Dynamics and Stability of Acoustic Wavefronts in the Ocean

Oleg A. Godin
CIRES/Univ. of Colorado and NOAA/Earth System Research Lab., Physical Sciences Division,
R/PSD99, 325 Broadway
Boulder, CO 80305-3328
phone: (303) 497-6558 fax: (303) 497-5862 email: oleg.godin@noaa.gov

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http://cires.colorado.edu

LONG-TERM GOALS

- To develop a method of modeling sound propagation in an environment with multi-scale inhomogeneities, which preserves the efficiency and intuitive qualities of the ray theory but is free from spurious environmental sensitivity and strong perturbations associated with ray trajectories.
- To investigate and quantify effects on underwater acoustic wavefronts of internal gravity waves, sea swell, "spice," and other small-scale processes in the water column.

OBJECTIVES

1. To assess significance of time dependence of the sound speed and flow velocity perturbations on predictability of acoustic wavefronts and timefronts.
2. To quantify horizontal refraction of sound by random meso-scale inhomogeneities at O(1)Mm propagation ranges.
3. To find the variance and bias of random ray travel times in the regime, where the ray displacement may be comparable to the vertical extent of the underwater waveguide but the clustering has not developed yet.
4. To determine, using a perturbation theory and numerical simulations, typical propagation ranges where clustering of chaotic rays replaces the anisotropy of ray scattering as the main physical mechanism responsible for acoustic wavefront stability.
5. To develop an efficient technique for modeling acoustic wavefronts and their perturbations in range-dependent and horizontally inhomogeneous oceans.
6. To model perturbations of acoustic wavefronts and timefronts by internal gravity waves, internal tides, sea swell, and "spice" in the ocean.
7. To determine, using a perturbation theory and full-wave numerical simulations, the range of acoustic frequencies where diffusion along the wavefront overtakes the anisotropy of ray scattering as the main physical mechanism responsible for acoustic wavefront stability.

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8. To investigate implications of wavefront stability on the downward extension of acoustic timefronts and deepening of lower turning points of steep rays due to small- and meso-scale physical processes in the upper ocean.

APPROACH

Our primary theoretical approach is an extension of the method employed in (Godin, 2003, 2007, 2009), where a novel perturbation technique has been developed to solve the eikonal equation and calculate wavefront and ray trajectory displacements, which are required to be small over a correlation length of the environmental inhomogeneities but not necessarily over the entire acoustic propagation path. In order to extend analysis to longer ranges, this method will be combined with perturbation approaches developed (for 2-D problems) in the context of the ray chaos theory (Brown et al., 2003; Virovlyansky, 2006; Makarov et al., 2010). Methods based on the geometrical acoustics are complemented by full-wave approaches (Brekhovskikh and Godin, 1999), including a normal-mode theory for range-dependent and horizontally inhomogeneous waveguides.

The analytical methods are complemented by numerical wavefront-tracing techniques. A major problem with a direct modeling of acoustic wavefronts in the ocean through numerical solution of the eikonal equation lies in the eikonal (and acoustic travel time) being a multi-valued function of position. A number of computational approaches to solve the eikonal equation without ray tracing have been developed in mathematical and seismological communities (Vidale, 1990; Sava and Fomel, 2001; Sethian, 2001, Benamou, 2003). However, most of these methods are only capable of tracing the wavefront of the earliest, first arrival and thus are not suitable for underwater acoustic applications. We adapt to ocean acoustics problems the Lagrangian wavefront construction techniques (Vinje et al., 1993, 1999; Lambaré et al., 1996; Sava and Fomel, 2001; Chambers and Kendall, 2008; Hauser et al., 2008), which have been developed in the context of exploration seismology and are capable of computing all arrivals. Extension of the existing wavefront construction techniques to long-range underwater sound propagation is a non-trivial and, in fact, rather challenging task because the number of ray arrivals and topological complexity of wavefronts in the ocean far exceed those in the geophysical applications considered to date. Following the ideas presented in (Godin, 2002), the wavefront construction techniques are being extended to moving and non-stationary (i.e., time-dependent) media.

Theoretical results and new modeling capabilities are being verified against numerical simulations performed with well-established ray and PE propagation codes.

The key individuals that have been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ESRL) and Nikolay A. Zabotin (CIRES/Univ. of Colorado). Dr. Zabotin focused on developing and testing an efficient computer code for modeling acoustic wavefront propagation in an ocean with range-dependent sound speed and current velocity. Dr. Godin took the lead in theoretical description of effects of the ocean currents, localized inhomogeneities, and sound-speed time-dependence on the acoustic wavefronts.

WORK COMPLETED

Distortions of wavefronts by localized scatterers have been quantified using new frequency- and time-domain asymptotic solutions for the acoustic Green's functions in a homogeneous fluid with soft, rigid, impedance, and fluid spherical inclusions in the open space and near interfaces (Godin, 2011a; Glushkov et al., 2012).

Contributions of the internal gravity wave-induced currents and time variations of the sound speed into fluctuations of acoustic timefronts have been studied theoretically using a recently derived exact wave equation for sound in inhomogeneous, moving, and non-stationary fluids (Godin, 2011b).

Emergence of regular, predictable wavefronts from wave fields scattered by the ocean surface and seafloor or generated by multiple incoherent sound sources has been investigated theoretically and experimentally in shallow and deep water, including horizontally inhomogeneous waveguides (Godin, 2012a, b; Godin et al., 2012).

A unified theory of normal modes of acoustic and internal gravity waves in oceanic waveguides has been derived for the purposes of self-consistent, full-wave description of the sound propagation through internal wave fields (Godin, 2012c).

The software we previously developed (Zabotin et al., 2012) to simulate acoustic wavefronts and timefronts in the range-dependent ocean has been extended to the horizontally inhomogeneous ocean where the sound speed and current velocity can depend on all three spatial coordinates. The acoustic wavefront tracing code has been benchmarked using analytic solutions of the eikonal equation in moving and motionless fluids.

RESULTS

A software package has been developed for numerical modeling of 3-D sound propagation in horizontally inhomogeneous ocean. We model acoustic wavefronts and timefronts in inhomogeneous, moving media without solving ray equations. (Rays are recovered, though, as a by-product of the wavefront construction.) The new software is an extension to 3-D problems of our earlier 2-D wavefront tracing code (Zabotin et al., 2012), which in turn was an adaptation for underwater sound and extension of the computer codes originally developed by Sava and Fomel (2001) for seismic modeling and imaging. The codes implement an approach known as Huygens wavefront tracing (HWT) (Sava and Fomel, 2001). HWT consists in solving by a finite-difference technique of a certain system of partial differential equations, which is equivalent to the eikonal equation but is formulated in the ray coordinate system. This should be contrasted with traditional ray tracing, where the eikonal equation is solved by numerically integrating a large number of ordinary differential equations describing individual rays. For wavefront tracing in inhomogeneous media, HWT is much more computationally efficient and robust than traditional ray codes (Sava and Fomel, 2001). Unlike many other eikonal solvers, the HWT method produces the output in ray coordinates and has the important ability to track multiple arrivals. With the HWT method, each wavefront is generated from the preceding one by finite differences in the ray-coordinates domain.

Adaptation of the HWT technique to underwater acoustics problems (Zabotin et al., 2012) included, in particular, (i) modification the underlying finite-difference algorithm to improve stability of wavefront predictions at long-range propagation; (ii) account of ocean currents and resulting acoustic anisotropy of the propagation medium; and (iii) development of functionality to efficiently model acoustic timefronts in addition to the wavefronts.

To verify our 3-D numerical model, an exact analytic solution of the eikonal equation has been found for wavefronts due to a point source in fluids with linear profiles of the sound speed and the flow velocity. Figure 1 shows a 3-D acoustic wavefront due a stationary point source and comparison of the analytic and numerical solutions for timefronts in a fluid with sound speed $c = \alpha z$ and flow velocity $\mathbf{u} = (u_0(1 + \gamma z), 0, 0)$, where $\alpha = 0.1\ \mathrm{s}^{-1}$, $u_0 = 500$ m/s, and $\gamma = 5\cdot10^{-5}\ \mathrm{m}^{-1}$. Exaggerated values of flow velocities are utilized here to illustrate accuracy of numerical predictions under more stringent conditions.

Application of the 3-D wavefront tracing to simulation of long-range sound propagation in the deep ocean is illustrated in Figure 2, where a wavefront in a range-independent ocean is compared to corresponding wavefronts in a single realization of an ocean with a random internal gravity wave field described by the Garrett- Munk spectrum. The high-resolution, multi-mode model of the internal gravity wave field employed in our simulations is described in (Godin et al., 2006). The wavefronts shown in Figure 2b are calculated in horizontally inhomogeneous and range-dependent oceans, i.e., with and without account for internal wave-induced cross-range variations in the sound speed. Well-known effects of the internal gravity waves on sound propagation (Brown et al., 2003; Virovlyansky, 2006; Makarov et al., 2010), such as travel-time perturbations, which translates into shifts of wavefronts in range, and extension of wavefront branches in depth, are apparent in both 2-D and 3-D wavefront simulations (Figure 2). The internal wave-induced acoustic perturbations tend to be underestimated when 3-D propagation effects are ignored. The effect of cross-range environmental gradients on extensions of the perturbed wavefronts in depth and appearance of shadow-zone arrivals proves to be particularly strong (Figure 2b). A systematic investigation of this effect is underway.

IMPACT/APPLICATIONS

Wavefront tracing has been established as a new approach to modeling underwater sound propagation, which readily accounts for 3-D propagation effects and provides an efficient and robust alternative to ray tracing.

RELATED PROJECTS

None.

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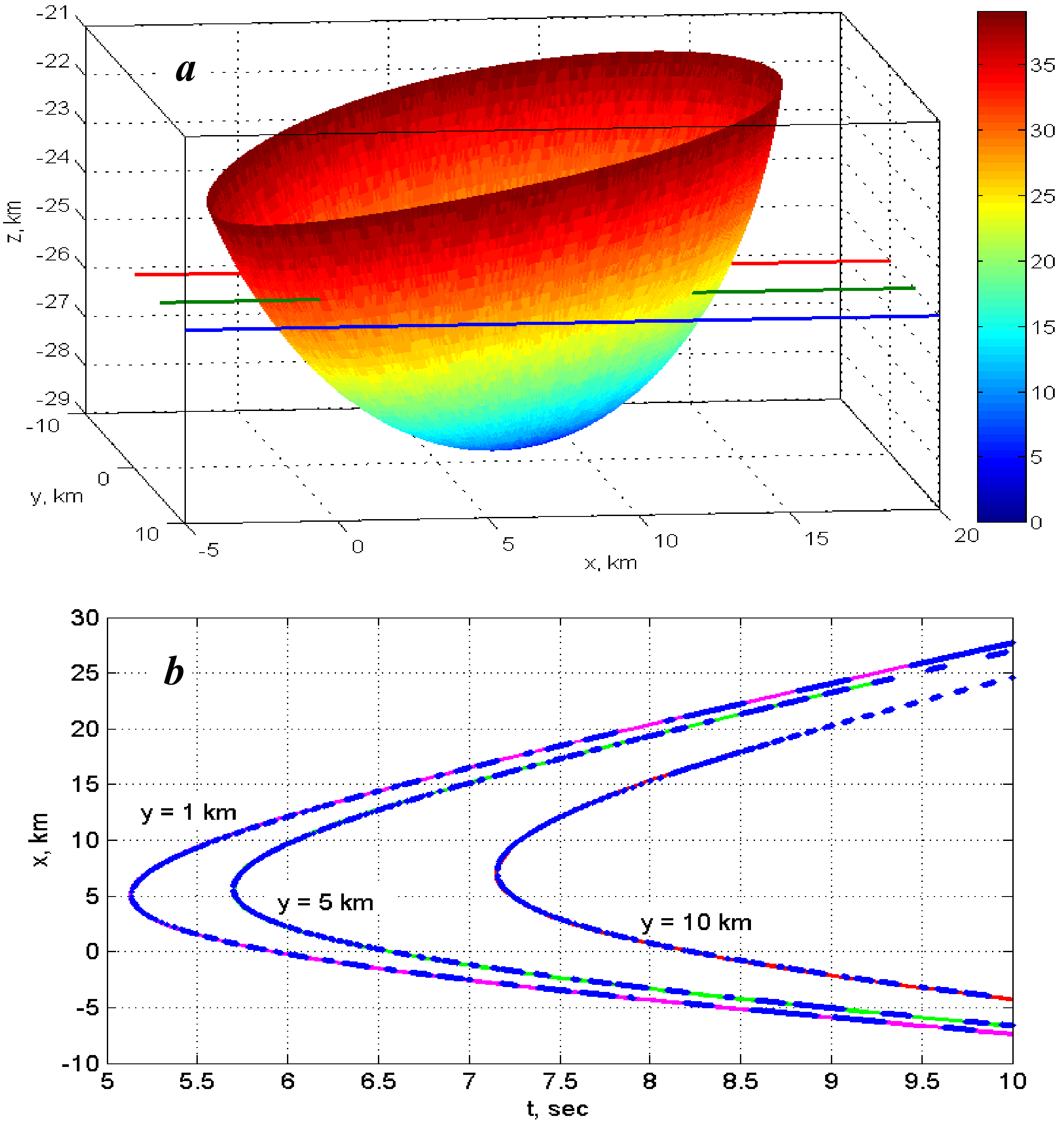

Figure 1. Acoustic wavefront (a) and timefronts (b) in a fluid with linear sound speed and current velocity profiles. The sound speed and current velocity are functions of depth z. Current velocity is parallel to Ox coordinate axis. A sound source is located at the point with coordinates (0, 0, 15km). The wavefront corresponds to travel time 6.5 s. The part of the wavefront shown in panel (a) is formed by rays with launch incidence angles (shown by color) from 0 to 38 degrees. Timefronts in panel (b) are calculated for the three straight lines depicted in panel (a). Analytic (lines) and numerical (dots) solutions are in an excellent agreement.

[The wavefront is a surface shown in 3-D within a volume, where x, y, and z coordinates range between –5 and 20, –10 and 10, and –29 and –21 km, respectively. The wavefront is elongated in the direction of the current. The timefronts are shown for x between –10 and 30 km and acoustic travel time t between 5 and 10 s along three parallel lines in the plane z = –25km.]

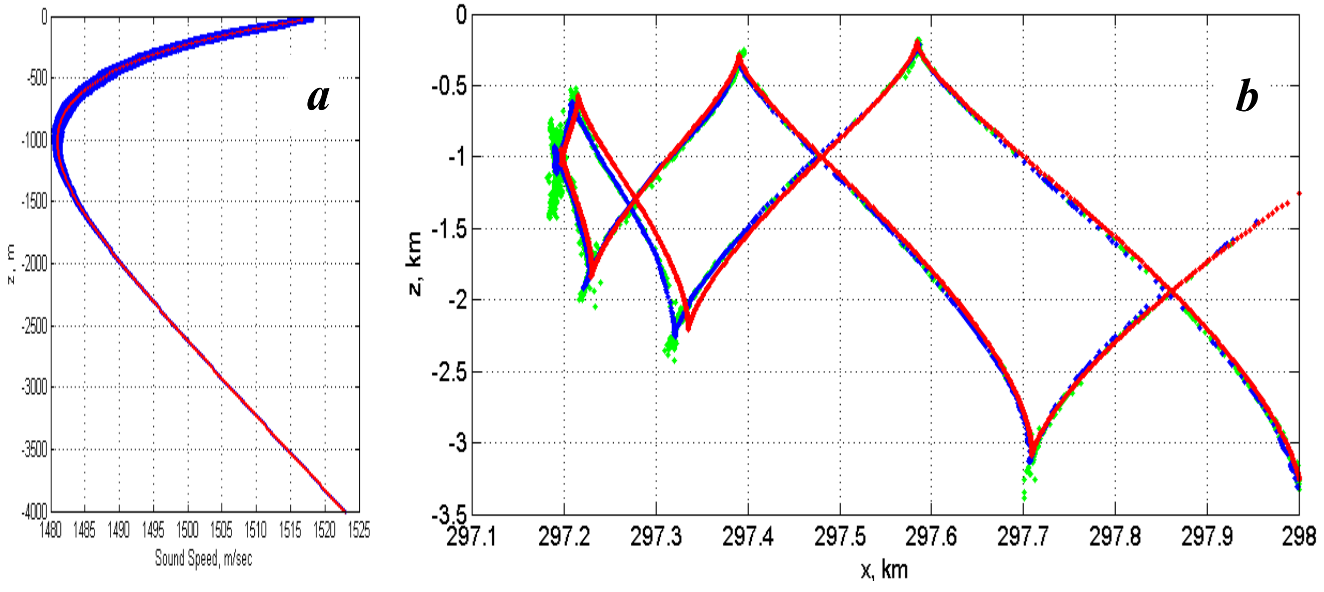

Figure 2. Acoustic wavefronts in an ocean with internal gravity waves. A point source is located at depth1 km, which is close to the axis of the underwater sound channel. In panel (a), sound speed profiles at different ranges and range-averaged sound speed profile are shown in blue and red, respectively. Panel (b) shows cross-sections of the wavefronts at travel time t = 200 s by the vertical plane containing the sound source. The wavefront in three-dimensionally inhomogeneous ocean (green) is compared to the wavefronts in a range-independent ocean (red) and in range-dependent ocean (blue).

[In panel (a), sound speed varies between about 1480 and 1524 m/s. Sound speed profiles have a minimum around 1 km depth. Internal wave-induced variations in the sound speed occur primarily above 1.2 km depth. In panel (b), wavefronts are shown for ranges between 297.1 km and 298.0 km and depths from 0 to 3.5 km. Internal waves effectively shift acoustic wavefronts in range and extend in depth, with the magnitude of the wavefront perturbations being strongly underestimated in 2-D calculations.]

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