# Applications of Quantum Chaos Concepts to Long-Range Ocean Acoustics

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## LONG-TERM GOALS

The long-term goals are:

1) to take advantage of the ever-changing ocean environment's effects in order to provide a more complete understanding of long-range acoustic pulse propagation,

2) to understand the extent of fundamental limitations on ray-based acoustic tomography; of particular interest is the breakdown range of semiclassical methods,

3) to develop the theory of the statistical fluctuations of the wavefield, and

4) to address important basic physics issues that arise in the ocean problem, but within a more general wave propagation in random media context.

## OBJECTIVES

There are three primary scientific objectives of this work: 1) to begin developing a geometric acoustics theory that addresses parametrically varying ocean environments in the presence of ray chaos, determines what information survives under such conditions, and determines how to extract it, 2) to develop the geometric acoustics theory of wavefield fluctuations, and 3) to determine the sensitivity of acoustic wavefields to relevant ocean environment parameters thereby connecting the scale of changes in the ocean to range scales of wavefield correlation decay.

## APPROACH

We consider acoustic propagation problems that allow for parabolic equation description. Advantage is taken of new semiclassical approaches to approximate time-evolving wavefields in systems possessing classically chaotic analogs. The methods rely on wave packets, heteroclinic orbit summations, and have been shown to be remarkably accurate in spite of relying on highly unstable chaotic trajectories. The approach is similar in spirit to the van Vleck approximate propagator, and the Gutzwiller trace formula. From this starting point, we consider systems whose governing equations can be expressed as varying with respect to a parameter; this can model, for example, a time-changing internal wave configuration. To study response and sensitivity, it is fruitful to apply perturbation theory to describe the changes arising in ensembles of classical trajectories underlying the wavefields. We compare semiclassical predictions with ‘exact’ numerical wavefield calculations.

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## WORK COMPLETED

The work completed this year is comprised of three avenues, one in collaboration with M. Wolfson, another with a WSU postdoc, Nicholas Cerruti, and the last with ocean chaos work collaborators. Dr. Wolfson and I have used a dynamical systems approach to derive analytic formulae describing the stability of early branches of the time front and the time wander of each branch due to internal waves. The work fully incorporates a Garrett-Munk spectrum of internal waves, and uses classical canonical perturbation theory in its approach. Dr. Cerruti and I have submitted a paper to *Physical Review Letters* describing the relationship between unstable classical rays and much more stable wave field evolution. Wave fields do not possess the kind of exponential instability seen in chaotic ray systems. Yet, there exists work showing that chaotic rays can be used to approximate evolving wave fields. The resolution of this paradox has been dubbed 'manifold stability' whereby collections of rays behave much more stably than the individual rays themselves. The results are relevant to decoherence in long range acoustic experiments, and other applications such as quantum computation as well. Finally, the ocean chaos group of collaborators has submitted a review article on ray methods in ocean acoustics. The latest results on intensity statistics and mode coupling are discussed in the language of Hamiltonian dynamical system theory.

## RESULTS

Dr. Wolfson and I have found that the crucial effect of eigenray constraints are to force a disappearance of the travel time variation good to second order in an expansion of the Hamiltonian. This is consistent with the experimental stability seen in early arrivals of the time front even under conditions that generate ray chaos. Further results are in preparation for publication. Dr. Cerruti and I have identified two main mechanisms for stability, and have found two main decoherence regimes. One is characterized by Gaussian decay of correlations, and the other by exponential decay. Classical perturbation theory was used to set the width of the Gaussian and the decay scale of the exponential.

## IMPACT/APPLICATION

The work is aimed at understanding the predictability and/or other limitations of ray methods in the presence of unstable dynamics. In addition, parametric variation, once understood, is often found to be one of the only successful ways of deducing otherwise difficult-to-ascertain information about complex systems such as the ocean environment. It may lead to new ocean acoustic tomography techniques.

## TRANSITIONS

It is too early to discuss how these results will eventually be used by others.

## RELATED PROJECTS

Additional work currently underway, but not described in this report, involves collaborations with the following individuals: M. Wolfson (WSU), J. Colosi (WHOI), and M. Brown (RSMAS-AMP).

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