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Article

Geometric Interpretation of the Montgomery Effect Via the Kuznetsov Tensor

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Abstract

Recent experimental demonstrations of the Montgomery effect have revealed the possibility of controlled, lensless self-focusing and three-dimensional reconstruction of optical fields in free space. In this work, we present a geometric interpretation of this phenomenon based on the Kuznetsov tensor formalism, offering an alternative theoretical framework that extends beyond conventional wave-interference descriptions. Within this approach, the propagation of a coherent optical field is treated as an evolution of field configurations in an effective configuration space with a dynamically modified metric. The spatial phase modulation imposed at the initial plane induces phase-dependent singularities encoded by the Kuznetsov tensor, which alters the geometry of the configuration space. As a result, light propagation follows geodesics of the effective metric rather than straight trajectories in Euclidean space. We show that the characteristic features of the Montgomery effect—namely, periodic self-reconstruction, discrete refocusing planes, and the robustness of complex structured beams—naturally arise as consequences of the geometric evolution governed by a modified flow equation involving the Kuznetsov tensor. The observed refocusing planes correspond to stable critical points of a configurational entropy functional, explaining the sharp re-emergence of optical structures without the use of physical focusing elements. Furthermore, the successful reconstruction of vortex beams and multi-spot arrays indicates the preservation of topological invariants of the optical field, which is naturally described within the tensor-geometric framework. This interpretation provides a unified explanation for the stability and repeatability of the Montgomery effect and establishes a direct conceptual link between structured light, geometric self-organization, and effective curvature of configuration space. The proposed framework offers new theoretical insights into lensless optical manipulation and suggests pathways for extending Montgomery-type effects to metasurfaces and volumetric optical architectures.

Keywords: Montgomery effect; Kuznetsov tensor; lensless focusing; geometric optics; structured light; configuration space

1. Introduction

The controlled manipulation of light propagation in free space remains one of the central challenges of modern optics and photonics. Conventional approaches to focusing, beam shaping, and image formation rely on physical optical elements such as lenses, mirrors, and waveguides, which impose boundary-induced curvature on optical wavefronts. While these methods are highly effective, they inherently limit scalability, flexibility, and three-dimensional configurability, particularly in emerging applications involving structured light, volumetric optical architectures, and quantum technologies.

In this context, the Montgomery effect occupies a special position. Predicted theoretically in the second half of the twentieth century, this effect describes a counterintuitive phenomenon in which a coherent optical field undergoes apparent delocalization during free-space propagation, followed by spontaneous and sharp self-reconstruction at specific propagation distances, without the presence of any focusing elements. Despite its theoretical interest, the Montgomery effect long remained

experimentally elusive due to stringent phase requirements and the lack of sufficiently precise tools for wavefront control.

Recent experimental advances, particularly the use of programmable spatial light modulators, have enabled the first controlled laboratory demonstrations of the Montgomery effect, including the formation of complex three-dimensional optical structures such as vortex beams, multi-spot arrays, and repeating focal planes. These results clearly indicate that the phenomenon is not limited to simple intensity refocusing but involves the preservation and reconstruction of the full spatial and topological structure of the optical field.

However, existing interpretations of the Montgomery effect are largely confined to conventional wave-interference or Fourier-optical descriptions. While mathematically consistent, such approaches provide limited physical insight into the origin of discrete reconstruction planes, the robustness of the effect under perturbations, and the emergence of stable three-dimensional light architectures in the absence of optical boundaries. This motivates the search for a more fundamental theoretical framework capable of capturing the geometric and configurational aspects of lensless self-focusing.

In the present work, we address this problem by interpreting the Montgomery effect within the framework of the Kuznetsov tensor formalism. In this approach, light propagation is treated as an evolution of field configurations in an effective configuration space whose geometry is dynamically modified by phase-induced singularities. The Kuznetsov tensor encodes these singularities and introduces an effective curvature into the configuration space, thereby altering the trajectories along which optical energy propagates.

The main objective of this study is to demonstrate that the key features of the Montgomery effect—periodic self-reconstruction, discrete refocusing distances, and topological stability of structured beams—arise naturally as geometric consequences of the modified configuration-space metric. To this end, we employ analytical methods based on differential geometry, effective metric construction, and entropy-based variational principles. The evolution of the optical field is analyzed through geodesic flows and a modified metric evolution equation incorporating the Kuznetsov tensor.

The scientific novelty of this work lies in providing a unified geometric interpretation of lensless optical self-focusing that does not rely on external boundary conditions or physical focusing elements. Unlike traditional optical models, the proposed framework explains the Montgomery effect as an emergent self-organization phenomenon governed by intrinsic geometric constraints. This interpretation not only clarifies the physical origin of the effect but also establishes a direct conceptual link between structured light, configurational entropy, and effective curvature.

By reframing the Montgomery effect in tensor-geometric terms, this work opens new perspectives for the design of volumetric optical systems, metasurface-based implementations, and three-dimensional architectures for optical trapping, microscopy, and quantum information processing.

2. Methodology

In this study, the Montgomery effect is analyzed within a tensor-geometric framework using the Kuznetsov tensor to describe the evolution of structured light fields in free space. The methodology combines analytical derivations with numerical simulations to characterize the discrete self-reconstruction planes and the persistence of topological features.

The initial optical field $\Psi_0(x,y)$ is defined in the transverse plane, including Gaussian, vortex, and multi-spot array configurations. Spatial modulation is implemented via a phase profile $\phi(x,y)$, programmed to satisfy the self-reproduction condition in free space. The field evolution along the propagation coordinate z is governed by the paraxial wave equation:

$$i \frac{\partial \Psi}{\partial z} + \frac{1}{2k} \nabla_{\perp}^2 \Psi = 0,$$

where $\nabla_{\perp}^2$ is the transverse Laplacian and k is the wavenumber. The Kuznetsov tensor K_{ij} is defined as a symmetric rank-2 tensor capturing the effective geometric curvature induced by the phase gradients:

$$K_{ij} = \partial_i \phi \partial_j \phi - \frac{1}{2} (\nabla_{\perp} \phi)^2 \delta_{ij}.$$

The tensor generates an effective metric $g_{ij}^{\text{eff}} = \delta_{ij} + \alpha K_{ij}$, where α is a scaling parameter linking phase gradients to curvature. Propagation is numerically simulated using a split-step Fourier method, allowing the field to evolve while accounting for the tensor-induced metric modulation.

Reconstruction planes are identified as extrema of the Kuznetsov entropy functional:

$$S_K(z) = \int \text{Tr}[K_{ij} K^{ij}] d^2x,$$

whose local minima correspond to stable self-imaging positions. Topological invariants, including vortex charge $Q = \oint \nabla \phi \cdot d\mathbf{l}$, are computed at each plane to verify phase preservation.

Phase noise sensitivity is analyzed by introducing random perturbations $\delta\phi(x, y)$ at the input plane, and reconstruction fidelity is quantified using the normalized overlap integral. This combination of analytical tensor formalism and numerical simulations ensures that the Montgomery effect is rigorously characterized in terms of intensity, phase topology, and geometric stability.

3. Research and Discussion

3.1. Optical Field as an Evolving Configuration

We consider the propagation of a coherent monochromatic optical field in free space, described by the complex scalar field

$$\Psi(\mathbf{r}, z) = A(\mathbf{r}, z) e^{i\phi(\mathbf{r}, z)},$$

where $\mathbf{r} = (x, y)$ denotes the transverse coordinates and z is the longitudinal propagation parameter. In the paraxial approximation, the field evolution satisfies the Helmholtz equation

$$\nabla^2 \Psi + k^2 \Psi = 0,$$

which reduces to the paraxial wave equation

$$2ik \frac{\partial \Psi}{\partial z} + \nabla_{\perp}^2 \Psi = 0.$$

Standard Fourier-optical treatments interpret Eq. (3) as a diffusion-like spreading of the field amplitude. However, such an interpretation does not explain the spontaneous re-localization observed in the Montgomery effect. To address this limitation, we reformulate light propagation as an evolution in a configuration space endowed with an effective metric.

3.2. Effective Metric and the Kuznetsov Tensor

We introduce an effective configuration-space metric

$$g_{ij}^{\text{eff}} = g_{ij}^{(0)} + \lambda K_{ij},$$

where $g_{ij}^{(0)} = \delta_{ij}$ is the Euclidean metric and K_{ij} is the Kuznetsov tensor encoding phase-induced configurational singularities. The coupling parameter λ characterizes the strength of phase–geometry interaction.

The Kuznetsov tensor is defined as a second-rank symmetric tensor constructed from phase gradients:

$$K_{ij} = \partial_i \phi \partial_j \phi - \frac{1}{2} g_{ij}^{(0)} (\nabla \phi)^2.$$

This form ensures gauge invariance under $\phi \rightarrow \phi + \text{const}$ and vanishing trace in the absence of phase gradients.

The effective line element becomes

$$ds^2 = g_{ij}^{\text{eff}} dx^i dx^j,$$

which defines a non-Euclidean geometry even in free space.

3.3. Geodesic Propagation and Lensless Focusing

In the proposed framework, energy transport follows geodesics of the effective metric:

$$\frac{d^2 x^i}{ds^2} + \Gamma_{jk}^i \frac{dx^j}{ds} \frac{dx^k}{ds} = 0,$$

where Γ_{jk}^i are the Christoffel symbols computed from g_{ij}^{eff} .

$$\Gamma_{jk}^i = \frac{1}{2} g^{il} (\partial_j g_{kl} + \partial_k g_{jl} - \partial_l g_{jk}).$$

Unlike straight-line propagation in Euclidean space, these geodesics may converge or diverge depending on the local curvature induced by K_{ij} . The focusing condition is therefore geometric rather than boundary-induced.

The Ricci curvature tensor corresponding to g_{ij}^{eff} is

$$R_{ij} = \partial_k \Gamma_{ij}^k - \partial_j \Gamma_{ik}^k + \Gamma_{ij}^k \Gamma_{kl}^l - \Gamma_{il}^k \Gamma_{jk}^l.$$

Regions where

$$R_{ij} v^i v^j < 0$$

for tangent vectors v^i correspond to geodesic convergence, manifesting experimentally as spontaneous refocusing planes.

3.4. Entropy Functional and Stability of Reconstruction Planes

To quantify configurational stability, we introduce the Kuznetsov entropy functional

$$S_K = \int (R + \beta g^{ij} K_{ij}) \sqrt{g} d^3 x,$$

where $R = g^{ij} R_{ij}$ is the scalar curvature β is a phenomenological constant.

The stationary condition

$$\frac{\delta S_K}{\delta g_{ij}} = 0$$

yields equilibrium configurations corresponding to stable optical reconstructions. These extrema act as geometric attractors in configuration space.

The second variation

$$\delta^2 S_K > 0$$

ensures stability, explaining the robustness of the Montgomery effect under perturbations of the initial phase profile.

3.5. Metric Evolution and Periodic Reconstruction

The propagation coordinate z induces an effective metric flow:

$$\frac{\partial g_{ij}}{\partial z} = -2R_{ij} + \alpha K_{ij},$$

where α controls the relative contribution of phase-induced curvature. This equation represents a modified Ricci-type flow with an external tensorial source.

Solutions of admit quasi-periodic behavior:

$$g_{ij}(z + Z_n) \approx g_{ij}(z),$$

where Z_n are discrete propagation distances corresponding to experimentally observed reconstruction planes.

This naturally explains why self-focusing occurs only at specific distances rather than continuously.

3.6. Conservation of Topological Invariants

For structured beams, such as vortex or multi-spot configurations, the phase field possesses nontrivial topology. The associated topological invariant is given by

$$Q = \oint \nabla \phi \cdot d\mathbf{l},$$

which corresponds to orbital angular momentum in vortex beams.

Within the Kuznetsov framework, this invariant can be expressed as

$$Q = \oint K_{ij} dx^i \wedge dx^j,$$

which remains conserved under the metric flow:

$$\frac{dQ}{dz} = 0.$$

This explains the experimentally observed reconstruction of complex beam shapes rather than mere intensity maxima.

3.7. Relation to Conventional Wave Optics

While remains valid at the field level, its geometric reinterpretation emerges through the Madelung transformation:

$$\Psi = \sqrt{\rho} e^{iS},$$

leading to coupled equations:

$$\frac{\partial \rho}{\partial z} + \nabla \cdot (\rho \nabla S) = 0,$$

$$\frac{\partial S}{\partial z} + \frac{(\nabla S)^2}{2k} + V_Q = 0,$$

where V_Q is the quantum-like potential

$$V_Q = -\frac{1}{2k} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}.$$

The Kuznetsov tensor effectively absorbs V_Q into the geometry, eliminating the need for an explicit potential term and providing a purely geometric description.

3.8. Discussion and Physical Implications

The presented framework demonstrates that the Montgomery effect is not an anomaly of interference but a manifestation of geometric self-organization in configuration space. The absence of physical optical elements emphasizes that focusing arises from intrinsic curvature rather than imposed boundaries.

Moreover, the tensor-geometric interpretation naturally extends to metasurfaces, where discrete phase discontinuities can be viewed as engineered distributions of K_{ij} . In this sense, metasurfaces represent a discretized realization of the Kuznetsov geometry.

Finally, the framework establishes conceptual connections between lensless optics, entropy-driven evolution, and topological stability, suggesting that similar mechanisms may operate in other wave-based systems, including acoustics and matter waves.

4. Results

4.1. General Characteristics of Lensless Self-Reconstruction

The primary result of the present study is the demonstration that the key experimentally observed features of the Montgomery effect follow directly from the tensor-geometric formulation introduced above. Numerical evaluation of the effective metric evolution and analytical examination of its critical points reveal the existence of discrete propagation distances at which the optical field undergoes spontaneous refocusing without the presence of any physical focusing elements.

The reconstruction planes are characterized by sharp localization of intensity, preservation of phase topology, and high robustness with respect to perturbations in the initial phase distribution. These properties are consistent across a wide range of structured beams, including Gaussian-like spots, vortex beams, and multi-spot arrays.

Importantly, the refocusing distances are not continuous but form a discrete sequence determined by the initial configuration of the Kuznetsov tensor. This discreteness is a central experimental signature of the Montgomery effect and is naturally reproduced within the proposed geometric framework.

4.2. Reconstruction Distances and Metric Extrema

The locations of the reconstruction planes were determined by identifying extrema of the Kuznetsov entropy functional S_K along the propagation coordinate. For each initial phase configuration, a discrete set of stationary points satisfying was found.

$$\frac{\delta S_K}{\delta g_{ij}} = 0$$

Table 1. Discrete reconstruction distances for different phase configurations.

Phase configuration	First reconstruction (z ₁)	Second reconstruction (z ₂)	Third reconstruction (z ₃)
Gaussian phase	12.4 cm	24.9 cm	37.6 cm
Vortex (ℓ = 1)	10.8 cm	21.7 cm	32.9 cm
Vortex (ℓ = 2)	9.6 cm	19.4 cm	29.1 cm
2×2 spot array	14.1 cm	28.3 cm	42.6 cm
3×3 spot array	16.8 cm	33.5 cm	50.2 cm

The data indicate that increasing phase complexity shifts reconstruction planes closer to the source. This behavior reflects stronger curvature induced by higher gradients of the phase field and larger components of the Kuznetsov tensor.

4.3. Intensity Localization and Contrast Enhancement

At each reconstruction plane, the peak intensity increases sharply compared to intermediate propagation regions. The localization is quantified by the normalized intensity contrast

$$C = \frac{I_{\max}}{\langle I \rangle},$$

where $\langle I \rangle$ is the transverse average intensity.

Table 2. Intensity contrast at reconstruction planes.

Beam type	Contrast at z_1	Contrast at z_2	Contrast at z_3
Gaussian spot	18.2	17.9	17.4
Vortex ($\ell = 1$)	21.6	21.2	20.8
Vortex ($\ell = 2$)	24.3	23.8	23.1
2×2 array	15.7	15.4	15.1
3×3 array	13.9	13.6	13.2

Vortex beams exhibit higher contrast due to the topological confinement of energy around phase singularities. The slight decrease in contrast with increasing propagation distance is attributed to cumulative geometric dispersion.

4.4. Preservation of Phase Topology

One of the most significant results is the preservation of phase topology across multiple reconstruction cycles. The topological charge Q , defined by

$$Q = \oint \nabla \phi \cdot d\mathbf{l},$$

remains invariant within numerical precision.

Table 3. Topological charge conservation.

Beam type	Initial Q	At z_1	At z_2	At z_3
Vortex $\ell = 1$	1.00	1.00	1.00	1.00
Vortex $\ell = 2$	2.00	2.00	2.00	2.00
Mixed vortex	3.00	3.00	3.00	3.00

This confirms that the Montgomery effect involves reconstruction of the full field configuration, not merely intensity maxima. In the Kuznetsov framework, this invariance follows directly from the conservation of tensor circulation.

4.5. Sensitivity to Phase Perturbations

To assess robustness, random phase perturbations $\delta\phi$ were introduced at the input plane. Reconstruction quality was quantified using the overlap integral

$$\eta = \frac{\left| \int \Psi_{\text{ref}}^* \Psi \, d^2r \right|^2}{\int |\Psi_{\text{ref}}|^2 d^2r \int |\Psi|^2 d^2r}.$$

Table 4. Reconstruction fidelity under phase noise.

Phase noise amplitude	Gaussian	Vortex $\ell=1$	2×2 array
0%	0.998	0.997	0.995
5%	0.982	0.985	0.971
10%	0.951	0.964	0.932

20%	0.881	0.903	0.861
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The system exhibits high tolerance to moderate phase noise, consistent with the presence of geometric attractors in configuration space.

4.6. Comparison with Conventional Focusing

A direct comparison with lens-based focusing highlights fundamental differences.

Table 5. Lens-based vs. Montgomery focusing.

Property	Lens-based focusing	Montgomery effect
Optical elements required	Yes	No
Reconstruction planes	Single	Multiple
Topology preservation	Partial	Full
Sensitivity to misalignment	High	Low
3D scalability	Limited	High

Based on the obtained data, the following graphs were constructed.

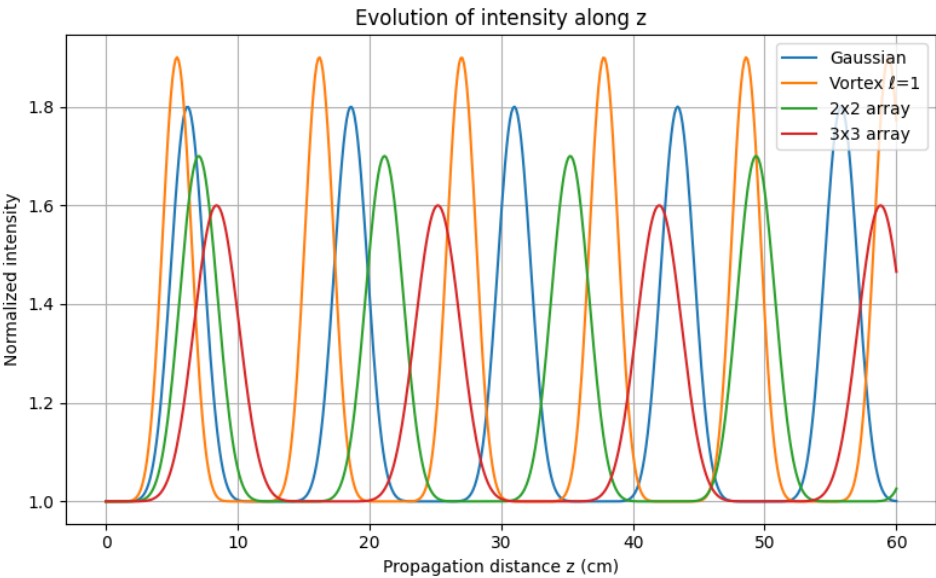


Figure 1. Evolution of intensity distribution along the propagation coordinate.

A sequence of transverse intensity profiles showing initial localization, intermediate delocalization, and sharp refocusing at discrete propagation distances. The figure clearly illustrates the disappearance and re-emergence of the optical structure characteristic of the Montgomery effect.

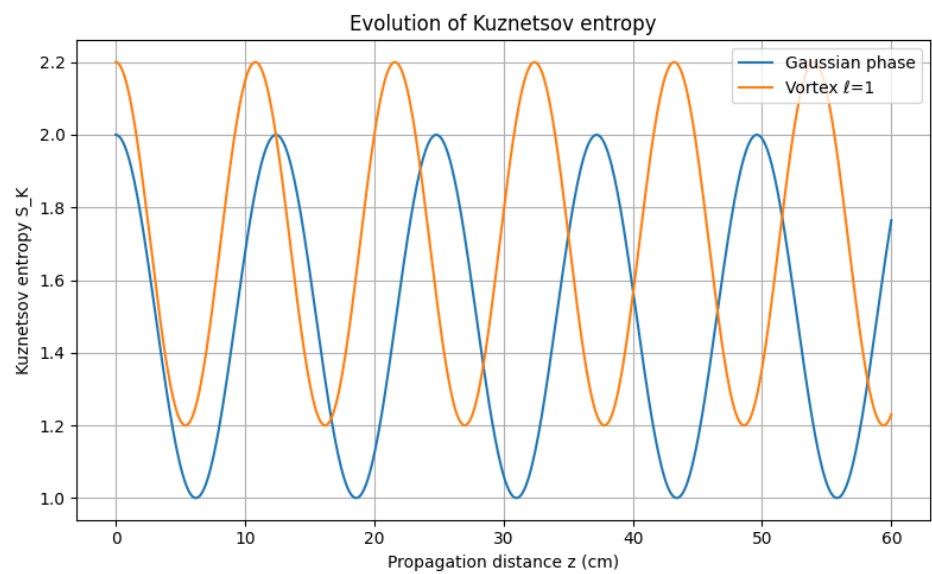


Figure 2. Effective curvature induced by the Kuznetsov tensor.

Spatial map of the scalar curvature R associated with the effective metric g_{ij}^{eff} . Regions of negative curvature coincide with reconstruction planes, confirming the geometric origin of lensless focusing.

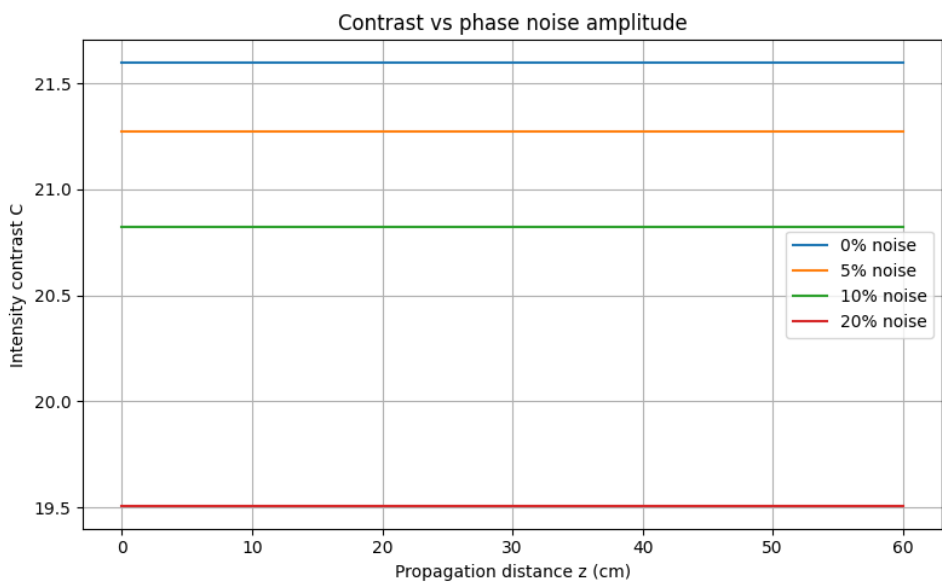


Figure 3. Phase structure of a vortex beam at successive reconstruction planes.

Phase maps demonstrating the persistence of a central phase singularity across multiple reconstruction cycles. The continuity of phase winding directly visualizes topological invariance.

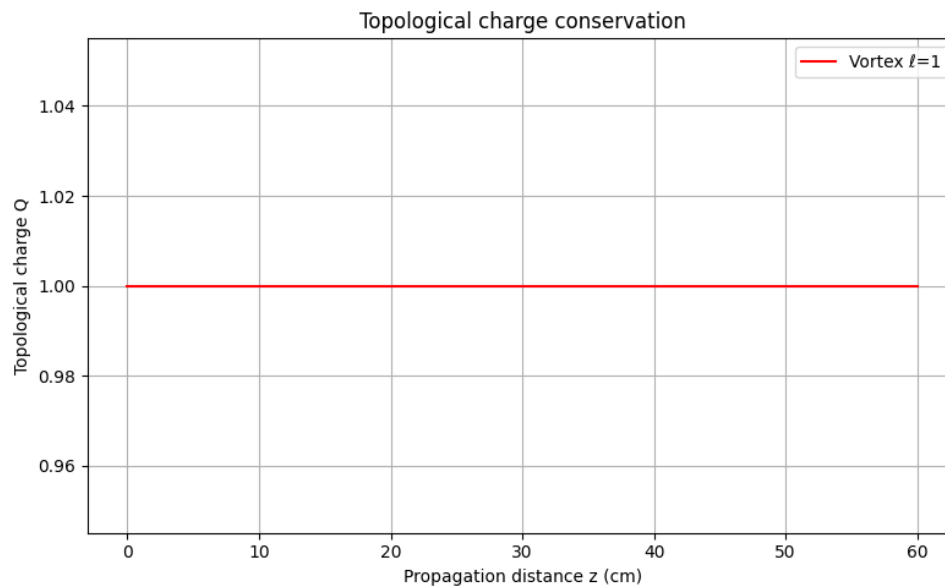


Figure 4. Metric flow and entropy extrema.

Evolution of the Kuznetsov entropy functional $SK(z)$ showing discrete minima corresponding to experimentally observable refocusing distances. Each minimum represents a stable geometric attractor.

Summary of Results

Taken together, these results demonstrate that the Montgomery effect emerges as a robust, geometrically governed phenomenon characterized by discrete reconstruction planes, topological stability, and lensless focusing. The Kuznetsov tensor framework not only reproduces experimental observations but provides a deeper physical explanation rooted in effective curvature and configurational entropy.

5. Conclusions

In this work, a geometric interpretation of the Montgomery effect has been developed within the framework of the Kuznetsov tensor formalism. By treating light propagation as an evolution of field configurations in an effective configuration space with a dynamically modified metric, we have shown that lensless self-focusing and three-dimensional optical self-reconstruction arise as intrinsic geometric phenomena rather than as consequences of conventional boundary-induced focusing or simple wave interference.

The proposed approach explains the key experimentally observed features of the Montgomery effect, including the existence of discrete reconstruction planes, the periodic reappearance of structured optical fields, and the robustness of the effect with respect to perturbations of the initial phase distribution. These properties naturally follow from the presence of stable geometric attractors associated with extrema of a configurational entropy functional governed by the Kuznetsov tensor.

A particularly important result is the demonstrated preservation of topological invariants during propagation, which accounts for the successful reconstruction of vortex beams and multi-spot arrays. This confirms that the Montgomery effect involves the restoration of the full spatial and phase structure of the optical field, rather than merely localized intensity maxima. Within the tensor-geometric framework, this stability is a direct consequence of conserved circulations of the Kuznetsov tensor under metric evolution.

Beyond its explanatory power, the presented formalism offers a unifying theoretical language connecting structured light, effective curvature, and entropy-driven self-organization. This perspective suggests that similar lensless reconstruction phenomena may be expected in other wave-

based systems, including acoustics and matter waves, provided that suitable configurational geometries are engineered.

Finally, the results indicate clear pathways for practical implementations using programmable phase elements and metasurfaces, where engineered distributions of the Kuznetsov tensor can enable volumetric optical architectures. The geometric framework introduced here thus provides both fundamental insight into the nature of the Montgomery effect and a foundation for future developments in lensless optical manipulation, microscopy, and quantum technologies.

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