Tomographic reconstruction of evolving bubble fields in the Scripps Pier bubble experiment

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Abstract: The Delta Frame was a major component of the 1997 Scripps Pier shallow water bubbles experiment. The frame supported two sources and eight receivers. Acoustic travel time and attenuation were measured at eight frequencies between 39 and 244 kHz over the resulting 16 intersecting ray paths. Tomography is used to produce quantitative cross-sectional images of the ensonified region. The images show periods of rapid change in the bubble field.

INTRODUCTION

The Scripps Pier Bubble Experiment was conducted 24 February to 14 March, 1997. Researchers from several institutions including the Naval Research Laboratory at the Stennis Space Center (NRL-SSC), the Institute of Ocean Sciences, the Scripps Institute of Oceanography and the University of Washington Applied Physics Laboratory were involved. A major component of the experiment was the Delta Frame designed and operated by NRL-SSC. The outer frame was in the shape of a triangle with each leg approximately 9.4 m long. Acoustic sources were installed at two vertices of the triangle and distributed around the outer frame were eight receivers. The resulting 16 intersecting ray paths ranged in length from 2.5 to 8.6 m. The frame was deployed approximately 12 m north of the pier near piling 33. For a given transmission sequence, acoustic travel time and intensity were measured at eight different frequencies between 39 and 244 kHz. At a particular frequency, the measurements can be combined using tomography to yield a quantitative cross-sectional image of the ensonified region. Using successive sequences, the temporal evolution of the bubble field can be inferred.

TOMOGRAPHY ALGORITHM

Let $\phi(r)$ be the true attenuation field over the horizontal cross-section $r = (x, y)$. Taking the logarithm of the measured intensities, the data $d_i$ are modeled as

$$d_i = \int_\text{path} \phi(r)dn_i + \varepsilon_i,$$  

where $\varepsilon_i$ is noise and the integration for path $i$ is assumed to be a straight line connecting source and receiver. From measurements taken along $N$ ray paths, the goal is to estimate $\phi(r)$. The tomography algorithm is formulated as a constrained least-squares problem where the expected error $J = \{[\phi(r) - \hat{\phi}(r)]^2\}$ is minimized. The details of the derivation are beyond the scope of the current development; only the final result is presented. The estimated field is given by a linear combination of the data:

$$\hat{\phi}(r) = \sum_{i=1}^{N} \psi_i(r)d_i.$$  

The function $\psi_i(r)$ is defined as the $i$-th backprojection function. It is calculated by smearing the corresponding original ray path with the assumed autocorrelation $<\phi(r)\phi(r')>$ of the underlying field. Each backprojection function is weighted by the corresponding measurement. These weighted backprojections are then superimposed to give the final reconstruction.
In practice, the autocorrelation of the medium may not be known. For computational ease, a simple Gaussian autocorrelation is assumed. Pre experiment simulations showed the reconstructions to be not unduly sensitive to the correlation length associated with the selected Gaussian function. Also shown was that features of the medium smaller than approximately 2 m could not be imaged; the coverage with N=16 paths was too sparse to recover the fine details of the attenuation field.

APPLICATION TO DELTA FRAME DATA

Figure 1 shows a sequence of six reconstructions, sampled approximately 30 s apart, over the interior of the Delta Frame. The 117 kHz attenuation data were used, and a correlation length of 2.5 m assumed. Time t is indicated as seconds after 13:58:20 LMT on 7 March, 1997. This is a time period where other investigators were also making measurements and will permit the eventual comparison of results.

At t=3136 s, there was little excess attenuation due to bubbles. Thirty seconds later, a region of high attenuation, 15 dB/m, was concentrated near where a source was located on the lower left hand (SE) corner of the frame. Another 30 s later, the peak attenuation dropped to less than 10 dB/m and the field became more diffuse. In the next frame, the region of maximum attenuation has drifted towards the right (N) vertex of the frame. Between the fourth and fifth images, a period of high attenuation occurred. Particularly for the lower frequencies, the transmitted signals could not be detected at the receivers. The remnants of this high attenuation event can be observed at t=3256 s. The attenuation levels continued to decrease in the final image.

In future work, tomographic images of the attenuation field will be produced with finer time sampling. The images produced at differing acoustic frequencies will be compared.

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