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Acoustic iso-propagation vortices for robust underwater communications

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Abstract

Underwater acoustic communications are limited by low information capacity and data rate[1]. While orbital-angular-momentum (OAM) multiplexing can address these issues[2], conventional OAM beams scale poorly in realistic ocean environments over long distances because their beam diameter increases with topological charge [3,4], amplifying crosstalk and alignment sensitivity over range. We address these challenges by introducing acoustic iso-propagation vortices (IPVs), engineered superpositions of OAM modes whose far-field envelope is effectively independent of the OAM topological charge, thus preserving a fixed spatial profile while retaining an orthogonal set of OAM states for multiplexing. The design leverages recent optical IPV theory in acoustics and is compatible with the existing transducer arrays used in previous studies [4]. We evaluate the wave propagation characteristics and modal-domain demultiplexing performance of multiplexed IPV channels in shallow-water channels using the BELLHOP ray-tracing framework with representative sound-speed profiles and surface roughness to simulate real ocean environments. Our theoretical study shows that, compared with conventional OAM beams, IPVs (i) maintain near-constant beam width across OAM topological charges, (ii) increase robustness by reducing modal coupling under turbulence and multipath propagation, and (iii) improve demultiplexing fidelity without increasing Receiver array aperture size or transmit power. These results indicate that, rather than OAM serving only as a fragile information-encoding capacity booster, acoustic IPVs have the potential to become a scalable physical-layer primitive for long-range, highly reliable underwater communication, and suggest immediate extensions to resilient MIMO-based underwater wireless communications and wide-aperture sonar.

1 Introduction

Oceans cover more than 70% of Earth's surface, making underwater communication essential for applications such as environmental monitoring, oceanographic exploration, autonomous robotics, and naval operations [5]. Among various transmission modalities, acoustic waves remain the most practical carrier underwater because radio-frequency electromagnetic waves are strongly absorbed within centimeters of seawater, and even blue–green optical light typically penetrates only on the order of 100–200 m before significant scattering [6,7]. By contrast, acoustic signals, due to the near-incompressibility of water and comparatively weak absorption and viscous losses, can propagate over long distances with relatively low attenuation [8]. A well-collimated acoustic beam can therefore propagate over several kilometers while retaining detectable intensity, enabling robust communication, sensing, and navigation [8–11]. Despite these advantages, underwater acoustic communication still faces major challenges. The available bandwidth is narrow, and together with multipath and temporal variability, constrains achievable data rates and compromises reliability in realistic complex environments [10–14]. Conventional acoustic communications, typically based on amplitude or phase modulation of plane or Gaussian pulses, are particularly vulnerable to turbulence-induced decorrelation and Doppler spreading [12,14,15].

To overcome these limitations, acoustic orbital angular momentum (OAM) multiplexing has emerged as a promising method for enhancing channel capacity and spectral efficiency [3,15,16]. OAM-carrying vortex beams possess helical phase fronts and are mutually orthogonal across topological charges, offering an

additional degree of freedom for parallel information channels [17]. However, conventional OAM beams are inherently charge-dependent: their beam diameter and diffraction-limited spreading increase with topological charge, leading to stronger crosstalk, alignment sensitivity, and reduced performance over long-range propagation [18]. This topological-charge-dependent diffraction fundamentally restricts scalability in realistic ocean environments, where maintaining large receiver apertures and precise alignment is often impractical.

Recent advances in optics introduced the concept of iso-propagation vortices (IPVs) [2], structured beams whose propagation profile remain nearly invariant across OAM topological charges (Fig. 1). We extend this idea to acoustics, proposing acoustic IPVs as a class of sound beams engineered as linear combinations of orthogonal OAM-mode bases that decouple beam geometry from their topological charge. Through carefully designed amplitude and phase modulation of transducer arrays, IPVs maintain a consistent intensity envelope and beam width across all topological charges while preserving the helical phase structure required for OAM multiplexing [2,3,15,19]. This topological-charge-invariant geometry directly enhances transmission robustness by reducing sensitivity to turbulence and aperture truncation [2,15,19].

In this work, we expand the optical IPV framework to underwater acoustics and evaluate its performance through full-wave simulations using the BELLHOP ray-tracing model under representative underwater conditions. By comparing IPV and conventional OAM beams across multiple propagation distances and turbulence conditions, we demonstrate that IPVs maintain topological-charge-independent diffraction, higher modal purity, which quantifies how much of the received energy remains in the intended mode after propagation, and greater resistance to turbulence and multipath distortion. These findings establish IPVs as a robust foundation for high-capacity underwater communications, providing a new pathway toward reliable, high-speed acoustic communications in complex oceanic environments.

2 Methodology

In this study, the underwater acoustic wave propagation is modeled using the BELLHOP ray-tracing model, which includes range-dependent sound-speed profiles, frequency-dependent absorption, and surface/bottom boundary losses over a simple geo-acoustic seabed [8]. Ray-tracing controls (launch-angle span/step, step length, bounce limits, interpolation) are selected by convergence testing so that subsequent refinements result in changes of < 1 dB at test points. Receivers are placed on a planar grid at the target ranges with sufficient spacing to resolve the vortex wavefront and innermost bright ring for all modes. The generation of acoustic vortex fields is based on the Laguerre–Gaussian (LG) beams. Specifically, the acoustic IPVs for each topological charge are represented by LG modes, where the radial index is assigned using a common global quality factor. By co-designing the radial and azimuthal indices, the effective beam width, near-field core radius, and far-field divergence can be made approximately invariant across modes, while the helical phase pattern of the OAM beams is retained. All modes are power-normalized to maintain a constant total radiated power and to prevent bias in subsequent comparisons. We evaluated the IPV communication capabilities using an inner product-based demultiplexing algorithm [4]: the received complex field is correlated with a bank of mode templates to form the channel matrix, from which we compute modal purity, inter-mode crosstalk, and orthogonality [9,19]. Results are averaged across turbulence conditions and are amplitude-normalized so that differences primarily indicate phase distortion and modal mixing rather than bulk transmission loss. To assess sampling sensitivity, analyses are repeated at several receiver-grid densities (e.g., 400–2500 sensors at a fixed range). We verify that modest adjustments to receiver-density, step length, and receiver sampling do not alter qualitative conclusions, and we document the OAM-to-IPV mapping, array geometry, and boundary conditions to ensure reproducibility. In this work, OAM-to-IPV mapping denotes the relationship between the desired OAM mode and the practical IPV beam synthesized in the acoustic domain. Specifically, it defines how a modal index is translated into the array excitation pattern and resulting spatial phase-amplitude structure, enabling consistent beam generation, propagation analysis, and modal demultiplexing. This structured simulation approach enabled comprehensive evaluation and validation of IPV wave propagation characteristics within controlled acoustic environments,

providing robust insights into IPV properties relevant to underwater acoustic communications.

This simulation platform establishes a rigorous, well-structured framework for simulating and analyzing IPVs in an underwater environment. By integrating convergence-validated ray tracing with power-normalized OAM/IPV beam synthesis and modal-domain demultiplexing, the approach ensures physically consistent results across different propagation conditions and receiver configurations. The systematic checks on sampling density and propagation parameters confirm the stability of the observed modal behaviors, forming a solid foundation for the subsequent performance evaluation and practical assessment of IPV-based underwater acoustic communications.

2.1 Generation and Characterization of Acoustic IPVs

In acoustics, vortex fields can be modeled using the same LG modal formalism as in optics [1]. The complex field distribution is given by:

$$LG_{\mathrm{l,\,p}}(r,\varphi,z) = \sqrt{\left[\frac{(2\cdot p!)}{(\pi\cdot(|l|+p)!\,)}\right]}\cdot\left[\frac{1}{w(z)}\right]\cdot\left[\left(\sqrt{2}\cdot\frac{r}{w(z)}\right)^{|l|}\right]\cdot L_{\mathrm{p}}{}^{(|l|)}\left(\frac{2r^2}{w(z)^2}\right)\cdot\exp\left(-\frac{r^2}{w(z)^2}\right)$$
$$\cdot\exp\begin{pmatrix} i\cdot k\cdot z\ +\ i\cdot\frac{k\cdot r^2}{2R(z)}+\ i\cdot l\cdot\varphi\ -\ i \\ \cdot(|l|+2p+1)\cdot\zeta(z)\end{pmatrix} \tag{1}$$

where $L_p^{|l|}$denotes the Laguerre polynomial, and $k = 2\pi/\lambda$ (with λ representing the acoustic wavelength) is the wavenumber. The beam parameters are given by

$$w(z) = w^0\cdot\sqrt{\left[1\ +\ \left(\frac{z}{z^0}\right)^2\right]}\quad,\quad \zeta(z) = \arctan\left(\frac{z}{z^0}\right),$$
$$R(z) = z\cdot\left[1\ +\ \left(\frac{z^0}{z}\right)^2\right],\quad z_0\ =\ \pi\frac{w0^2}{\lambda},\ w_0\ =\ \sqrt{\lambda\frac{z^0}{\pi}}\ ; \tag{2}$$

in which $w(z)$ represents the beam radius at axial distance z, $w_0$denotes the beam waist radius, $\zeta(z)$ is the Gouy phase shift, $R(z)$ is the radius of curvature of the wavefront, and z_0 is the Rayleigh range.

Conventional OAM beams are commonly implemented as $LG_{l,0}$ modes, where the radial index is $p = 0$. For such beams, both the beam size and the widening increase with the magnitude of the topological charge. In contrast, IPV is defined by the size of the innermost ring of an LG mode. The radial index p is configured as a function of the topological charge l such that the innermost-ring quality factor, M_{IR}^2, remains constant.

The innermost ring size $\rho_{IR}(z)$ and the corresponding quality factor are given by

$$\rho_{IR}(z)\ \approx\frac{(|l|+2)}{2\ sqrt(|l|+2p+1)}w(z);$$
$$M^2_{IR(l,p)}\ \approx\frac{(|l|+\ 2)^2}{[4(|l|+\ 2p\ +\ 1)]} \tag{3}$$

2.2 Modeling of ocean turbulence

To model the complex turbulent ocean environment, we applied the Nikishov spectrum [20]. Identical environmental parameters and numerical controls are used for IPV and reference OAM cases to ensure a fair comparison. Small-scale fluctuations are introduced via phase-only turbulence screens inserted every 50 m along the path. Each screen follows a Kolmogorov $-11/3$ spectrum between specified inner and outer scales given by

$$\Phi_1(k) = 0.388 * 10^{-8}\varepsilon^{-\frac{1}{3}}k^{-\frac{11}{3}}\left(1 + 2.35(k\eta)^{\frac{2}{3}}\right)$$

$$* \frac{X_T}{w^2}(w^2 e^{-A_T\delta} + e^{-A_S\delta} - 2we^{-A_{TS}\delta}) \quad (4)$$

where ε is the dissipation rate of kinetic energy per unit mass, X_T is the dissipation rate of temperature variance η is the Kolmogorov microscale given as $\eta = (\nu^3/\varepsilon)^{1/4}$, and ν is the kinematic viscosity. $A_T = 1.863 * 10^{-2}$, $A_S = 1.9 * 10^{-4}$, and $A_{TS} = 9.41 * 10^{-3}$. δ is given by $\partial = 8.284(k\eta)^{4/3} + 12.978(k\eta)^2$. The spectrum is scaled to achieve a realistic per-segment phase variance, and multiple random seeds are simulated to obtain ensemble statistics.

3 Results

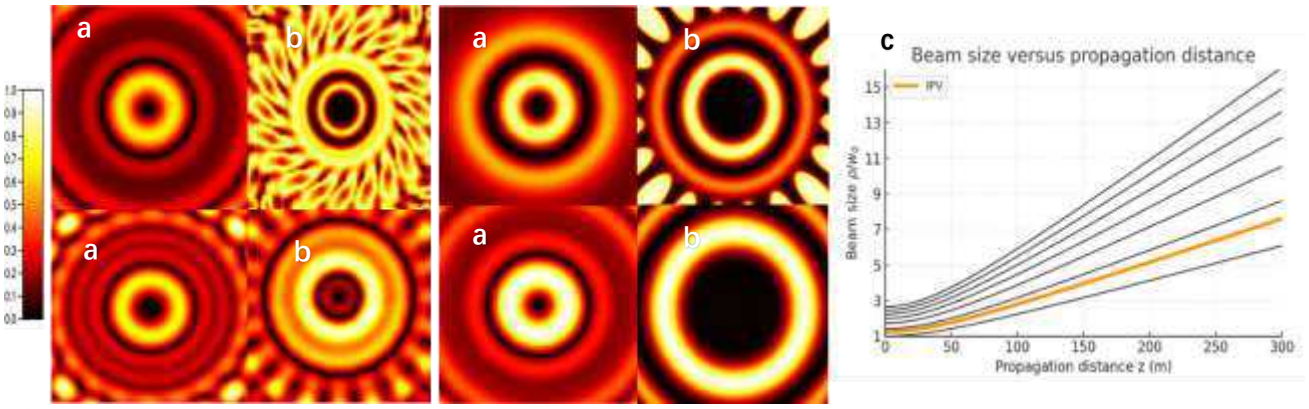


Figure 1: Comparison of the acoustic sound pressure field of the innermost ring between (a) IPV and (b) normal OAM waves at topological charge from 2 to 5. (c) The Beam diffraction of IPV wave compared to conventional OAM waves.

3.1 Topological charge-independent beam size widening over ranges.

Beam size widening over the range directly determines how much acoustic energy a finite receiver aperture at a long distance from the transducer array can capture, as well as how sensitive each channel is to misalignment, turbulence, or range uncertainty. As the beam footprint expands, only a limited portion of the acoustic power falls within the receiver array, increasing sensitivity to pointing errors and small range offsets. Increased beam size widening also amplifies the impact of environmental distortions, such as turbulence-induced phase errors, on the spatial structure of each OAM charge, resulting in larger fluctuations in received level and channel stability. When different OAM topological charges diffract at different rates, the one with a larger topological charge becomes weaker and noisier than the one with a lower topological charge, which complicates power balancing and limits the usable order range. Our results show that conventional LG OAM beams exhibit exactly this behavior: their toroidal-patterned amplitude profile radius and singular low-intensity core diameter grow quickly with the topological charge (Fig. 1), so a fixed-size receiver array collects only a small fraction of the power in higher topological charge. A larger beam size widening also leads to faster intensity density decay, making OAM channels with larger topological charges more vulnerable to environmental perturbations. In contrast, simulation results show that acoustic IPV beams maintain an almost identical beam width and widening rate across all tested topological charges, indicating that propagation behavior is effectively independent of the topological charge (Fig. 1). Thus, all IPV modes can be received, processed, and demultiplexed using the same aperture and sampling resolution. This eliminates the need for topological charge-specific adjustments, preserves balanced signal-to-noise ratios across modes, and stabilizes phase recovery by keeping the spatial overlap between transmitted and received fields nearly topological charge-invariant. Because every IPV topological charge shares a similar propagation geometry, small alignment shifts, mild turbulence, or range variations affect all modes similarly, maintaining predictable multi-channel performance. Overall, this OAM-independent beam size allows IPV beams to address a key propagation weakness of conventional OAM beams

and provides a robust, scalable basis for underwater acoustic multiplexing.

3.2 Environmental Robustness, Mode Orthogonality, and Inter-Mode Crosstalk Analysis

Robust modal bases for underwater acoustic multiplexing must maintain their structure and orthogonality in the presence of environmental variability, since loss of robustness directly translates into increased inter-mode crosstalk, reduced demultiplexing accuracy, and increased bit error rate. In practical communications, even small deviations from ideal orthogonality accumulate with range and time. Thus, a basis with minimal inter-mode crosstalk under turbulence and sound-speed fluctuations is crucial for reliable and repeatable communication and sensing. Conventional OAM beams are intrinsically sensitive to phase distortions because their information is encoded spatially in a helical phase front [3,15]. Random phase perturbations and path-dependent refraction readily disrupt this vortex structure, converting power from a given topological charge into other OAM modes. In an underwater environment, multi-path interference and boundary interactions further distort the toroidal-shaped intensity profile, enhancing modal coupling and reducing the effective orthogonality of the OAM basis. [20] As a result, OAM modes with larger topological charges tend to decorrelate rapidly with range [15,22], especially in turbulent or strongly stratified environments.

To evaluate the stability of IPV beams in realistic underwater conditions, Kolmogorov −11/3 phase screens were introduced every 50m, which is smaller than the typical internal-wave coherence length (100m) [23] in ocean turbulence and ensures adequate longitudinal resolution of phase fluctuations while satisfying the weak-scattering requirement of the split-step model, along a 500 m propagation path to mimic the turbulence in the ocean, with both summer and winter sound-speed profiles considered. Under these varying conditions, the nine-mode IPV set maintains high modal purity across all tested modes, whereas conventional OAM beams exhibit

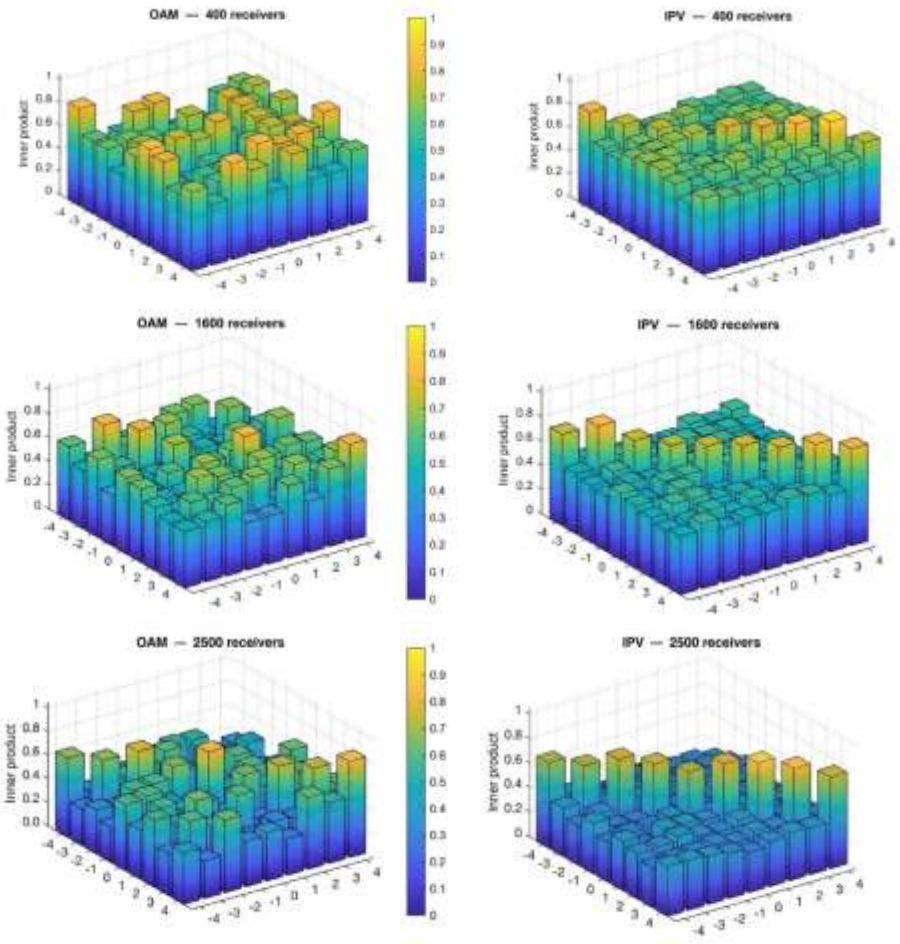


Figure 2. The crosstalk of OAM and IPV with (a) 400 receivers, (b) 1,500 receivers, and (c) 2,500 receivers at 500m.

notable inter-mode coupling when $|\ell| \geq 3$. This difference indicates that IPV beams better preserve their intended information content during long-range propagation through turbulent water columns. This result confirms that IPVs maintain both structural stability and modal separation in environments where OAM beams typically suffer from coherence loss, highlighting their robustness in realistic ocean environments.

Mode orthogonality and inter-mode crosstalk were quantified using inner products between received fields and a set of mode templates. The resulting channel matrices reveal that, at a range of 500m, IPV beams consistently achieve 5%-10% lower off-diagonal crosstalk than conventional OAM beams, indicating better modal separation and higher fidelity (Fig. 2). These results are observed consistently across receiver grids of approximately 400, 1,500, and 2,500 sensors, confirming that IPV performance remains stable across different sampling resolutions. As the propagation distance increases in a turbulent underwater environment, the IPV basis retains less crosstalk over longer ranges than OAM, though both beams exhibit a gradual decrease in orthogonality. The gap between IPV and OAM becomes more pronounced with increasing distance (Fig. 3), indicating that IPV beams exhibit greater resistance to cumulative phase distortion and crosstalk. These findings collectively demonstrate that IPV beams provide a more stable modal framework for multiplexing, resulting in lower crosstalk, improved demultiplexing accuracy, and more consistent signal recovery in complex underwater environments. Overall, these observations establish IPV beams as a robust, well-orthogonal modal basis that is better suited than conventional OAM for reliable high-capacity underwater acoustic communication in realistic ocean environments.

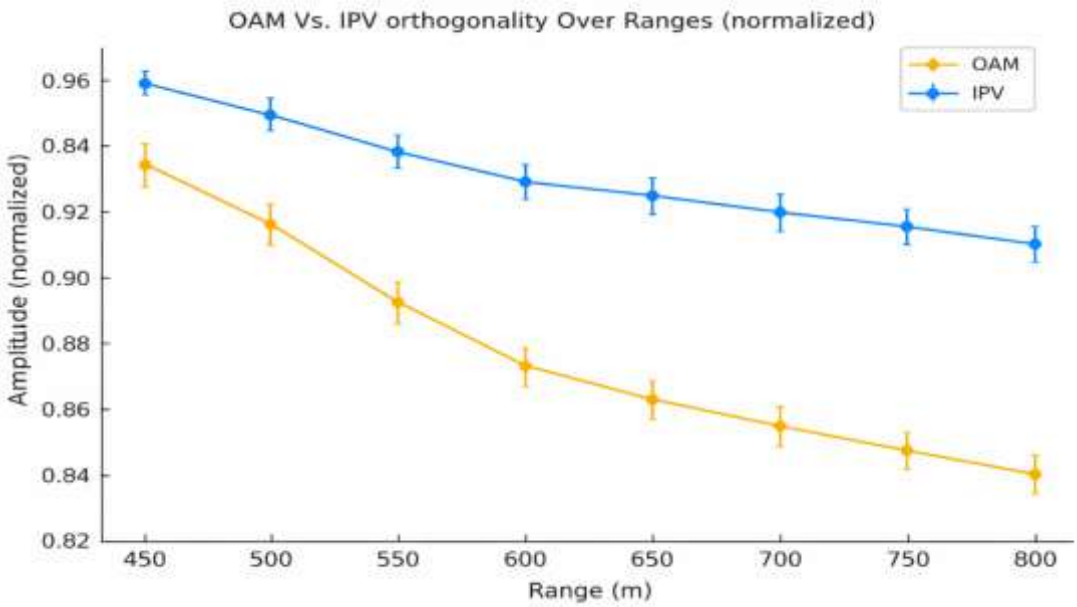


Figure 3. Normalized mode orthogonality versus range in a turbulent shallow-water channel for OAM and IPV bases. Both decay with distance, but IPV degrades more slowly; the gap widens beyond mid-range and the uncertainty bands overlap less at long range, indicating a consistent IPV advantage. Because values are amplitude-normalized, the difference mainly indicates reduced phase distortion and modal mixing with IPV rather than transmission loss. This follows from the fixed-quality-factor design, which keeps beam size and divergence nearly order-independent and yields cleaner modal separation.

3.3 Multiplexing Results

Multiplexing performance is evaluated by comparing IPV and conventional OAM transmissions using the same inner-product-based demultiplexing framework. For conventional OAM beams, charge-dependent diffraction and environmental distortions introduce significant inter-mode coupling, leading to increased crosstalk and degraded demultiplexing fidelity as propagation distance increases (Fig. 4). In contrast, IPV-based multiplexing yields consistently clearer modal channel matrices with lower crosstalk terms across all tested receiver grid densities (Fig. 4). Because all IPV modes share a nearly identical propagation envelope, the received channels

maintain balanced power and phase fidelity, improving modal separation and conditioning of the multiplexed channel matrix against turbulence. As a result, IPV multiplexing exhibits reduced inter-mode crosstalk and more stable multi-channel performance over the same transmission range under similar ocean turbulence, demonstrating its advantage for high-capacity underwater acoustic communications in realistic environments.

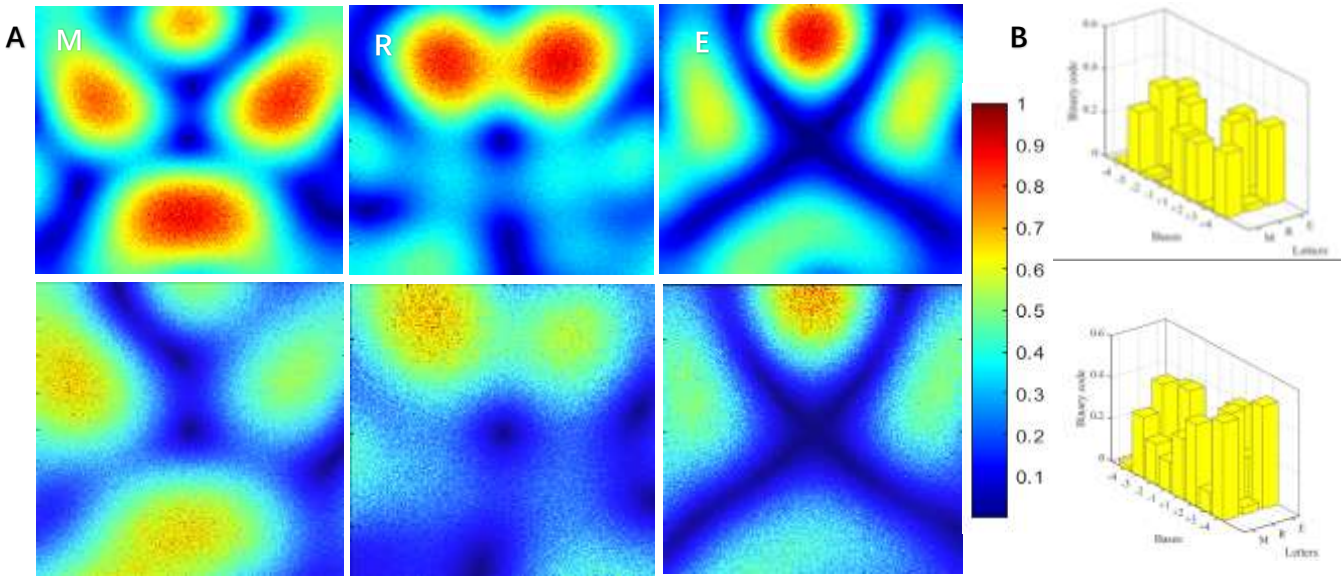


Figure 4. (A) Multiplexing result of IPV (upper row) and conventional OAM (lower row) waves at a distance of 5000 times the wavelength, with a frequency of 16,000 Hz, under light turbulence. (B) The matrix of demultiplexed signals indicating that the IPV wave (top) maintains a more stable beam structure and clearer modal distribution compared to the conventional OAM wave (bottom), which exhibits stronger diffraction and mode distortion at long propagation

4 Conclusion

This study demonstrates that acoustic IPVs provide reliable, independent channels in underwater environments, overcoming key limitations of conventional acoustic OAM beams, including the coupling between beam size, diffraction, and topological charge that degrades modal orthogonality during propagation due to the coupling between beam size, diffraction, and OAM topological charge in conventional acoustic OAMs. Embedding a charge-dependent radial index generates IPVs that achieve a topological charge-invariant beam width that remains stable, though beam widening occurs over long propagation distances. Simulation results indicate that the IPV maintains higher modal purity and exhibits significantly less crosstalk between modes than its conventional LG OAM counterparts under identical sound-speed profiles and ocean turbulence. The findings indicate that IPV is a promising platform for high-capacity, diffraction-resilient acoustic communications. By eliminating the dependence of beam width on topological charge, IPVs enable uniform mode behavior, improved signal integrity, and enhanced robustness against environmental variations such as turbulence, directly addressing the limitations that have constrained OAM-based underwater systems, transforming OAM from a capacity-oriented but fragile mechanism into a reliable and scalable communication strategy in complex, realistic underwater environments.

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Author Contribution Declaration

J.H. performed the simulations. J.H. and C.W. performed data analysis. J.H. and C.W. wrote the main manuscript text and prepared the figures. T.Z., M.E.K., Y.D., G.W., J.K., and C.S. joined the discussion of the results. C.S. supervised the research and obtained the funding support. All authors reviewed the manuscript.

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