightarrow \) an estimate of the coefficients obtained w/ data from any region inside the volume allows to estimate the field in the whole volume

---

**Test case: feature horizontal section + acoustics**

**Feature to estimate:** 31\textsuperscript{st} December ROMS model output

Oceanographic feature @ 1-m depth [°C]

---

**Test case: 3D EOF plots**
Test case: EOFs in acoustic inversion

500 and 1000 Hz

Test case: Transect 3
Latitude × longitude view, constant depths

Test case: Acoustic inversion results
Ocean volume estimation error statistics
Future work
▶ Synchronize Measures | Forecasts | Inversion outcomes (Bellhop, SAGA, etc.) in space and time
▶ Predict the acoustic signals in selected transects, using the appropriate Bayesian network
▶ Solve the sonar equation

Further: use 3D EOFs

Thank you