Valerian Tatarskii and Acoustic Wave Propagation in Random Media

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Introduction

Stars twinkling in the night sky due to atmospheric turbulence, dancing webs of bright sunlight on the bottom of a swimming pool with a wavy surface, and a handclap echoing through trees in a forest all exemplify the field of *wave propagation in random media* (WPRM). WPRM has applications throughout science and technology, including in seismology, optics, radio communication, medicine, global positioning system (GPS) navigation, and astronomy. Examples of WPRM furthermore abound in acoustics. Sound is randomly scattered by internal-wave fields in the ocean and upper atmosphere, turbulence in the lower atmosphere, buildings in an urban environment, fish schools, and biological organs and tissue.

Applications of WPRM generally fall into two categories. The first category is where a known signal is randomized or degraded by the medium, leading to a loss of otherwise recoverable signal information. An example application is underwater communication and navigation where random medium effects limit data rates and localization precision of sources and receivers. In the second category, the signal randomization itself is of fundamental interest because it provides information about the random medium, for example, the size and density of a fish school or the strength of turbulence in the ocean or atmosphere.

In either case, the common objective of WPRM is to relate statistical characteristics of a sound signal (e.g., the variances of the amplitude and phase fluctuations) to random medium statistics and propagation parameters such as distance and signal frequency. This relationship is generally rather complex because sound signals are scattered and diffracted by many random inhomogeneities with different sizes.

Atmospheric turbulence consists of interacting eddies spanning six orders of magnitude, from 1 mm to about 1 km. In 1941, Kolmogorov formulated the famous −5/3 power law describing the middle part of this spectrum that is characterized by decay of large eddies into smaller ones.

The Kolmogorov spectrum set the stage for studies of acoustic and electromagnetic wave propagation through atmospheric turbulence, which was the origin of modern WPRM. Using this spectrum and geometrical acoustics, Krasilnikov (1945) calculated the variances of the amplitude and phase fluctuations of acoustic signals and compared the results with experimental data. Later, Obukhov (1953) realized that diffraction impacts these variances and adopted an approximation developed by Rytov (1937), originally for light diffraction by ultrasound, to correct the calculations.

Despite these accomplishments and other studies, the field of WPRM did not reach maturity until the publication of two monographs by Tatarskii (1959, 1967). The monographs clearly and rigorously presented the modern physical understanding of atmospheric turbulence spectra and showed how various statistical characteristics of electromagnetic and acoustic waves can be expressed as functions of those spectra. These books were translated into English and ushered in several decades of highly productive, global, interdisciplinary WPRM research. As Wheelon (2001, 2003) stated in his own books on WPRM, “These volumes are dedicated to Valerian Tatarskii who taught us all.”

The main purposes of this article are to highlight Tatarskii’s role in the field of WPRM and to provide a summary of recent research on sound propagation through atmospheric turbulence and ocean internal waves that builds on his legacy.

Tatarskii as a Scientist and Mentor

Valerian Tatarskii’s (1929–2020) scientific career started at a fortuitous place and time. Vladimir Krasilnikov was

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Tatarskii's MS advisor in the early 1950s at Moscow State University, Moscow, Russia, and he formulated Valerian's thesis topic: sound propagation in a turbulent atmosphere. In 1953, Tatarskii began work under Alexander Obukhov (a prominent atmospheric physicist and statistician), at what later became the Institute of Atmospheric Physics, in Moscow. Obukhov asked Tatarskii to apply the Rytov method to a variety of problems in acoustic and electromagnetic wave propagation. The powerful results obtained were summarized in Tatarskii's PhD dissertation, completed in 1957, and in his first book (1959).

The Rytov method describes weak (unsaturated) fluctuations in propagating waves. Motivated by various applications, many scientists subsequently worked on advanced methods for the challenging problem of strong fluctuations. To this end, Tatarskii pioneered the use of diagram techniques (Tatarskii, 1967) and the Markov approximation (Tatarskii, 1969). He also contributed to development of other methods such as parabolic equations, variational derivatives, and the Feynman path integral. These new methods enabled solution of many challenging problems, and many phenomena were explained or discovered, such as the saturation of intensity fluctuations and random medium backscattering enhancement. These methods and results were summarized in Tatarskii's second book (1967) and a later book coauthored with Rytov and Kravtsov (Rytov et al., 1989).

Figure 1. *Participants of the First Meeting on Wave Propagation in Random Media, Tallin, Estonia, 1988.* ***From left: first row:*** *Yu. Kravtsov, Mrs. Tatarskaya, V. Tatarskii, Ü. Mullamaa (local host), A. Ishimaru, Mrs. Lang, A. Orekhova (interpreter), Mrs. Flatté, V. Varadan, S. Flatté, A. Gurvich;* ***second row:*** *V. Vorob'ev, V. Shishov, M. Nieto-Vesperinas, R. Hill, R. Lang, I. Besieris, Y. Kuga;* ***third row:*** *Yu. Barabanenkov, I. Yakushkin, A. Saichev, V. Freilikher, V. Brekhovskikh, E. Bakhar, Mrs. Bakhar, L. Tsang, K. Yeh, V. Klyatskin;* ***fourth row:*** *I. Granberg (organizing committee), C. Rino, G. Brown, V. Zavorotny, V. Ostashev, J. Dainty, V. Sekistov.*

From the beginning, WPRM has been an interdisciplinary field. To build on this, in 1988, Tatarskii (Russia) and Ishimaru (United States) organized the first meeting on "Wave Propagation in Random Media" held in Tallin, Estonia (**Figure 1**). About three dozen leading Russian and foreign scientists, representing widely ranging specialties, participated. The meeting led to a new journal, *Waves in Random Media* (now *Waves in Complex and Random Media*).

Early papers on WPRM were often qualitative; turbulence was represented as circles and waves as bending rays. Tatarskii's books, on the other hand, rigorously described from first principles the full complexity of turbulent media wave propagation. Tatarskii combined his extensive physics background in several areas with a unique ability to present complicated topics clearly. Many scientists working in the field considered Tatarskii to be a mentor. Steven Clifford, director of the NOAA Wave Propagation Laboratory, held Tatarskii in such high esteem that he recruited him in the early 1990s to work there.

Tatarksii was similarly skilled at mentoring students. After reading his books, many young scientists wanted to study under his guidance. Tatarskii was remarkably proficient at rooting out errors in students' handwritten calculations. He advised his students to do the derivations once, put their notes aside, repeat the derivations, and then see whether the results coincide.

When working on his second book, Tatarskii usually wrote about 15 handwritten pages a day. Remarkably, these handwritten pages turned out to be the only draft of the book and read quite clearly! Although Tatarskii used to mention Voltaire's aphorism "Perfect is the enemy of good," his books and papers are remarkably close to perfect in their ability to explain complicated problems. Although Tatarskii understood his contributions to the field, he remained humble: "I do not think very fast" and "There are people in Russian Academy of Sciences who are smarter than me."

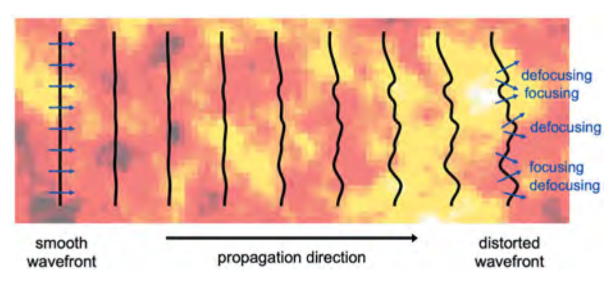


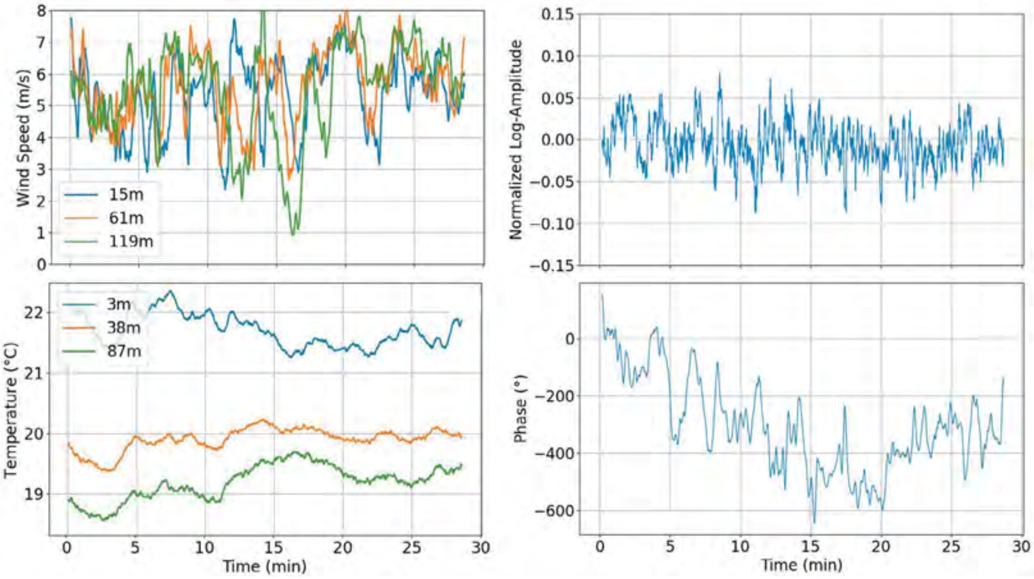
Figure 2. *Wave propagation in a randomly inhomogeneous medium.* ***Orange*** *and* ***yellow****, positive and negative sound speed fluctuations, respectively.*

Introduction to Wave Propagation in Random Media

Consider a plane wave with amplitude A_0 and phase ϕ_0 traveling in the $+x$ direction in a homogeneous medium. The sound pressure is given by $p_0=A_0\cos(k_0x-\omega t+\phi_0)$, where $k_0=\omega/c_0$ is the wavenumber, c_0 is the sound speed in the homogeneous medium, ω is the angular frequency, and t is time. When the plane wave propagates (**Figure 2**) through a randomly inhomogeneous medium with sound speed $c=c(x,y,z,t)$, where y and z are the coordinates perpendicular to x, the amplitude A and phase ϕ are perturbed from their original values (A_0 and ϕ_0, respectively). The wave front propagates faster through the inhomogeneities where the sound speed fluctuation is positive and slower where it is negative. As a result, the initially plane wave front distorts (**Figure 2**). Where the distorted wave front is locally concave, the sound is focused and the amplitude increases; where it is locally convex, the sound is defocused and the amplitude decreases. Fluctuations in the velocity of the medium (wind in the atmosphere, current in the ocean) produce similar effects.

Figure 3 provides an example of atmospheric sound propagation. It depicts a 28-min record of wind speed and temperature (which is mainly responsible for the sound speed variations) at three different heights above the ground around midday in partly cloudy conditions (Kamrath et al., 2021). Also shown are the corresponding records of log amplitude [i.e., $\ln(A/A_0)$] and phase for 600-Hz signals propagating over a 68-m path. Even for paths this short, atmospheric acoustic signals exhibit pronounced random variations. As explained in the **Introduction**, the relationship between the statistical characteristics of log-amplitude and phase fluctuations (**Figure 3**, *right*) and statistics of the wind speed and temperature fluctuations (**Figure 3**, *left*) is rather complex. The log-amplitude variations are caused mainly by small-scale turbulent eddies, whereas the phase variations are driven by the largest, most energetic eddies.

Figure 3. ***Left:*** *wind speed (****top****) and temperature (****bottom****) at three heights above the ground versus time.* ***Right:*** *log amplitude (****top****) and phase (****bottom****) of the sound pressure versus time. Adapted from Kamrath et al., 2021.*



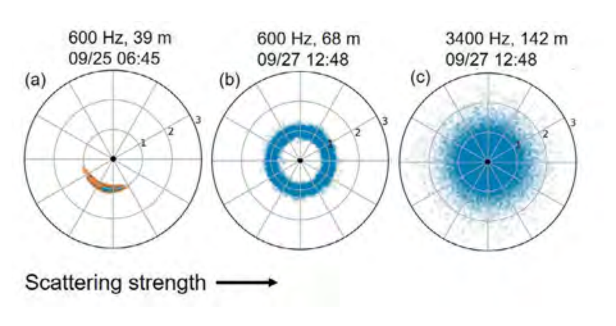


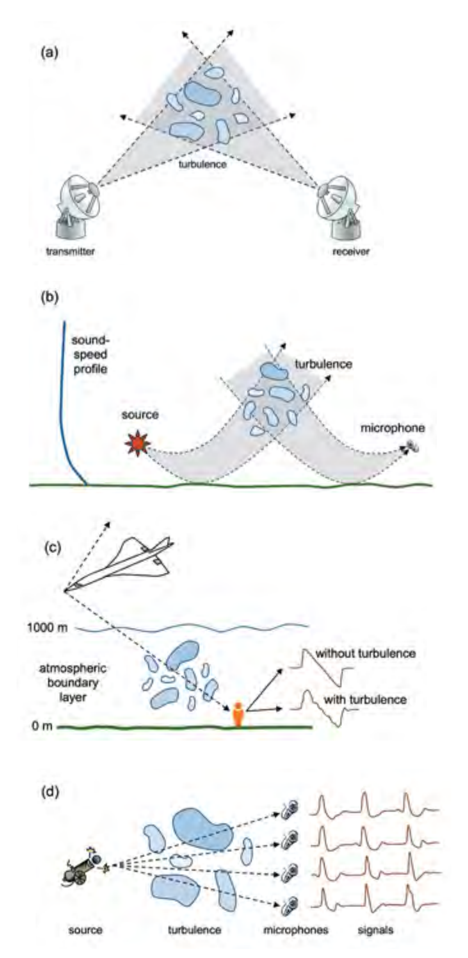
Figure 4. *Amplitude and phase fluctuations for scattered signals as depicted on polar diagrams. Three different cases, arranged by the strength of the scattering, are shown. These cases involve data for amplitude and phase fluctuations in different meteorological conditions (Kamrath et al., 2021).* ***a:*** *For weak amplitude and phase fluctuations, samples (**blue and orange dots**) are in a small arc on the unit circle and correspond to samples before and after an atmospheric event that caused a transition in the signal behavior.* ***Samples*** *correspond to those from the signal's complex time series, whose normalized amplitude and phase correspond to distance from the origin (**black dots**) and polar angle.* ***b:*** *For still small amplitude fluctuations and large phase fluctuations, samples spread around the unit circle, creating a bull's-eye pattern. Dots appear as "clouds" due to the high point density.* ***c:*** *For strong amplitude and phase fluctuations, center of the unit circle fills in.*

Polar grids (also called *phasor diagrams*) provide an insightful characterization of the amplitude and phase fluctuations. **Figure 4** shows distinctive patterns produced for differing scattering strengths. For weak (unsaturated) amplitude and phase fluctuations, complex signal samples are confined to a small arc on the unit circle (**Figure 4a**). When the amplitude fluctuations are still small but the phase fluctuations are large, the samples spread around the entire unit circle, creating a bull's-eye pattern (**Figure 4b**). When both the amplitude and phase fluctuations are strong, the center of the unit circle fills in (**Figure 4c**). The amplitude and phase fluctuations also depend on the strength of diffraction (Colosi, 2016).

Sound Propagation in a Turbulent Atmosphere

Figure 5 illustrates different practical situations where turbulence has significant impacts on atmospheric sound propagation. The first is *sodar* (sonic detection and ranging; **Figure 5a**) (Bradley, 2010). Sodar is the acoustical counterpart of radar (radio detection and ranging) and the atmospheric counterpart of oceanic sonar (sound navigation and ranging). The sound signal, typically consisting of a short pulse in the low kilohertz range, is transmitted into the atmosphere and then scattered by turbulent eddies, thus returning an echo to the receiver. The transmit and receive antennas use parabolic reflectors or phased loudspeaker arrays to enhance the signals. When the transmit and receive antennas are at different locations, the system is *bistatic*; when antennas are colocated, it is *monostatic*. Sodars provide wind profiling up to altitudes of about 2 km above ground as well as information on the intensity of temperature and velocity fluctuations.

Figure 5. *Practical situations where turbulence significantly affects sound propagation.* ***a:*** *Acoustic remote sensing of the atmosphere with sonic detection and ranging (sodar).* ***b:*** *Sound scattering into a refractive shadow zone.* ***c:*** *Acoustic pulse propagation.* ***d:*** *Coherence loss of acoustic signals. See text for detailed description of each situation.*



Acoustic tomography provides another approach to sensing the lower atmosphere based on interactions between the sound waves and turbulence. Because the travel time of acoustic signals depends on the temperature and wind velocity fields through which they propagate, the travel times along multiple transmission paths through a cross section of the atmosphere can be inverted to image the structure of those fields (Wilson and Thomson, 1994).

Another situation where the turbulence effects are important occurs when sound is refracted upward near the ground, as shown in **Figure 5b**. Refraction can significantly impact noise near highways, airports, factories, and wind turbines. When the sound propagates upwind or with a negative temperature gradient, upward refraction occurs, which is beneficial from a noise mitigation perspective. In fact, at longer distances from the source (typically around several hundred meters), the upward refraction can create a *shadow zone* into which no sound energy penetrates according to ray acoustics.

However, in the 1980s and 1990s, as fully wave-based numerical methods for atmospheric sound propagation were developed, it became apparent that even when diffraction into shadow zones was properly calculated, sound levels were still consistently underpredicted. Gilbert et al. (1990) found that by including scattering from turbulence in the calculations, sound levels in the shadow dramatically increased, thus eliminating the bias. The scattering has other impacts such as smoothing interference patterns between the direct and ground reflection paths and between modes in near-ground waveguides for downwind propagation. An earlier *Acoustics Today* article by Wilson et al. (2015) discusses near-ground scattering and refraction effects, with example calculations and visualizations.

The third application is the impact of atmospheric turbulence on pulse propagation, such as explosions and sonic booms (**Figure 5c**). On average, turbulence decreases the peak amplitude, increases the rise time, and elongates the tail of pulses. These effects tend to make sonic booms more tolerable to listeners (e.g., Stout et al., 2021) and are thus an important design consideration for "low-boom" supersonic aircraft, which involve shaping the airframe so as to tailor the characteristics waveform and perception of the boom. Turbulence is generally the strongest within the atmospheric boundary layer (ABL), which extends from the ground up to about 200-3,000 m, depending on weather conditions. Strong turbulence can also occur at the interface between the ABL and the free troposphere above.

Last, there is the role of atmospheric turbulence in reducing acoustic signal coherence (**Figure 5d**). A pair of signals is said to be coherent when the amplitude and phase relationships between the signals are consistent. By randomizing the signal amplitude and phase as they propagate, turbulence reduces coherence when the signals arrive at sensors (Ostashev and Wilson, 2015). The loss in coherence, which can occur over separations in space, time, and frequency, impacts the performance of outdoor acoustical systems. Many processing techniques, such as cross- correlation and beamforming, depend on high-signal coherence to provide high-resolution localization and boost the signal-to-noise ratio. Examples include "acoustic cameras" for accurately locating and identifying noise sources, gunfire and artillery direction-finding systems (Costley, 2020), and ground-based microphone arrays for tracking aircraft.

Sound Propagation in a Fluctuating Ocean

Conceptually, sound propagation in a fluctuating ocean is similar to the atmosphere. However, there are specifics that confounded gaining an understanding of the topic first identified in the late 1940s amid the rapid development of naval applications after the war. A first-order understanding of weak fluctuations was not in place until the mid-1970s.

One of the main impediments was a misunderstanding and lack of measurements of ocean sound speed fine structure. For over a decade, misguided attempts were made to borrow treatments involving homogeneous isotropic turbulence from atmospheric WPRM.

The pioneering work of Garrett and Munk (1972) established that ocean fine structure was dominated by random fields of internal gravity waves that were inhomogeneous and anisotropic; had their own intrinsic time evolution dictated by the dispersion relationship; and, most important, followed a "mostly" universal spectral form termed the Garrett-Munk (GM) spectrum (Spindel and Worcester, 2016). Internal gravity waves are similar to ocean surface waves created by the density difference between air and water; however, internal waves fill the

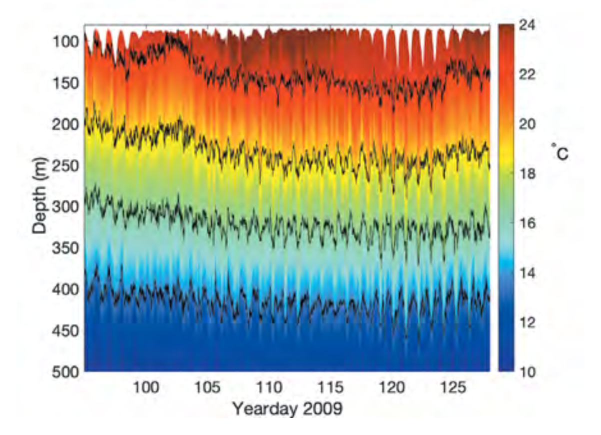


Figure 6. *An example of the depth and time structure of temperature fluctuations over a month in the Philippine Sea. The temperature fluctuations are from the lifting and falling of density surfaces (**black lines**), primarily caused by internal waves with periods from a few minutes to a little over a day.*

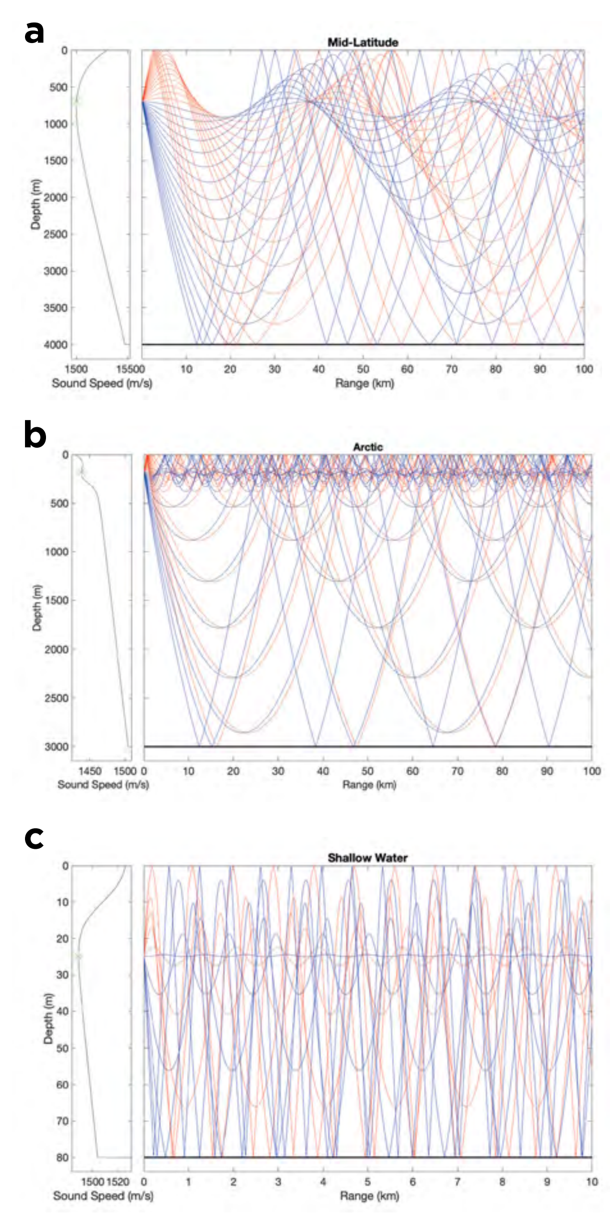
entire ocean volume and ride on the more gentle, stable water-column density gradient.

Figure 6 shows an example of internal waves in the Philippine Sea that compare well with the GM model (Colosi et al., 2019). Internal waves are seen to change the temperature (and therefore the sound speed) of water parcels as they rise and fall vertically with the waves. Internal waves following the GM spectrum are found nearly everywhere in the world's oceans, although anomalous places with departures from the GM spectrum include regions of abrupt topography, the Arctic, and the Mediterranean Sea.

One other critical factor is that the propagation occurs in a relatively strong waveguide. In ocean waveguides, sound does not travel in straight lines but along curved trajectories that oscillate around the horizontal as the wave moves down range (see **Figure 7**). In the deep ocean basins (average water depth of roughly 4,400 m), a volumetric waveguide is formed by decreasing the sound speed from the surface as the water temperatures drops and increasing the sound speed with depth in the isothermal abyssal ocean as pressure increases. In midlatitudes (**Figure 7a**), the sound speed minimum (sound-channel axis) is near 1,000 m depth.

As the latitude increases (**Figure 7b**), the minimum moves to shallower depths until it is near the surface in the arctic. The deep ocean waveguide typically traps sound that propagates within a ±15° cone around the horizontal. In shallow-water cases, say tens or hundreds of meters water depth, the waveguide is established primarily by the surface and seafloor boundaries (**Figure 7c**). Last, another aspect of waveguide propagation is that as the range increases so do the number of possible acoustic paths that connect the source and receiver. The

Figure 7. *Examples of sound speed profiles (**left**) and acoustic paths (**right**) for midlatitude (**a**), Arctic (**b**), and shallow-water (**c**) environments. **Green stars** on the sound speed profiles indicate the source depth. See text for details.*

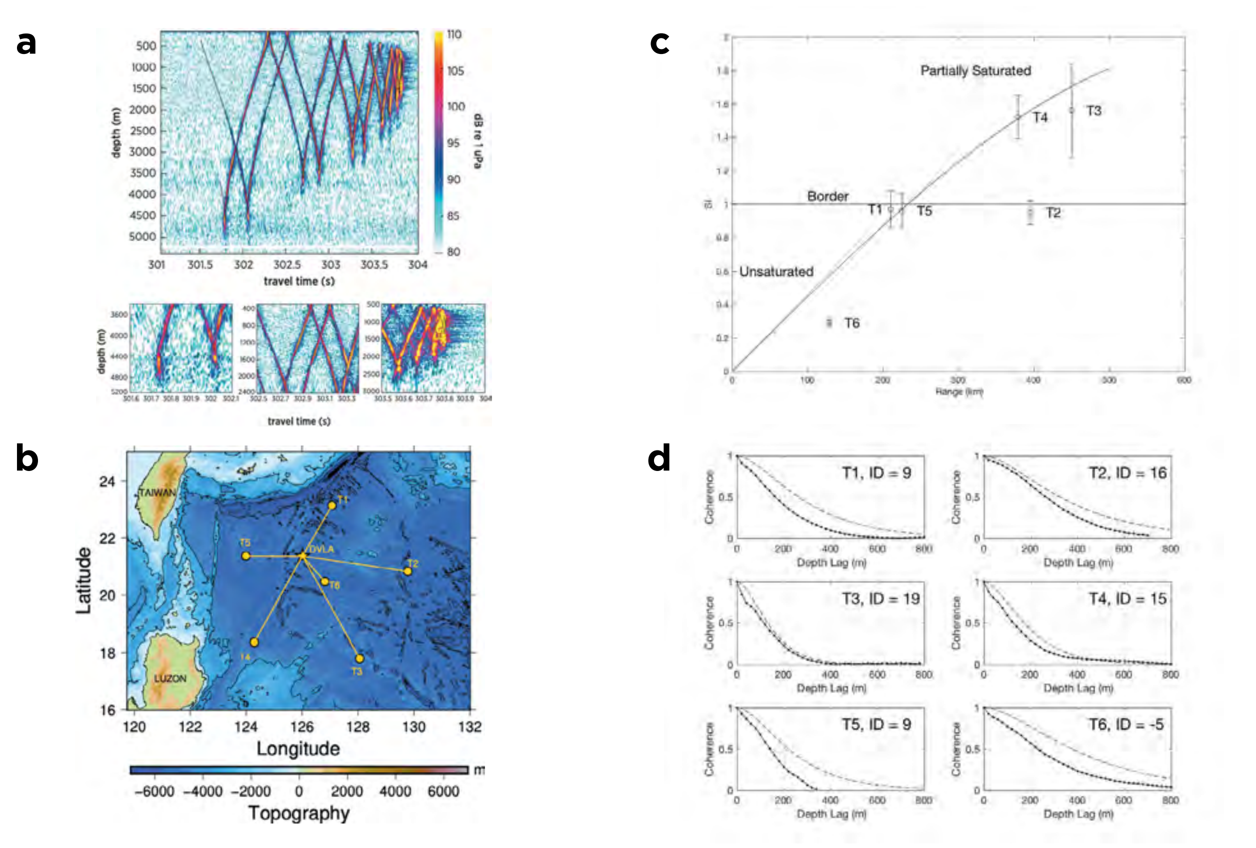


different paths will experience different fluctuations from the random ocean.

Armed with the GM spectrum, the next major breakthrough was provided by Munk and Zachariasen (1976) who used the Rytov method and integrated all the ocean factors: internal waves, inhomogeneity (variation with position), anisotropy (variation in direction), a dispersion relation, and a waveguide. The result was a first-order description of the ocean weak-fluctuation (unsaturated) regime, and the calculations they carried out were in agreement with the available observations and the Monte Carlo simulation mostly to within factors of 2. The strong fluctuation and saturation regimes were analyzed soon thereafter by Flatté and Dashen using the Feynman path integral methods (Flatté et al., 1979; Flatté, 1983a) and by Dozier and Tappert (1978) using coupled mode theory. Remarkably, although some of the details changed, this follow-on work, especially path-based treatments, maintained a strong connection to the physical picture provided by the Munk and Zachariasen (Rytov) formulation.

A fascinating outgrowth of this theoretical work was that acoustical field statistical moments could be expressed analytically in terms of specific ocean process parameters such as internal waves, leading to the suggestion of internal-wave tomography (Munk et al. 1981; Flatté 1983b). This contrasts with previous work in which the acoustical moments were written in terms of ad hoc correlation functions divorced from ocean dynamics. During this time, there was a blossoming of acoustic remote sensing (Clay and Medwin, 1977), leading to a new field, *acoustical*

Figure 8. *A time front (**a: top**) showing observed acoustic intensity in decibels from a 450-km range transmission from location T3 to a water column spanning vertical array (DVLA) in the Philippine Sea (**b**). **a: Bottom**, magnified views of different regions of the time front. The broadband sources at the T-moorings had center frequencies of 250 Hz (except T2 whose center frequency was 170 Hz) and transmitted at a depth near the sound channel axis at roughly a 1,000-m depth (**b**). Observed scintillation index (**c**) and observed (**black lines**) and theory (**gray lines**) vertical coherence (**d**) demonstrate amplitude and phase variability. **a** From Colosi et al., 2019, with permission of Cambridge University Press.*



oceanography, that addresses questions in biological, chemical, geological, and physical oceanography.

The rapid, theoretical advancement of sound propagation through ocean internal waves in the 1970s contrasts sharply with the difficulty of carrying out ocean experiments to test the theories to better than orders of magnitude. Here a newly proposed acoustic remote-sensing technique by Munk and Wunsch (1979), termed *ocean acoustic tomography*, comes to the rescue. Ocean acoustic tomography utilizes precisely timed and navigated acoustic arrays to observe various acoustic path travel times between the array nodes, allowing a mapping of large to midscale ocean structures that are difficult if not impossible to sample with traditional instruments such as ships and floats (Worcester et al., 2005).

The observed variations in travel times are an indication of variations in ocean temperature along the acoustic paths. Thus, as the ocean warms/cools, the travel times decrease/increase (Munk et al., 1994). The instrumentation of ocean acoustic tomography is precisely what is needed to quantify internal-wave-induced fluctuations because removing timing and navigation errors leaves signal fluctuations only due to ocean effects. In addition, the development of large-aperture vertical arrays proved useful for both fields. In tomography, large vertical apertures provide many additional paths and increased horizontal resolution, whereas in fluctuation studies, the arrays provide a look at the correlation properties of the signals in both depth and time.

These acoustic-sensing technologies have been refined over nearly four decades. As an example, **Figure 8** shows data from the 2010–2011 Philippine Sea experiment. Here, a six-mooring transceiver array and a water column-spanning vertical receiver recorded 250-Hz center-frequency broadband transmissions over a whole year for ranges from 125 to 450 km (**Figure 8b**) (Colosi et al., 2019).

Figure 8a shows an example time front that is defined as the time history of wave front intensity as it sweeps by a vertical receiver at fixed range. Each point of the time front can be associated with a ray path that samples the ocean in a specific way. The early-arriving paths cycle steeply through the ocean, whereas the late-arriving paths are confined closer to the sound-channel axis (**Figure 7a**). The variation in acoustic intensity along the time front is an indication of scintillation, and there are corresponding phase fluctuations. **Figure 8c** shows that the scintillation index (normalized intensity variance) increases with the increasing propagation range, indicative of the transition from the unsaturated to the strong fluctuation regime. Phase fluctuations also drive the loss of coherence in depth increasingly so as distance from the source (range) increases (**Figure 8d**).

Finally, the development of the theoretical and observational understanding of sound propagation through the internal-wave field has important implications for practical applications. Although the subject was born of naval needs (detection, localization, classification), the burgeoning remote-sensing applications in acoustical oceanography often mean that internal waves are an irreducible noise that limits the recoverable information. But, at the same time, the acoustic fluctuations carry information about the ocean internal-wave field, a wave field that is an important link in the ocean energy cascade from large to small scales. And last, internal wave effects are an important consideration in the design and implementation of underwater navigation and communication systems, most ambitious of which is an underwater GPS (UGPS) (Van Uffelen, 2021).

Concluding Remarks

This article introduced theoretical and experimental approaches employed by WPRM, particularly for sound propagation in a turbulent atmosphere and fluctuating ocean. Related phenomena occur in other branches of physics, which are amenable to the tools developed by Tatarskii and others. For example, the Earth's lithoshperic crust is modeled as a stratifed medium with random heterogeneities, which scatters seismic waves (Sato et al., 2012). WPRM predicts the broadening of earthquake codas and peak arrival delays, which are used to retrieve lithospheric statistical properties.

There are also many other examples of WPRM in acoustics. Medical ultrasound tomography (Treeby et al., 2019), which predates tomography in the ocean and atmosphere, enables imaging of soft tissue using the effects of tissue inhomogeneities on ultrasound attenuation, travel time, and scattering.

Although turbulence and internal waves exemplify *continuous* random media, many *discrete* random media are also of interest, such as forests and fish schools. Clapping your hands in a forest creates a long echo, similar to the elongated tails of pulses in a turbulent atmosphere. Scattering in continuous and discrete random media have many similarities and can often be described with the same equations (Ostashev et al., 2018).

We hope that this article has helped to illuminate the origins of WPRM and Tatarskii's contributions to the subject while providing interesting examples of its applications to the atmosphere and ocean and to remote sensing of these media.

References

Bradley, S. (2010). *Atmospheric Acoustic Remote Sensing: Principles and Applications*. CRC Press, Boca Raton, FL.

Clay, C. S., and Medwin, H. (1977). *Acoustical Oceanography: Principles and Applications*. John Wiley & Sons, New York, NY.

Colosi, J. A. (2016). *Sound Propagation Through the Stochastic Ocean*. Cambridge University Press, New York, NY.

Colosi, J. A., Cornuelle, B. D., Dzieciuch, M. A., Worcester, P. F., and Chandrayadula, T. K. (2019). Observations of phase and intensity fluctuations for low-frequency, long-range transmissions in the Philippine Sea and comparisons to path-integral theory. *The Journal of the Acoustical Society of America* 146(1), 567-585.

Costley, R. D. (2020). Battlefield acoustics in the First World War: Artillery location. *Acoustics Today* 16(2), 31-39.

Dozier, L. B., and Tappert, F. D. (1978). Statistics of normal mode amplitudes in a random ocean. I. Theory. *The Journal of the Acoustical Society of America* 63(2), 353-365.

Flatté, S. M. (1983a). Wave propagation through random media: Contributions from ocean acoustics. *Proceedings of the IEEE* 71(11), 1267-1294.

Flatté, S. M. (1983b). Principles of acoustic tomography of internal waves. In *Proceedings OCEANS'83*, San Francisco, CA, August 29 to September 1, pp. 372-377.

Flatté, S. M., Dashen, R., Munk, W. H., Watson, K. M., and Zachariasen, F. (1979). *Sound Transmission Through a Fluctuating Ocean*. Cambridge University Press, New York, NY.

Garrett, C., and Munk, W. H, (1972). Space-time scales of internal waves. *Geophysical Fluid Dynamics* 3(3), 225-264.

Gilbert, K. E., Raspet, R., and Di, X. (1990). Calculation of turbulence effects in an upward-refracting atmosphere. *The Journal of the Acoustical Society of America* 87(6), 2428-2437.

Kamrath, M. J., Ostashev, V. E., Wilson, D. K., White, M. J., Hart, C. R., and Finn, A. (2021). Vertical and slanted sound propagation in the near-ground atmosphere: Amplitude and phase fluctuations. *The Journal of the Acoustical Society of America* 149(3), 2055-2071.

Kolmogorov, A. N. (1941). The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. Doklady Akademii Nauk SSSR 30(4), 299-303. (In Russian.)

Krasilnikov, V. A. (1945). Sound propagation in a turbulent atmosphere. *Doklady Ackademii Nauk SSSR* 47(7) 486-489 (in Russian).

Munk, W. H., and Wunsch, C. (1979). Ocean acoustic tomography: A scheme for large scale monitoring. *Deep Sea Research Part A. Oceanographic Research Papers* 26(2), 123-161.

Munk, W. H., and Zachariasen, F. (1976). Sound propagation through a fluctuating stratified ocean: Theory and observation. *The Journal of the Acoustical Society of America* 59(4), 818-838.

Munk, W. H., Worcester, P., and Wunsch, C. (1994). *Ocean Acoustic Tomography*. Cambridge University Press, New York, NY.

Munk, W. H., Worcester, P., and Zachariasen, F. (1981). Scattering of sound by internal wave currents: The relation to vertical momentum flux. *Journal of Physical Oceanography* 11(4), 442-454.

Obukhov, A. M. (1953). Sound and light propagation in a weakly inhomogeneous atmosphere. *Izvestiya Akademii Nauk SSSR. Seriya Geofizicheskaya* 2, 155-165 (in Russian). Reprinted in *Waves in Random Media* 4, 9-19 (1994).

Ostashev, V. E., and Wilson, D. K. (2015). *Acoustics in Moving Inhomogeneous Media*, 2nd ed. CRC Press, Boca Raton, FL.

Ostashev, V. E., Wilson, D. K., Muhlestein, M. B., and Attenborough, K. (2018). Correspondence between sound propagation in discrete and continuous random media with application to forest acoustics. *The Journal of the Acoustical Society of America* 143(2), 1194-1205.

Rytov, S. M. (1937). Diffraction of light by ultrasonic waves. *Izvestiya Akademii Nauk SSSR, Seriya Fizicheskaya* 2, 223-259 (in Russian).

Rytov, S. M., Kravtsov, Y. A., and Tatarskii, V. I. (1989). *Principles of Statistical Radio Physics*. Springer, Berlin, Germany.

Sato, H., Fehler, M. C., and Maeda, T. (2012) *Wave Propagation and Scattering in the Heterogeneous Earth*. Springer, Berlin, Germany.

Spindel, R. C., and Worcester, P. F. (2016). Walter H. Munk: Seventy-five years of exploring the seas. *Acoustics Today* 12(1), 36-42.

Stout, T. A., Sparrow, V. W., and Blanc-Benon, P. (2021). Evaluation of numerical predictions of sonic boom level variability due to atmospheric turbulence. *The Journal of the Acoustical Society of America* 149, 3250-3260.

Tatarskii, V. I. (1959). *Wave Propagation in a Turbulent Medium*. USSR Academy of Sciences, Moscow (in Russian). English translation: McGraw-Hill, New York, NY (1961).

Tatarskii, V. I. (1967). *The Effect of the Turbulent Atmosphere on Wave Propagation*. Nauka, Moscow, USSR (in Russian). English translation: Israel Program for Scientific Translation, Jerusalem (1971).

Tatarskii, V. I. (1969). Light propagation in a medium with random refractive index inhomogeneities in the Markov random process approximation. *Soviet Physics JETP* 29(6), 2106-2117.

Treeby, B. E., Jaros, J., Martin, E., and Cox, B. T. (2019). From biology to bytes: Predicting the path of ultrasound waves through the human body. *Acoustics Today* 15(2), 36-44.

Van Uffelen, L. J. (2021) Global positioning systems: Over land and under sea. *Acoustics Today* 17(1), 52-60.

Wheelon, A. D. (2001). *Electromagnetic Scintillation. Vol. 1: Geometrical Optics*. Cambridge University Press, New York, NY.

Wheelon, A. D. (2003). *Electromagnetic Scintillation. Vol. 2: Weak Scattering*. Cambridge University Press, New York, NY.

Wilson, D. K., and Thomson, D. W. (1994). Acoustic tomographic monitoring of the atmospheric surface layer. *Journal of the Atmospheric and Oceanic Technology* 11, 751-769.

Wilson, D. K., Pettit, C. L., and Ostashev, V. E. (2015). Sound propagation in the atmospheric boundary layer. *Acoustics Today* 11(2), 44-53.

Worcester, P. F., Munk, W. H., and Spindel, R. C. (2005). Acoustic remote sensing of ocean gyres. *Acoustics Today* 1(1), 11-17.

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