Seabottom Acoustics Parameters from Reverberation Vertical Coherence in Shallow Water

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ABSTRACT

Acoustic reverberation in shallow water involves a two-way sound propagation and boundary scattering process. It must, therefore, contain rich information on seabottom acoustic parameters. Reverberation from one shot offers a continuous spatial sampling of surrounding sound field. Thus, inversion of seabottom acoustic parameters from shallow-water reverberation is very attractive for saving time and cost. Wide band reverberation data have been collected from the first China-US joint ocean acoustics experiment in the Yellow Sea (Yellow Sea '96) and from the Asian Sea International Acoustic Experiment (ASIAEX01) in the East China Sea. Using the R-mode method and introducing a concept of average angular spectrum for sound propagation, Zhou developed a theoretical model for reverberation spatial coherence and average reverberation intensity in shallow water [Zhou, Acta Oceanologia Sinica, 1, No. 2, 212-218 (1979) and Acta Acustica, 5, No. 2, 86-99 (1980)]. In the current paper, this model is converted back to a more familiar summation of normal-modes. With this model, the sound velocity/attenuation in sediments and bottom scattering strength are derived for low- and mid-frequencies from at-sea experimental data (YS78, YS96 and ASIAEX01), including reverberation vertical coherence and average reverberation intensity.
I. MOTIVATIONS:

1. Engineering application
   Optimal array processing requires...

2. Physics
   Forward: how Ocean environments effect on RVC
   Backward: inversion of seabottom Acoust. Parameters
   (Rev. derived $S_b(\theta)$ is often mixed with
   uncertainty of $C_2$ and $\alpha_2$.)

Urick: (1970) → HC/VC measurements
Popov et al (1994)]
Reverberation challenges many basic research topics in shallow water

Sea bottom geoacoustic Models
$\rho(z), C_p(z,f), C_s(z,f), \alpha(z,f)$

Forward propagation

Bottom scattering

Bottom scattering Models
(LF Mechanics)

Backward propagation

Surface roughness
Volume imhomogeneities
Subbottom layers
Bubbles

$S$ → Forward propagation → Bottom scattering → Backward propagation → Rev.
Reverberation at SY-3

The East China sea
f=1000 Hz, 1/3 Oct.
SD=50m  RD=86.5m
II. THORY

The sound field intensity in shallow water can be expressed as a sum of normal modes:

\[
|\psi(r, z; z_0)|^2 = \frac{2\pi}{r} \sum \left\{ \frac{|\Phi_n(z_0)|^2 |\Phi_n(z)|^2}{k_n N_n^2} e^{-2\beta_n r} \right\} + \frac{2\pi}{r} \sum \sum_{n \neq m} \frac{\Phi_n(z_0)\Phi^*_m(z_0)\Phi_n(z)\Phi^*_m(z)}{k_n^{1/2}k_m^{1/2} N_n N_m^*} e^{i(k_n - k_m^*)r} \right\}
\]
\[ |\Phi_n(z)|^2 = \frac{c_1}{k_n \tan \theta(z)} \]

\[ k_n = k(z) \cos \theta(z) \]

\[ 2 \int_{\xi_n}^{\eta_n} \sqrt{k^2(z) - k_n^2} \, dz + \varepsilon_{\xi_n} + \varepsilon_{\eta_n} = 2n\pi \]

\[ \frac{d}{dn} \int_{\xi_n}^{\eta_n} f(z, n) \, dz = \int_{\xi_n}^{\eta_n} f'(z, n) \, dz + f(\eta_n, n) \frac{d\eta_n}{dn} - f(\xi_n, n) \frac{d\xi_n}{dn} \quad (2) \]
Angular spectrum expression on average intensity of Shallow-water sound propagation (Brekhoverkikh,Zhou)

\[ I(r, z; z_0) = \frac{4}{r} e^{-\alpha r} \int \frac{e^{2 \ln |v(\theta)| r / s(\theta)}}{S \times \tan \theta(z)} d\theta(z_0) = \frac{2e^{-\alpha r}}{r} \int I_{aps}(\theta, r, z; z_0) d\theta(z_0) \quad (3) \]

\[ I_{aps}(\theta, r, z; z_0) = \frac{2 e^{-2\beta_n r}}{S \times \tan \theta(z)} = \frac{2 e^{2 \ln |v(\theta)| r / s(\theta)}}{S \times \tan \theta(z)} \quad (4) \]

weighting process in an angular domain for average characteristics in shallow water: Sound propagation, Noise, Reverberation Spatial coherence, etc.

Simple Intuitive
Angular spectrum expression on average reverberation intensity in shallow water

\[ R(r, z; z_0) = \int \int \frac{e^{-\alpha r}}{r} I_{aps}(\theta, r, z_h; z_0) \times AM_b(\theta, \phi) \times \frac{e^{-\alpha r}}{r} I_{aps}(\phi, r, z; z_h) d\theta d\phi \]

\[ = \int \int \frac{e^{-\alpha r}}{r} \frac{2e^{2\ln|v(\theta)|r/s(\theta)}}{S \times \tan\theta(z_h)} \times AM_b(\theta, \phi) \times \frac{2e^{2\ln|v(\phi)|r/s(\phi)}}{S \times \tan\phi(z)} \frac{e^{-\omega r}}{r} d\theta(z_0) d\phi(z_h) \quad (5) \]

\[ d\theta(z_0) = \frac{2\pi}{S_n k(z_0) \sin \theta_n(z_0)} dn \quad (6) \]

→ a summation of normal-modes by
Zhang and Jin (1984,1987)
VERTICAL COHERENCE

For sound propagation by Smith (1976) and Zhou (1979):

\[
\rho_v (\Delta z, r, z; z_0) = \frac{\iint I_{aps} (\theta, r, z; z_0) |S(w)|^2 e^{-jk\Delta \sin(\theta)} d\theta dw}{\iint I_{aps} (\theta, r, z; z_0) |S(w)|^2 d\theta dw} \tag{7}
\]

For reverberation (Zhou, 1979):

\[
\rho_{rv} (\Delta z, r, z; z_0) = \frac{\int \frac{e^{-2\beta_n r}}{S \times \tan \theta (z)} M[\theta (z_h)] [\cos [k(z)\Delta \sin(\theta (z))]] d\theta (z_h)}{\int \frac{e^{-2\beta_n r}}{S \times \tan \theta (z)} M[\theta (z_h)] d\theta (z_h)}
\]
\[ \rho_{R_v}(\Delta z, r, z; z_0) = \]
\[ \times \left\{ \sum_n \frac{e^{-2\beta_n r} \cos[k(z)\Delta z \sin\theta_n(z)] M[\theta_n(z_h)]}{S_n^2 \times \tan\theta_n(z) k(z_h) \sin\theta_n(z_h)} \right\}^{-1} \]

\[ S_n \approx -\frac{2\pi}{(dk_n / dn)} \]
III. MEASUREMENTS

The experiments were conducted at 3 sites in China Seas by using explosive source with 1 kg gram TNT charges.

Seabed is very flat at YS78/YS96 sites; rather flat at AIAEX01. The mean grain diameter of sediments: 0.070mm (YS78), 0.0643mm (YS96) and 0.105mm (? ASIAEX01). Seabed are mainly find sand-silty sand.

The YS78 data from hydrophones/4-channel analog recorder
The YS96:16 hydrophones/16-channel digital recorder
The ASIAEX01: 32/32

All hydrophone arrays were designed by IOA, and suspended from ship
Sound velocity profiles for YS78, YS 96 and ECS ASIAEX01

Sound Velocity Profile

Depth (m)

Sound Velocity (m/s)

Yellow Sea '78

Yellow Sea '96

ASIAEX01 (ECS)
IV. (a) MODEL/DATA COMPARISONS

Measurement and Prediction, F=800 Hz, Yellow Sea, 10/78

RV coefficients at 800 Hz as a function time and hydrophone separation and Δz in the Yellow Sea, 1978. Data are average values over 12 explosive signals. Δz=0.55m - 3.85m
RVC as a function of time and frequency in the Yellow Sea, 1996. Hydrophone separation = 2m. The data are average values of 5 shots and 8 pairs of hydrophones, located at depths from 42m to 66m.
RVC as a function of time and frequency in the East China Sea (ASIAEX01), 2001. Hydroplane separation = 4m. The data are average values of 3 shots and 8 pairs of hydrophones, located at depths from 56.5m to 90.5m.
IV. (b) INVERSION OF SOUND SPEED AND ATTENUATION FROM YS96 RVC

\[ F = 600 \text{ Hz, } dz = 2 \text{ m, Yellow Sea, 08/26/96} \]

\[
C_2 = 1632 \text{ m, } \alpha_2 = 0.227f \text{ (dB/m.kHz)}
\]
Inverted $C_2$ from Rev. Coherence, Yellow Sea, 08/26/96
seabed reflection coefficient - $\ln |V(\theta)| = Q \theta$
(c) INVERSION OF SOUND SPEED AND ATTENUATION FROM ASIAEX01 RVC

\[ F = 300 \text{ Hz}, \ dz = 4 \text{ m}, \ \text{East China Sea, 06/03/01} \]

\[ C_2 = 1637 \text{ m}, \ \alpha_2 = 0.16f \text{ (dB/m.kHz)} \]
Inverted $C_2$ from Rev. Coherence, East China Sea, 06/03/01

Frequency (Hz)

Sound speed in sediments (m/s)
seabed reflection coefficient: $\ln |V(\theta)| = Q \theta$
V. SUMMARY AND DISCUSSION

1. The RVC, expressed by the angular spectrum, has been converted back to a more familiar summation of normal-modes.
2. Measured RVC at 3 sites in the China Seas are good agreement with the theoretical model.
3. The sound velocity and attenuation, inverted from RVC, are close to others, inverted from propagation data. Model/data comparisons show that the RVC can be a powerful characteristic for use in fast inversion of seabottom acoustic parameters (and in derivation of bottom scattering strength).
4. Be careful! Different seabottom scattering models would cause some uncertainty on inversion results of bottom acoustic parameters. Thus, a scattering model with more physical base is desirable for numerical modeling. (under working)
5. For at-sea experiment design and lab data analyses on RVC, one needs carefully to consider the R/N noise ratio and $\Delta z/\lambda$ ratio etc.
Thanks to
   IOA colleagues
   YS96 & ASIAEX team members

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