

Topological robustness of optical skyrmions in underwater turbulent channels

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Abstract

Optical skyrmions are polarisation-structured light fields whose Stokes vectors form topologically non-trivial mappings on the Poincaré sphere. We numerically investigate the propagation of Néel-type optical skyrmions over a 20 m underwater turbulent channel modelled by the Nikishov spectrum and a split-step angular-spectrum method. Robustness is quantified using an effective finite-aperture skyrmion number reconstructed from the normalised Stokes field. Under moderate turbulence, about 60% of the initial value is retained after 20 m. Using a common Jones-vector field fidelity under matched conditions, skyrmions outperform LG_0^1 orbital-angular-momentum and radially polarised beams by 4.24% and 4.52%, respectively. Parameter studies show that unit-charge skyrmions with larger beam waists and a wavelength of 532 nm are more robust, while Néel and Bloch textures perform similarly. The enhanced resilience arises from common-mode phase perturbations and the globally distributed polarisation topology.

1. Introduction

Sea water is a hostile medium for light. Absorption and scattering limit transmission distances to tens of meters even under favourable conditions, and turbulence – driven by temperature and salinity microstructure – introduces stochastic phase distortions that scramble beam profiles and degrade signal quality [1–3]. Despite these challenges, underwater optical wireless communication (UOWC) remains attractive because it offers bandwidths that acoustic links cannot match [4–6].

One strategy for coping with turbulence is to encode information in the spatial structure of light. Orbital angular momentum (OAM) beams, which carry helical phase fronts, have been proposed for underwater multiplexing [7–11]. The idea is appealing-OAM modes are, in principle, orthogonal and unbounded in number – but practice has been less kind. Turbulence distorts the helical wavefront, causing energy to leak between modes. Several experiments have documented this crosstalk, and the consensus is that OAM-based links require either adaptive optics or very short ranges to remain viable [12–15].

Vector beams, whose polarisation varies spatially, offer a partial remedy. Because polarisation is less sensitive than phase to refractive-index fluctuations, radially and azimuthally polarised beams survive turbulence somewhat better than OAM [16–18]. Recent studies have extended underwater structured-light propagation analyses to hyperbolic-Gaussian vortex beams in vertical anisotropic ocean turbulence, including adaptive-optics correction and communication-performance evaluation [19, 20]. Related work has also examined the propagation of Gaussian and Bessel-Gaussian vortex beams with fractional topological charges in turbulent media [21]. These studies demonstrate that the apparent robustness of a structured beam depends strongly on the selected field metric, turbulence model, and receiver, motivating the metric-controlled comparison adopted here.

A more radical departure comes from optical skyrmions. Borrowed from condensed-matter physics, where magnetic skyrmions have been studied for decades [22, 23], the optical version refers to a light field whose Stokes vector covers the Poincaré sphere in a topologically non-trivial way. The skyrmion number N_{sk} , which is an integer counting

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how many times the sphere wraps, is a global invariant that cannot change under smooth, local perturbations. This topological protection is precisely what might shield information from turbulence.

Recent work has demonstrated skyrmion generation using metasurfaces, q -plates, and spatial light modulators [24–27]. Free-space propagation has been analysed, and one group has examined atmospheric turbulence [28–30]. Underwater propagation, however, remains unexplored. Ocean turbulence differs qualitatively from its atmospheric counterpart: the Nikishov spectrum, rather than the Kolmogorov–von Kármán form, governs refractive fluctuations, and the interplay of temperature and salinity introduces an additional degree of freedom [31, 32].

Here we fill this gap. Using split-step angular spectrum simulations with statistically realistic phase screens, we propagate Néel-type skyrmions through 20 m of oceanic turbulence and track the evolution of N_{sk} . We compare performance against OAM and radially polarised beams, and we survey how beam and channel parameters affect survival. The picture that emerges is encouraging: skyrmions do not eliminate turbulence degradation, but they handle it better than alternatives.

2. Theory

2.1. Constructing the skyrmion field

We work with paraxial, monochromatic beams whose polarisation state varies across the transverse plane. A convenient representation uses the Stokes vector $\mathbf{s} = (s_1, s_2, s_3)$. For a Néel-type skyrmion, the skyrmion number N_{sk} is an integer that counts the times $\mathbf{n}(x, y) = \mathbf{n}(r \cos \theta, r \sin \theta)$ wraps around a unit sphere, which is defined as

$$N_{\text{sk}} = \frac{1}{4\pi} \iint \mathbf{n} \cdot \left(\frac{\partial \mathbf{n}}{\partial x} \times \frac{\partial \mathbf{n}}{\partial y} \right) dx dy, \quad (1)$$

where $\mathbf{n}(x, y)$ is the vector field which constructs a skyrmion, $\mathbf{n} = (\cos \alpha(\theta) \sin \beta(r), \sin \alpha(\theta) \sin \beta(r), \cos \beta(r))$. $\alpha(\theta)$ is the radial profile interpolating between 0 and π , $\alpha(\theta) = m\theta + \gamma$, with the topological charge m and initial phase γ . $\beta(r)$ is the polar angle radial profile interpolating between 0 and π . When $\beta(r) = 0$, the polarisation is right-circular (RCP); when $\beta(r) = \pi$, it is left-circular (LCP). Intermediate values trace out elliptical states, passing through linear polarisation at $\beta(r) = \pi/2$.

For a beam with the waist size of ω_0 , the expression of optical skyrmion is

$$E = E_0 \left(-\frac{r^2}{\omega_0^2} \right) \cdot \frac{1}{\sqrt{2}} \begin{pmatrix} \cos \frac{\beta(r)}{2} + \sin \frac{\beta(r)}{2} \cdot e^{im\theta} \\ i \left[\cos \frac{\beta(r)}{2} - \sin \frac{\beta(r)}{2} \cdot e^{im\theta} \right] \end{pmatrix}. \quad (2)$$

2.2. Numerical evaluation of skyrmion number

At each propagation plane, the Stokes parameters are calculated from the propagated Jones field $E = [E_x, E_y]^T$ as:

$$\begin{cases} s_0 = |E_x|^2 + |E_y|^2 \\ s_1 = |E_x|^2 - |E_y|^2 \\ s_2 = 2 \operatorname{Re}(E_x E_y^*) \\ s_3 = 2 \operatorname{Im}(E_x E_y^*) \end{cases}. \quad (3)$$

The local unit Stokes vector is

$$\mathbf{n} = \frac{(s_1, s_2, s_3)}{\sqrt{s_1^2 + s_2^2 + s_3^2}}. \quad (4)$$

The skyrmion number is evaluated on the discrete grid with a lattice solid-angle method. Each square cell is divided into two oriented triangles, and the solid angle of a triangle with unit vectors $\mathbf{n}_a$, $\mathbf{n}_b$, and $\mathbf{n}_c$ is

$$\Omega = 2 \arctan 2 \left[\mathbf{n}_a \cdot (\mathbf{n}_b \times \mathbf{n}_c), 1 + \mathbf{n}_a \cdot \mathbf{n}_b + \mathbf{n}_b \cdot \mathbf{n}_c + \mathbf{n}_c \cdot \mathbf{n}_a \right]. \quad (5)$$

The skyrmion number is

$$N_{\text{sk}} = \frac{1}{4\pi} \sum \Omega. \quad (6)$$

For an ideal continuous field on a compact domain with a fixed boundary, N_{sk} is integer valued. In the present simulations, however, the field is sampled on a finite grid and evaluated over a finite aperture with a non-ideal boundary; turbulence can also move polarisation singularities into or out of the integration region.

2.3. Modelling underwater turbulence

Ocean turbulence arises from the interplay of temperature T and salinity S fluctuations, both of which affect the refractive index. The Nikishov spectrum captures this coupling:

$$\Phi_n(\kappa) = 0.388 \times 10^{-8} \varepsilon^{-\frac{1}{3}} \kappa^{-\frac{11}{3}} \left[1 + 2.35(\kappa\eta)^{\frac{2}{3}} \right] \times \frac{\chi_T}{\omega^2} \left[\omega^2 e^{-A_T \delta} + e^{-A_S \delta} - 2\omega e^{-A_{TS} \delta} \right], \quad (7)$$

where κ is the spatial wavenumber, ε is the turbulent kinetic energy dissipation rate, η is the Kolmogorov microscale, $\eta = (v^3/\varepsilon)^{1/4}$, χ_T is the temperature variance dissipation rate, and ω is the parameter describing the relative contributions of T and S . The constants A_T , A_S , A_{TS} and the function $\delta(\kappa, \eta)$ are given in [33].

Phase screens are generated by filtering white noise with Φ_n and inverse-Fourier-transforming. Each screen represents a thin slab of turbulence; concatenating many screens, interspersed with free-space propagation via the angular spectrum method, yields the split-step simulation.

2.4. Numerical details

Table 1 lists the parameters used throughout unless otherwise noted. The 532 nm wavelength sits in the blue-green window where seawater absorption is minimised. A 256×256 grid over a 20 mm aperture provides adequate sampling; doubling the grid size changed s by less than 2%. Each data point reflects an average over 100 independent turbulence realisations, enough to converge the mean to within a few percent.

Table 1.
Baseline simulation parameters.

Parameter	Value
Wavelength λ	532 nm
Beam waist ω_0	3 mm
Grid	256×256
Aperture	$20 \text{ mm} \times 20 \text{ mm}$
Propagation range	0–20 m
Step size	1 m
Turbulence realisations	100
Topological charge m	1

The oceanic turbulence cases used in this work are specified by the complete parameter sets listed in Table 2. Here ε is the dissipation rate of turbulent kinetic energy, and ω is the relative temperature-salinity contribution parameter. Throughout this article, the labels weak, moderate, and strong refer only to the three numerical cases the dissipation rate of temperature variance $\chi_T = 10^{-10} \text{ K}^2 \text{ s}^{-1}$, $10^{-9} \text{ K}^2 \text{ s}^{-1}$, and $10^{-8} \text{ K}^2 \text{ s}^{-1}$, respectively, while the other parameters are held fixed.

Table 2.
Nikishov spectrum parameters.

Parameter	Value
Dissipation rate of turbulent kinetic energy ε	$1 \times 10^{-5} \text{ m}^2 \cdot \text{s}^{-3}$
Relative temperature-salinity contribution parameter ω	−4.5
Microscale η	$1 \times 10^{-3} \text{ m}$

3. Results and discussions

Before subjecting the beam to turbulence, it helps to verify that the field construction works as intended. Figure 1 collects the relevant diagnostics. Figure 1(a) shows the intensity s_0 , a Gaussian with a 3 mm waist. Near the axis, where $\alpha \approx 0$, the ellipses collapse to circles-RCP, coloured red. As r increases, the ellipses elongate and rotate, passing through linear states (green lines) around $r = \omega_0$. Beyond this, they close back into circles of opposite handedness-LCP, coloured blue. This continuous winding from pole to pole of the Poincaré sphere is what distinguishes askyrmion from an ordinary vector beam. Figure 1(b)–(d) plot the individual Stokes components. The two-lobed patterns in s_1 and s_2 reflect the $\cos(\theta)$ and $\sin(\theta)$ azimuthal factors; the concentric rings in s_3 trace out the radial profile $\cos \beta(r)$, positive at centre and negative at edge.

Figure 2 shows the Stokes data onto a sphere. The arrows, originating from the surface and pointing outward, confirm that the field covers the sphere once, consistent with $N_{\text{sk}} = 1$.

Figure 3 tracks the beam through moderate turbulence at five locations: $z = 0, 5, 10, 15$, and 20 m. Each column corresponds to a distance; each row shows a different observable. The intensity (row 1) spreads and develops speckle as expected. More interesting are the Stokes maps (rows 2–4). At $z = 5$ m, the two-lobe patterns in s_1 and s_2 remain clear; by 10 m, they have begun to blur; at 20 m, the lobes are barely recognisable. Yet the concentric structure

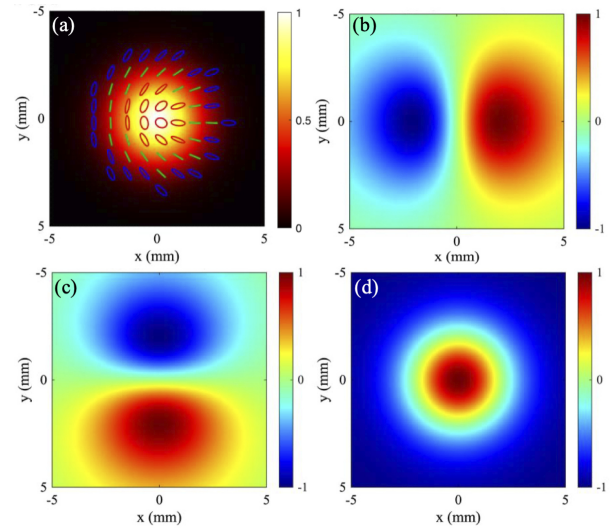


Fig. 1. Initial Néel-type optical skyrmion at $z = 0$. (a) Normalised total intensity s_0 with representative polarisation ellipses; the ellipse colour denotes the handedness of the local polarisation state. (b)–(d) Normalised Stokes components s_1 , s_2 , and s_3 , respectively. The wavelength is 532 nm, beam waist is 3 mm, and topological charge is $m = 1$. All Stokes components are normalised to their respective extrema for visualisation.

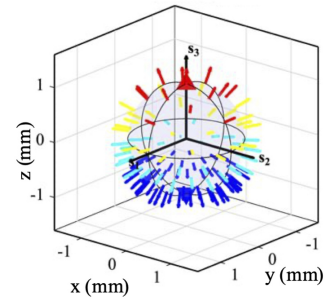


Fig. 2. Mapping of the initial normalised Stokes vectors onto the Poincaré sphere.

in s_3 persists throughout and its azimuthal symmetry protects it from the turbulence, which introduces random tilts rather than systematic swirl.

We now turn to ensemble statistics. Figure 4(a) plots the mean N_{sk} vs. distance for moderate turbulence; shading indicates ± 1 standard deviation. The skyrmion number falls roughly linearly with distance, reaching about 0.6 at 20 m. Fluctuations grow with distance but remain modest, and the standard deviation at 20 m is around 0.1. Figure 4(b) compares retention rates $\eta = N_{\text{sk}}(z)/N_{\text{sk}}(0)$ for three turbulence levels. Under weak turbulence, η stays above 0.8 out to 20 m; under strong turbulence, it drops to roughly 0.3. The curves do not collapse onto a single master curve when rescaled by turbulence strength, indicating some nonlinearity in the degradation process. As shown in Fig. 4(c), for a middle propagation distance, the probability density of η at $z = 10$ m shows approximately Gaussian distributions whose widths increase with turbulence strength. Crucially, no realisations yielded $\eta = 0$; even under strong turbulence, some topological character always survived. Figure 4(d) examines different water types. Clear ocean (low χ_T , low ε) supports retention above 90% at 20 m; turbid harbour water, at the opposite extreme, retains only 30%. Coastal conditions fall in between.

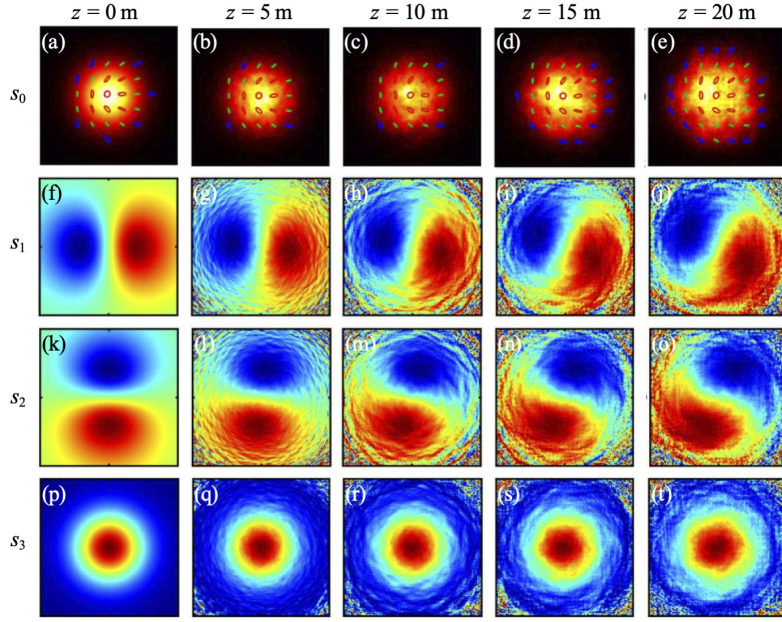


Fig. 3. Propagation of the Néel-type optical skyrmion through the moderate-turbulence case at $z = 0, 5, 10, 15$, and 20 m. Rows show the normalised total intensity s_0 and normalised Stokes components s_1 , s_2 , and s_3 . The maps are normalised independently for visualisation.

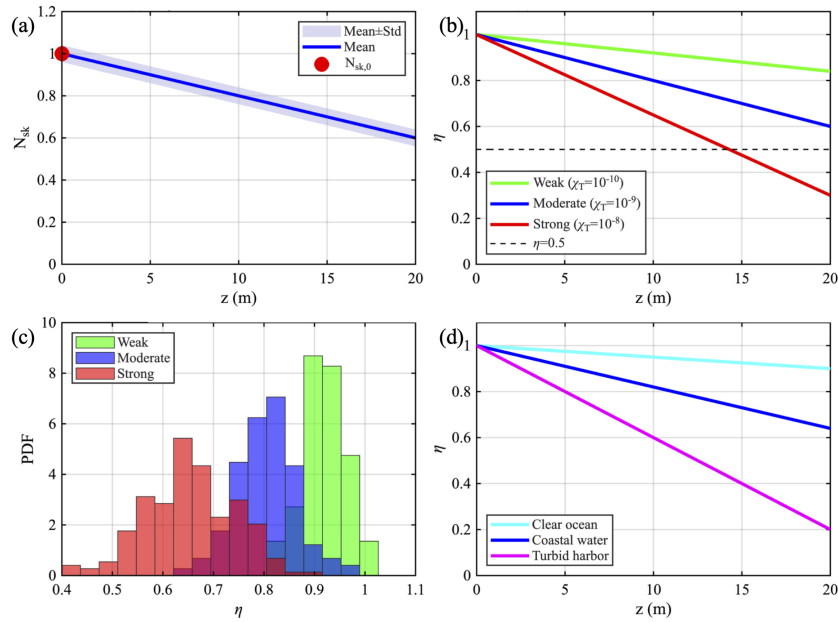


Fig. 4. Statistical evolution of the effective skyrmion number: (a) mean N_{sk} vs. distance; (b) retention rates of η ; (c) probability density of η at $z = 10$ m; (d) η in clear ocean, coastal water and turbid harbour water.

A central question is whether optical skyrmion outperforms existing structured beams. Figure 5 compares the Jones-vector field fidelity F of the optical skyrmion, the LG_0^1 OAM beam, and the radially polarised beam under matched conditions, including the same wavelength, input power, second-moment beam radius, receiver aperture, propagation grid, and turbulence realisations. The fidelity of all three beams decreases with 20 m underwater propagation distance because of turbulence-induced phase distortions and diffraction. Nevertheless, the optical skyrmion maintains a consistently higher fidelity, with the difference becoming more evident at longer distances.

After 20 m of underwater propagation, the mean fidelity of the skyrmion remains 0.769800, compared with 0.738453 for the OAM beam and 0.736945 for the radially polarised beam, corresponding to relative improvements of approximately 4.24% and 4.52%, respectively. These results indicate that, under a common metric and equivalent channel conditions, the globally distributed polarisation texture of the optical skyrmion is retained more effectively than the modal or polarisation structures of the two reference beams. The shaded regions represent the statistical variation over independent turbulence realisations.

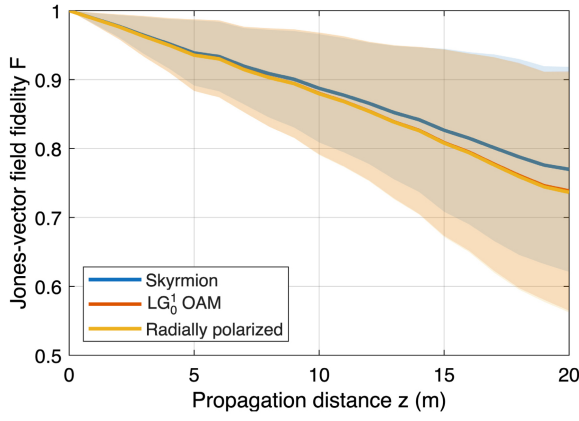


Fig. 5. Jones-vector field fidelity comparison of skyrmion, OAM, and radial beam.

Finally, we explore how beam parameters affect robustness. **Figure 6(a)** varies the topological charge m . Higher order skyrmions ($m=2, 3$) degrade faster; their steeper polarisation gradients are more vulnerable. For maximum robustness, $m=1$ is the pragmatic choice. **Figure 6(b)** shows that larger beam waists help. A 5 mm waist retains nearly 80% at 20 m, vs. 60% for 2 mm. The intuition is straightforward: turbulence acts on length scales comparable to the outer scale (typically centimeters to meters), so larger beams average over more uncorrelated patches. As shown in **Fig. 6(c)**, wavelength matters, too. Green light (532 nm) performs best, consistent with minimal absorption in seawater. Blue (450 nm) suffers from scattering; red (650 nm) from absorption – both reduce the effective signal and indirectly worsen topological fidelity. Finally, **Figure 6(d)** compares Néel and Bloch skyrmions, which differ in the azimuthal orientation of the in-plane polarisation component. Performance is nearly identical, suggesting that the protection mechanism depends primarily on the winding number, not the fine details of the texture. The resilience and robustness for optical skyrmions during underwater turbulent channels

which we observe can be understood heuristically. Turbulence imposes random, spatially varying phase shifts on both polarisation components. If these shifts were perfectly correlated between E_x and E_y , the Stokes vector would rotate uniformly and N_{sk} would be unaffected. However, changing N_{sk} requires more than local turbulence requires bringing antipodal points on the Poincaré sphere into coincidence, which would demand phase gradients steeper than anything Kolmogorov-type turbulence typically produces.

The relative resilience observed for the skyrmionic field can be understood from the way in which the information is encoded. In the present non-birefringent scalar-turbulence model, each thin phase screen imposes approximately the same local phase perturbation on the x - and y -polarised components. This common-mode phase is largely removed when the normalised Stokes vector is constructed. Differences between the two components arise during subsequent diffraction because they contain different spatial-mode contents; therefore, the polarisation texture is not perfectly preserved. Nevertheless, the skyrmionic information is distributed over the global mapping of the transverse plane onto the Poincaré sphere. A smooth local deformation does not change the mapping degree provided that the field remains continuous and polarised, no polarisation singularity crosses the integration boundary, and the boundary polarisation remains fixed. By contrast, an OAM symbol is recovered by projection onto a particular helical phase mode, so local phase perturbations directly redistribute power among neighbouring azimuthal modes. A radially polarised beam possesses a spatial polarisation pattern, but it does not necessarily cover the entire Poincaré sphere or carry a non-zero skyrmion degree; its pattern fidelity can therefore decrease continuously without a topological transition. This mechanism explains the relative advantage found under the tested conditions, but it should not be interpreted as absolute protection against finite-aperture clipping, absorption, scattering, depolarisation, or sufficiently strong turbulence.

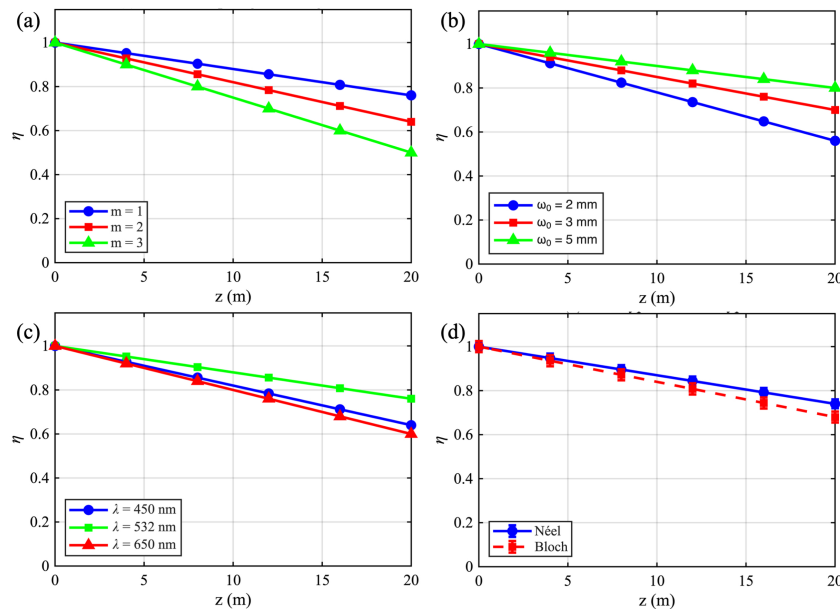


Fig. 6. Beam parameters optimisation: (a) topological charge; (b) beam waist; (c) centre wavelength; (d) Néel vs. Bloch skyrmion types.

Several simplifications limit the quantitative accuracy of our results. Our turbulence model assumes statistical homogeneity and isotropy-assumptions that break down near boundaries or in stratified layers. Second, we did not model the detector. Real polarimeters have finite aperture, alignment tolerances, and noise floors that could alter the recovered N_{sk} .

If the simulations hold up experimentally, skyrmions could improve underwater links in at least two ways: first, by extending range: the 40–85% retention advantage over OAM translates directly into longer reach at fixed error rate. Second, by simplifying hardware: skyrmion detection can, in principle, be done with Stokes polarimetry, which requires only waveplates and polarisers, rather than the interferometric or mode-sorter setups needed for OAM. On the other hand, skyrmion generation is non-trivial. Current methods involve metasurfaces or cascaded waveplates, neither of which is easy to miniaturise or mass-produce. Cost and complexity will ultimately determine whether skyrmion-based links can compete with simpler intensity-modulated systems.

4. Conclusions

In this paper, we examined how Néel-type optical skyrmions propagate through underwater turbulence. The main findings are as follows. First, the skyrmion number degrades with distance, but more slowly than one might expect. Even under strong turbulence, a non-negligible fraction of the initial topology survives 20 m of propagation. Second, skyrmions outperform both OAM and radially polarised beams in matched comparisons. The advantage stems from the global, distributed nature of the topological invariant, which averages over local distortions. Third, beam design matters. Unit-charge skyrmions with large waists and green wavelength offer the best resilience. Whether these advantages translate into practical gains for underwater communication remains to be demonstrated experimentally. But the results suggest that optical skyrmions deserve a closer look as candidates for robust structured-light links in challenging environments.

Authors' statement

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