Wide-Band Target Depth Estimation in a Scattering Ocean Environment

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ABSTRACT

This paper concerns target depth estimation using wideband active sonar multipath returns. Detailed full-field modeling of target returns is complicated by spectral amplitude and phase distortions induced by unknown target scattering, uncertainty in the bulk group delay, and unmodeled propagation effects. However, since the relative delays of the multipath return are relatively robust to modeling errors, the approach considered in this work consists of estimating a subset of the relative delays present in the data and using them with a depth-dependent likelihood function derived from ray-traces based on the ocean environment. This maximum-likelihood depth estimate (MLDE) algorithm is compared with an alternative full-field matched-field depth estimate (MFDE) approach in terms of results obtained with a real mid-frequency active sonar.

INTRODUCTION

- Matched-field processing (MFP) for active sonar is complicated by the fact that the complex target scattering function is unknown and introduces unknown phase and amplitude differences between scattered modes (Bucker, 1996; Yang and Yates, 1994; Perkins *et al*, 1992).
- We consider depth estimation using wide-band signals, which have the potential to resolve some of the multipath arrivals scattered by the target.
- A limitation of the ray acoustic models for wideband returns is their inability to handle frequency dependent spectral distortion that is not explained by the usual linear superposition of scaled and delayed versions of the transmitted signal.
- Spectral distortions are partially due to 1) the inability of the acoustic ray propagation code to model the unknown, frequency-dependent nature of the bistatic target scattering function, and 2) bulk group delay jitter.
- Two signal models are presented for wideband multipath target returns and associated algorithms for the depth estimation problems they represent: 1) a wideband MFDE approach which extends the previous narrow-band MFDE (Hickman and Krolik, 2004), and 2) a delay-based MLDE approach which uses measured delay differences from time-domain target returns.

1 MFDE Signal Model

$$\mathbf{x}_{mn} = \mathbf{H}_{mn}(r_n, z, v_n)\mathbf{s}_{mn} + \boldsymbol{\eta}_{mn}$$

- Frequency-domain observation for the m^{th} subband and n^{th} observation is denoted by $\mathbf{x}_{mn}$.
- $\mathbf{H}_{mn}(r_n,z,v_n)$ is the frequency-domain replica matrix for a target at range r_n, depth z, and velocity v_n.
- The i^{th} column of $\mathbf{H}_{mn}(r_n,z,v_n)$ is the spectral contribution of the multipath i^{th}.
- The complex vector $\mathbf{s}_{mn}$ describes the scattering on each multipath, assumed Gaussian.
- $\boldsymbol{\eta}_{mn}$ is complex Gaussian additive noise.

2 MFDE Algorithm

- Since $\mathbf{x}_{mn}$ is Gaussian, the log-likelihood of it can be calculated as a function of depth hypothesis.
- $\mathbf{R}_{mn}(z)$ is the covariance matrix of $\mathbf{x}_{mn}$ for hypothesized target depth z.

$$\mathbf{R}_{mn}(z) = \mathbf{H}_{mn}(z)\mathbf{H}_{mn}^{H}(z) + \sigma_\eta^2 \mathbf{I}_\eta$$

- The log-likelihood $L_{mn}(z|\mathbf{x}_{mn})$ is calculated for the m^{th} subband and n^{th} observation.

$$L_{mn}(z|\mathbf{x}_{mn}) = -\ln(\pi^W \det(\mathbf{R}_{mn}(z))) - \mathbf{x}_{mn}\mathbf{R}_{mn}^{-1}(z)\mathbf{x}_{mn}^H$$

- The log-likelihoods are integrated over subband and observation for each depth hypothesis.
- The depth hypothesis at which the integrated likelihood takes on its maximum is the estimated depth.

$$\hat{z}_{\text{MFDE}} = \arg\max_z \left(\sum_{m,n} L_{mn}(z|\mathbf{x}_{mn})\right)$$

3 MLDE Data Model

$$y_{kn}(t,z) = \sum_i (m_k(t) * \phi_{in}(t) * q(t - \tau_{in}(z))) + v_{kn}(t)$$

- The time-domain observation for the k^{th} subband and n^{th} observation for a target at depth z is denoted by $y_{kn}(t,z)$.
- $m_k(t)$ denotes the sub-band matched filter for the k^{th} subband.
- $\phi_{in}(t)$ is the *unknown* impulse response of the target for the i^{th} multipath and n^{th} observation.
- $q(t)$ is the transmitted broad-band time series.
- $\tau_{in}(z)$ is bulk delay along the i^{th} multipath for the n^{th} observation as a function of source depth, z.
- $v_{nk}(t)$ is additive noise for the k^{th} subband and n^{th} observation

4 MLDE Algorithm

- A depth estimation should be insensitive to bulk group delay, robust to uncertainty in multipath phase and amplitude scaling, and robust to target and bottom scattering distortions.
- This motivates the two-step delay difference estimation approach employed here which 1) measures the time difference $\Delta\tau_{kn}$ between the two strongest peaks in the sub-band matched filter output $y_{kn}(t,z)$, and 2) inputs the $\Delta\tau_{kn}$ to a likelihood function which is then maximized.
- The empirical likelihood of depth z_{hyp}, given $\Delta\tau_{kn}$ is

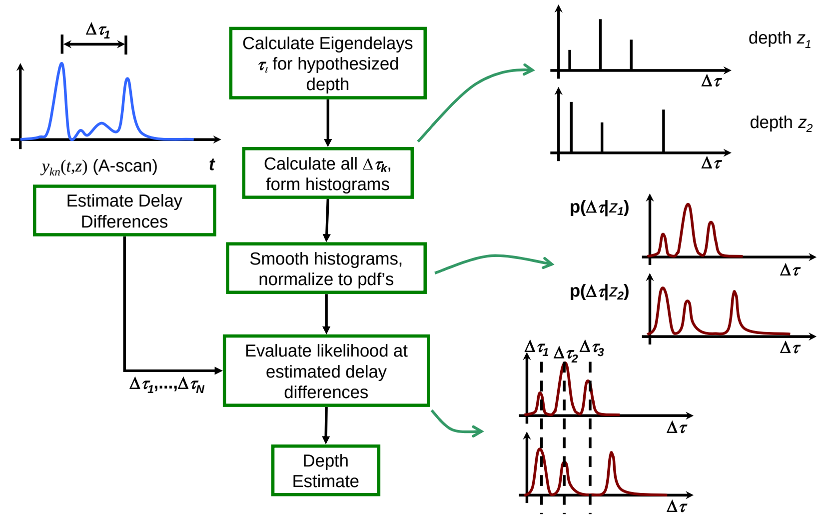
$$l_n(z_{\text{hyp}}|\Delta\tau_{kn}) = C\sum_{\substack{i,j \\ i\neq j}} g(\Delta\tau_{kn} - d_{ijn}(z_{\text{hyp}}))$$

where $d_{ijn}(z_{\text{hyp}})$ is the delay difference between two distinct multipaths and g is a smoothing kernel whose width is proportional to the uncertainty in the measurements $\Delta\tau_{kn}$.

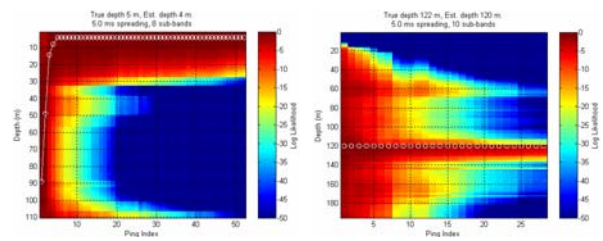
- The depth estimate is taken to be the hypothesized depth at which the log-likelihood (integrated over subband and observation indices) achieves its maximum:

$$\hat{z}_{\text{MLDE}} = \arg\max_z \left(\sum_{k,n} \log(l_n(z|\Delta\tau_{kn}))\right)$$

- The diagram on the right illustrates the processing chain entailed by the MLDE algorithm.

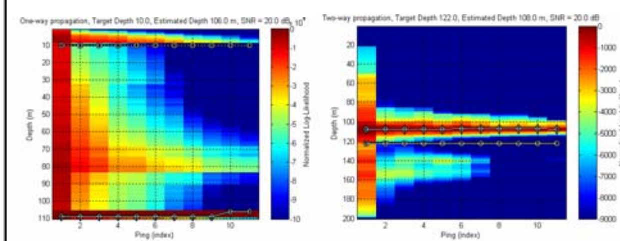


5 MLDE Real Data Results



- The signal employed for the water column target had an 800 Hz bandwidth, and was split into eight bands.
- The transmitted signal for the surface target had a bandwidth of 400 Hz and was split into five sub-bands for processing.
- The signal to noise ratio for the data from both targets was approximately 20 to 25 dB.
- The above plots show the evolving depth dependent log-likelihood as pings are accumulated.
- The true depth of the surface target (above left) was 5 meters, and the MLDE estimate is 4 meters.
- The true depth of the water column target (above right) was 122 meters, the MLDE estimate is 120 meters.

6 MFDE Real Data Results



- The same real data is processed here by the wide-band MFDE algorithm.
- The same number of subbands were used in each case.
- The above plots show the evolving depth dependent log-likelihood as pings are accumulated.
- The true depth of the surface target (above left) was 5 meters, and the MLDE estimate is 106 meters.
- The true depth of the water column target (above right) was 122 meters, the MLDE estimate is 108 meters.

- **The MFDE and MLDE both seem to perform well with the submerged echo repeater target, while only the MLDE gives a good result with the surface target. This may be due to the fact that the surface target (a ship's hull) probably induces larger spectral distortions.**
- **In current work, we are obtaining better performance using a Markov model for frequency-dependent fading to estimate relative delays prior to MLDE.**

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