

Generalized rainbow patterns of ellipsoidal droplets simulated by the vectorial complex ray model

Qingwei DUAN,^{1,2} Fabrice R.A. ONOFRI³, Xiang'e HAN,¹ and Kuan Fang REN^{1,2}

¹School of Physics, Xidian University, Xi'an 710071, China

²CORIA-UMR 6614, Normandie Université, CNRS, 76801 Saint-Etienne du Rouvray, France

³Aix-Marseille Université, CNRS, IUSTI, UMR 7343, 13453 Marseille, France



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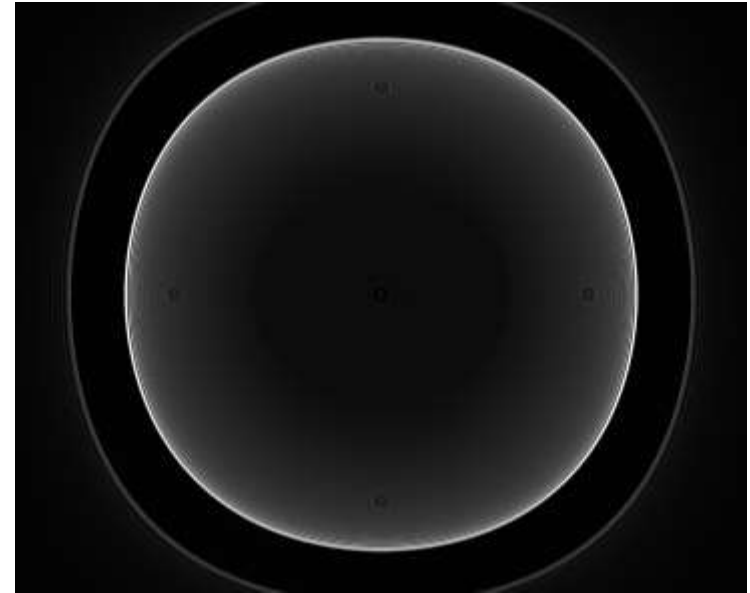
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Background | Rainbows of spherical droplets



(a) A natural rainbow
(The sun is the light source)

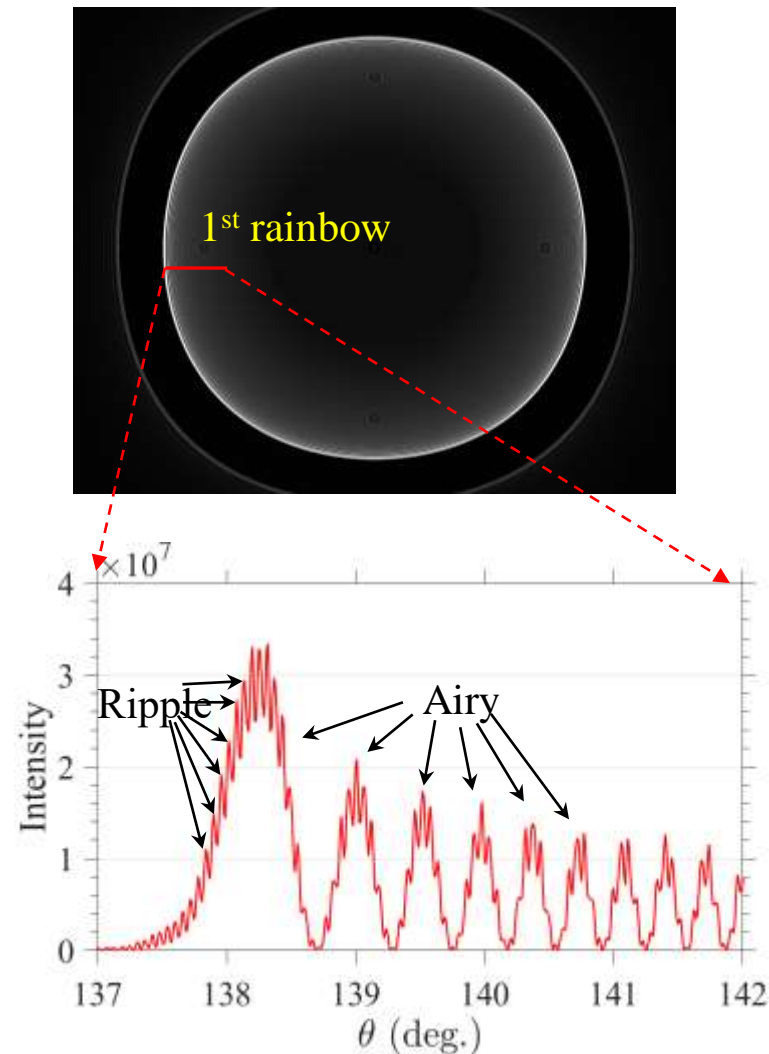


(b) A monochrome rainbow
(A laser is the light source)

Fig.1. Rainbows of **spherical** droplets

Background | Rainbows of spherical droplets

By rainbow signals, one can obtain the droplet's refractive index (temperature), size, evaporation rate etc. [1-8].



- [1] N. Roth, K. Anders, and A. Frohn, **Appl. Opt.** 30, 4960 (1991).
- [2] J. P. A. J. van Beeck, D. Giannoulis, L. Zimmer, and M. Riethmuller, **Opt. Lett.** 24, 1696 (1999).
- [3] Han X. Study of refractometry of rainbow and applications to the measurement of instability and temperature gradient of a liquid jet, Ph.D. thesis, University of Rouen (2000).
- [4] J. Hom, N. Chigier, **Appl. Opt.** 41(10):1899–1907 (2002).
- [5] X. Wu, H. Jiang, Y. Wu, J. Song, G. Gréhan, S. Saengkaew, L. Chen, X. Gao, and K. Cen, **Opt. Lett.** 39, 638 (2014).
- [6] Y. Wu, J. Promvongsa, X. Wu, K. Cen, G. Gréhan, and S. Saengkaew, **Opt. Express** 23, 30545 (2015).
- [7] Y. Wu, J. Promvongsa, S. Saengkaew, X. Wu, J. Chen, and G. Gréhan, **Opt. Lett.** 41, 4672-4675 (2016)
- [8] Y. Wu, L. Shi, X. Wu, J. Shen, L. Chen, and K. Cen, **Opt. Lett.** 44, 5699-5702 (2019)

generally **limited to spherical droplets**

Background | Generalized rainbow patterns

However, **not all droplets are perfectly spherical**. For non-spherical droplets, their rainbow scattering patterns **can be rather complicated**.

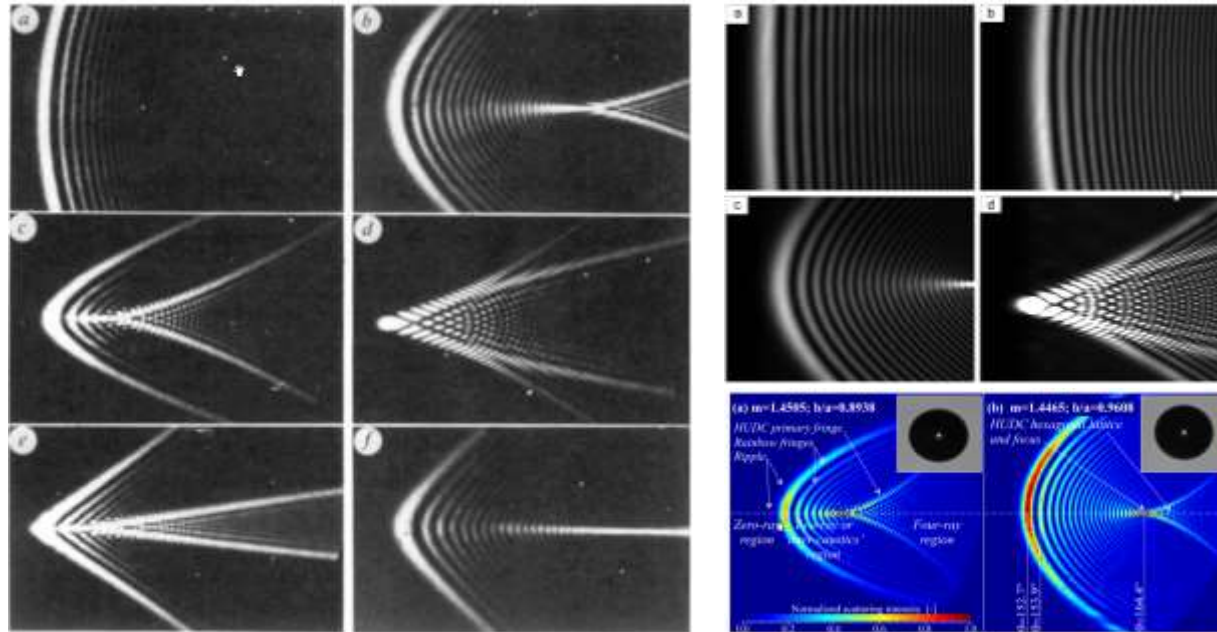


Fig.2. **Experimental observation** of the rainbow patterns formed by oblate spheroidal drops[1-4].

Generalized Rainbow Patterns

- [1] P. L. Marston and E. H. Trinh, **Nature** 312:529–531 (1984).
- [2] O. Jobe, D. B. Thiessen, and P. L. Marston, **J. Quant. Spectrosc. Radiat. Transf.** 202:147–153 (2017)
- [3] H. Yu, F. Xu, and C. Tropea, **Opt. Express** 21:25761–25771 (2013).
- [4] F. R. Onofri, K. F. Ren, M. Sentis, Q. Gaubert, and C. Pelcé, **Opt. Express** 23, 15768–15773 (2015).

| Light Scattering Theories | Applicable Scenario |
|---|---|
| Analytical models (LMT, GLMT, Debye etc.) | spherical particles |
| Numerical methods (T-Matrix、DDA、FDTD etc.) | non-spherical, but very small particles (typically, size para. $x < 200$) |

However, due to surface tension, small droplets are usually spherical.

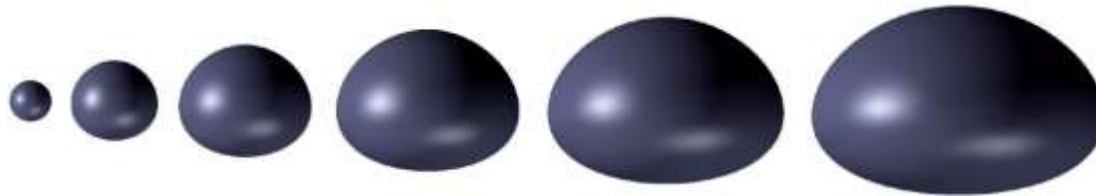


Fig.3. Shape of raindrops as their diameter increases from 1 mm to 6 mm

Generally, the size of a non-spherical drop is much greater than incident wavelength. Size parameter is typically over 1000, far beyond the applicable range of numerical methods.

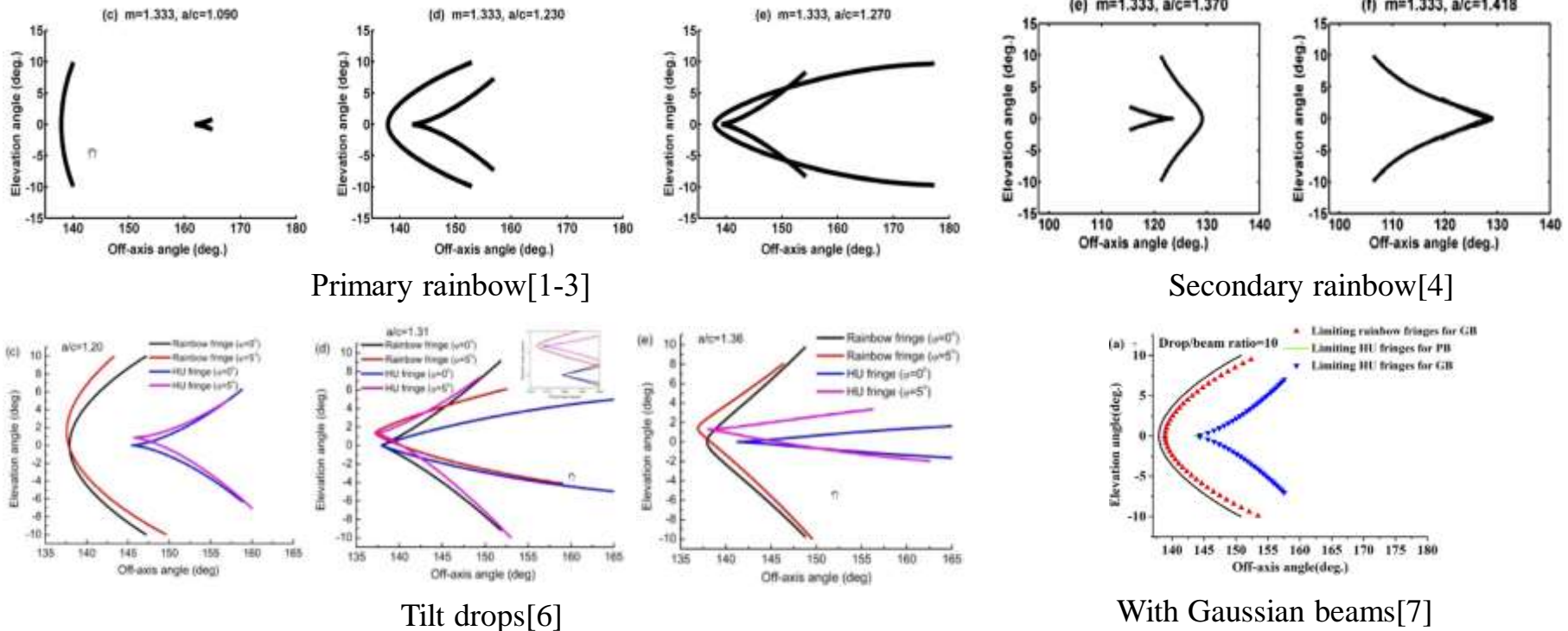
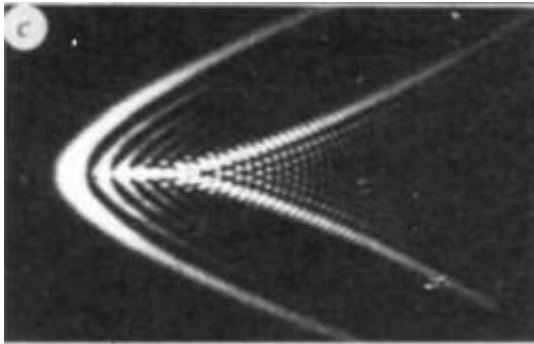


Fig. 4. Optical caustics obtained by ray tracing methods

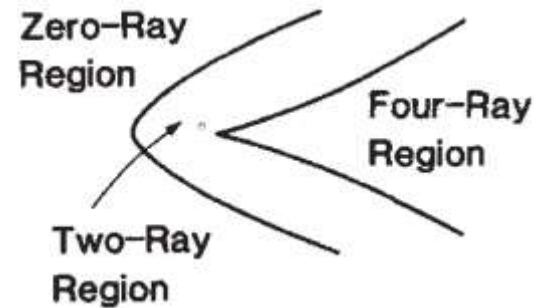
- [1] J. F. Nye, **Nature** 312, 531–532 (1984).
- [2] J. F. Nye, **Proc. Royal Soc. London. Ser. A: Math. Phys. Sci.** 438, 397–417(1992).
- [3] H. Yu, F. Xu, and C. Tropea, **Opt. Express** 21, 25761–25771 (2013).
- [4] H. Yu, F. Xu, and C. Tropea, **Opt. Lett.** 38, 4469–4472 (2013).
- [6] H. Yu, J. Shen, C. Tropea, and F. Xu, **Opt. Lett.** 44, 823–826 (2019)
- [7] J. Wang, H. Yu, J. Shen, B. Yang, and C. Tropea, **Opt. Express** 29, 377-384 (2021)

Limitation of conventional ray-tracing methods

By pure ray tracing method, **only the 'skeleton' is obtained.**



Experimental observation



Ray tracing result

To acquire the intensity of scattering field, one has to know

- 1) the amplitude (Fresnel coefficients & Divergence factor of wavefront)
- 2) the phase (due to reflection, optical path & focal lines)

◦ ◦ ◦

conventional ray-tracing methods fail



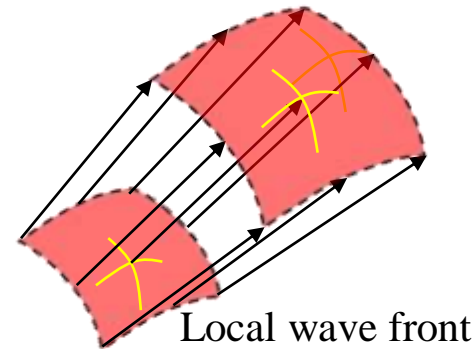
Kuan Fang Ren et al., *Opt. Lett.* 36(3), 370–372 (2011).

Aim ◆ Scattering of **large particles of any smooth surface**

Ray properties

Direction
Amplitude
Phase
Polarization

Curvature of wave front



Local wave front

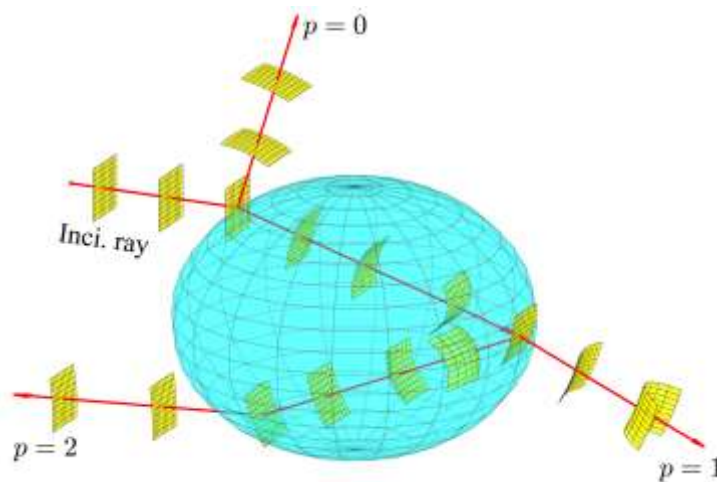


Fig. Variation of a local wavefront in the scattering by an ellipsoidal drop.
($m = 1.333$, $\lambda = 632.8$ nm, $a=b= 1.0$ mm, $c = 0.75$ mm).

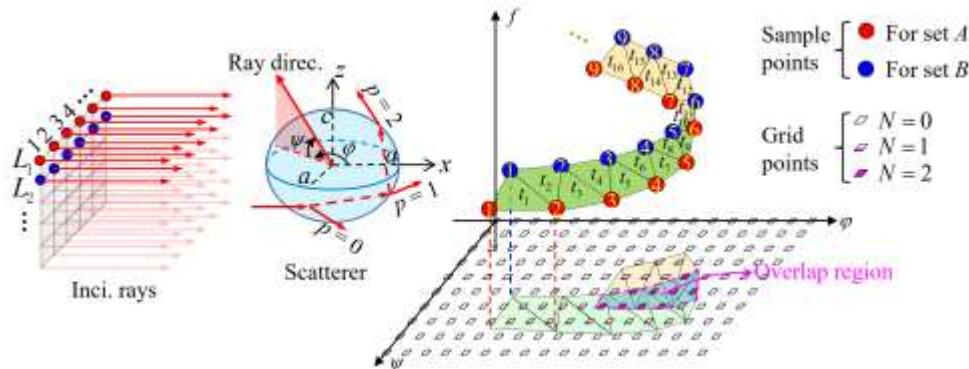
The **shifts in amplitude/phase due to wave front** → directly calculated

Research status of VCRM

| |
|--|
| In 2011, the VCRM was proposed [Ren et al. <i>Opt. Letters</i> , 36(3):370–372] |
| In 2015, experimental examination [Onofri et al. <i>Opt. Express</i> , 23:15768–15773] |
| In 2015, numerical examination by the MLFMA [Yang et al. <i>JQSRT</i> , 162:143–153] |
| In 2012, ellipsoid particles [Ren et al. <i>JQSRT</i> , 113:2419–2423] |
| In 2012, elliptical cylinders [Jiang et al. <i>Appl. Optics</i> , 51:8159–8168] |
| In 2013, Gaussian beam by elliptical cylinders [Jiang et al. <i>JOSA A</i> , 30: 1548–1556] |
| In 2015, parameter measurement of an oblate droplet. [Onofri et al. <i>Opt. Express</i> , 23:15768–15773] |
| In 2022, Airy theory revisited by combining VCRM and PO [Zhang et al. <i>Opt. Letters</i> , 47(9) 2149-2152] |
| In 2016, wave-front distortion considered in 3D ray tracing of a spheroid. [Sun et al. <i>JQSRT</i> , 179:1–10] |
| In 2019, 3D scattering by real liquid jets . [Duan et al. <i>JQSRT</i> , 179:1–10] |
| In 2021, 3D scattering by oblate droplets . [Duan et al. <i>Optics Letters</i> 46(18) 4585-4588] |

2D or 2D+

3D space



Recently, a **triangulation-based interpolation method** was proposed which enables VCRM to calculate the 3D scattering field, and proposed the **VCRM3D (VCRM for 3D scattering)**.

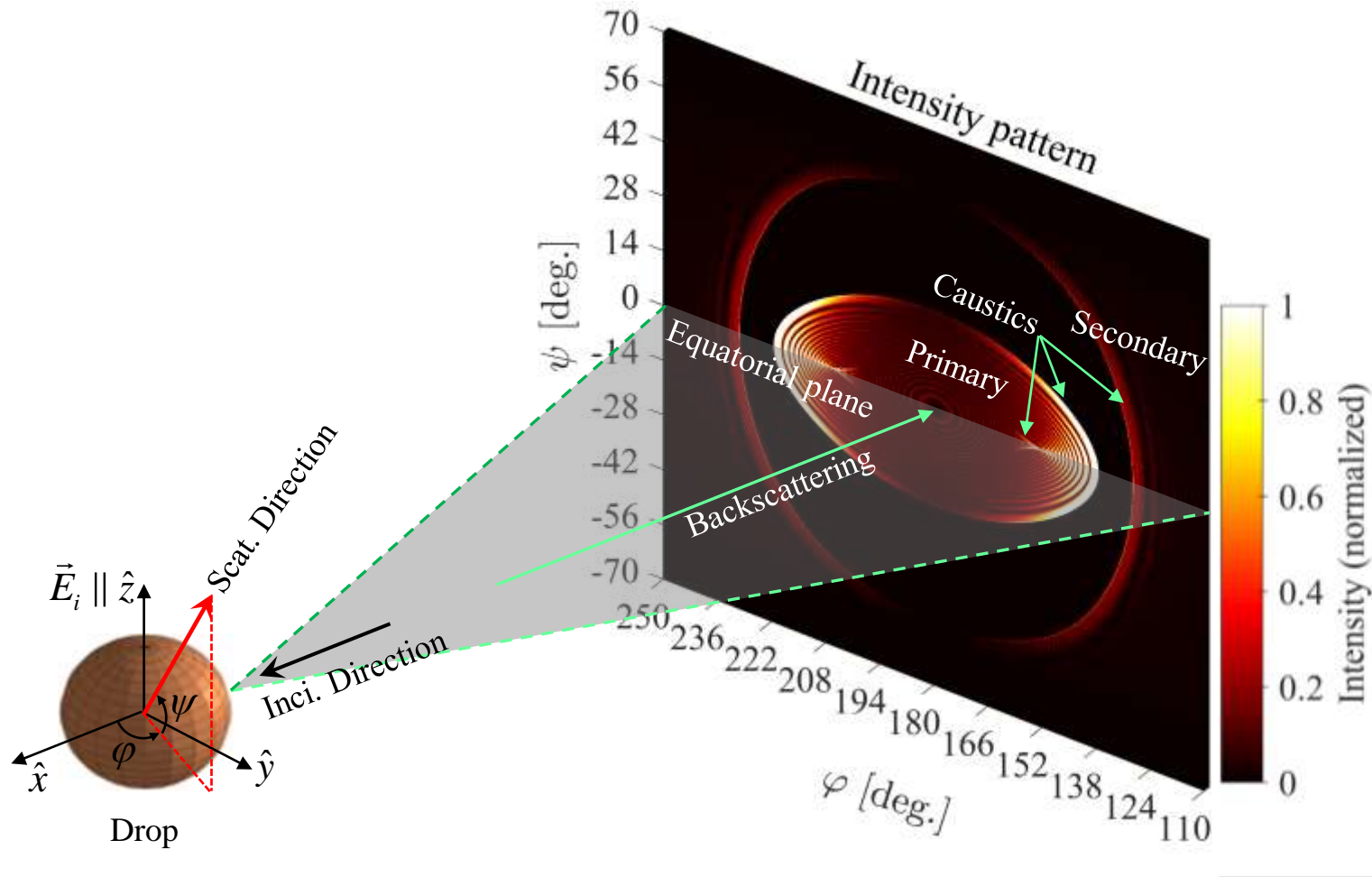


Fig. 5. Primary and secondary rainbow patterns of an oblate drop simulated with the VCRM3D.

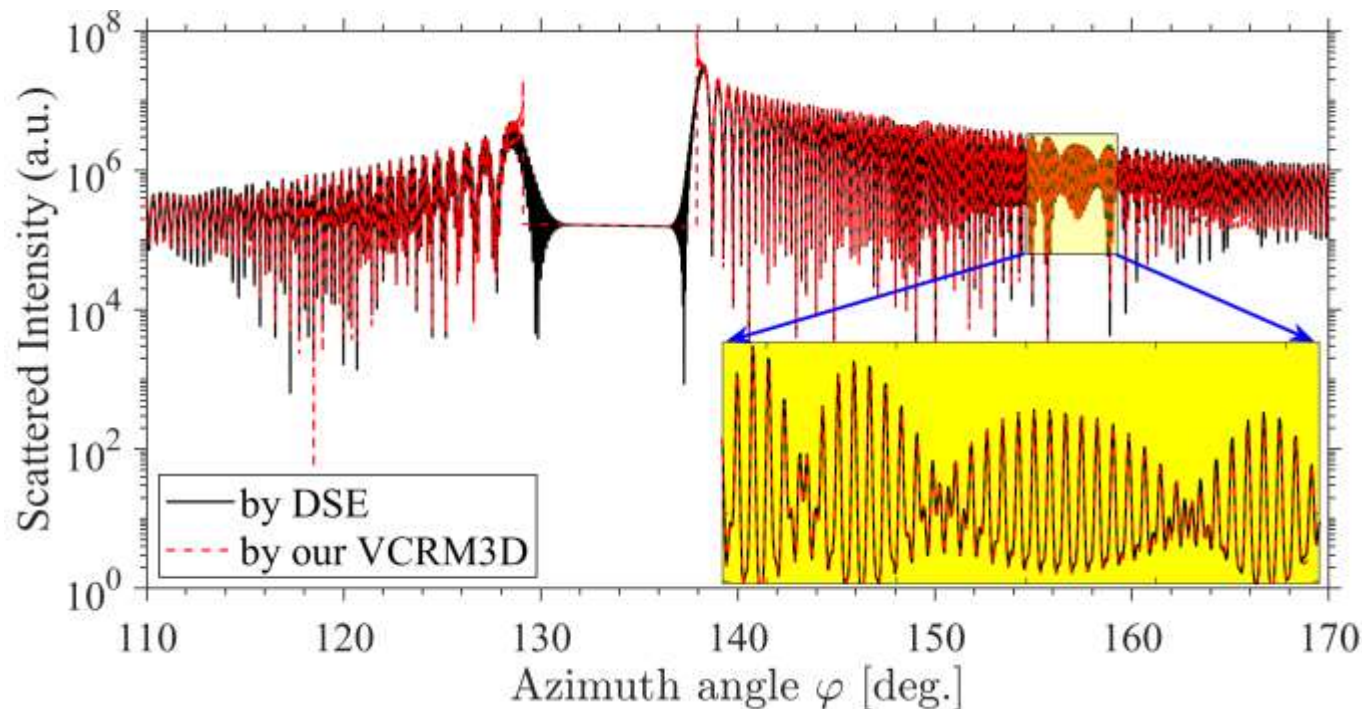


Fig. 6. Comparison of the VCRM3D with DSE for the light scattering intensity by a spherical drop of radius $a=500\text{ }\mu\text{m}$.

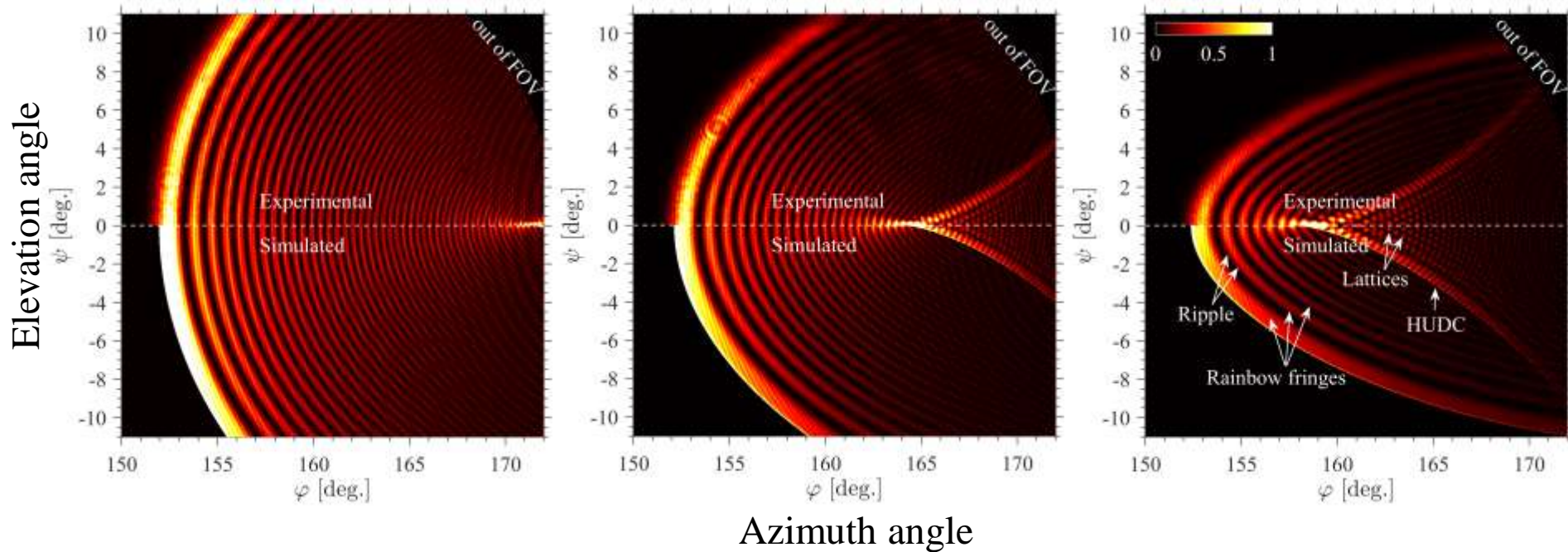
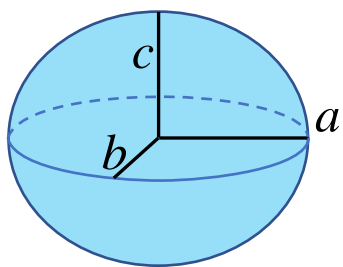


Fig. 7. Comparison of the VCRM3D with the experimental results for the primary rainbow of oblate drops in order of increasing shape deformation.

To be published...

Results



Ellipsoidal drop

$a = 100 \mu\text{m}$ (constant)

$m = 1.333$ (constant)

$\lambda = 632.8 \text{ nm}$

size para. ≈ 1000

Time cost per image:

15 min on PC (i9-13000ks)

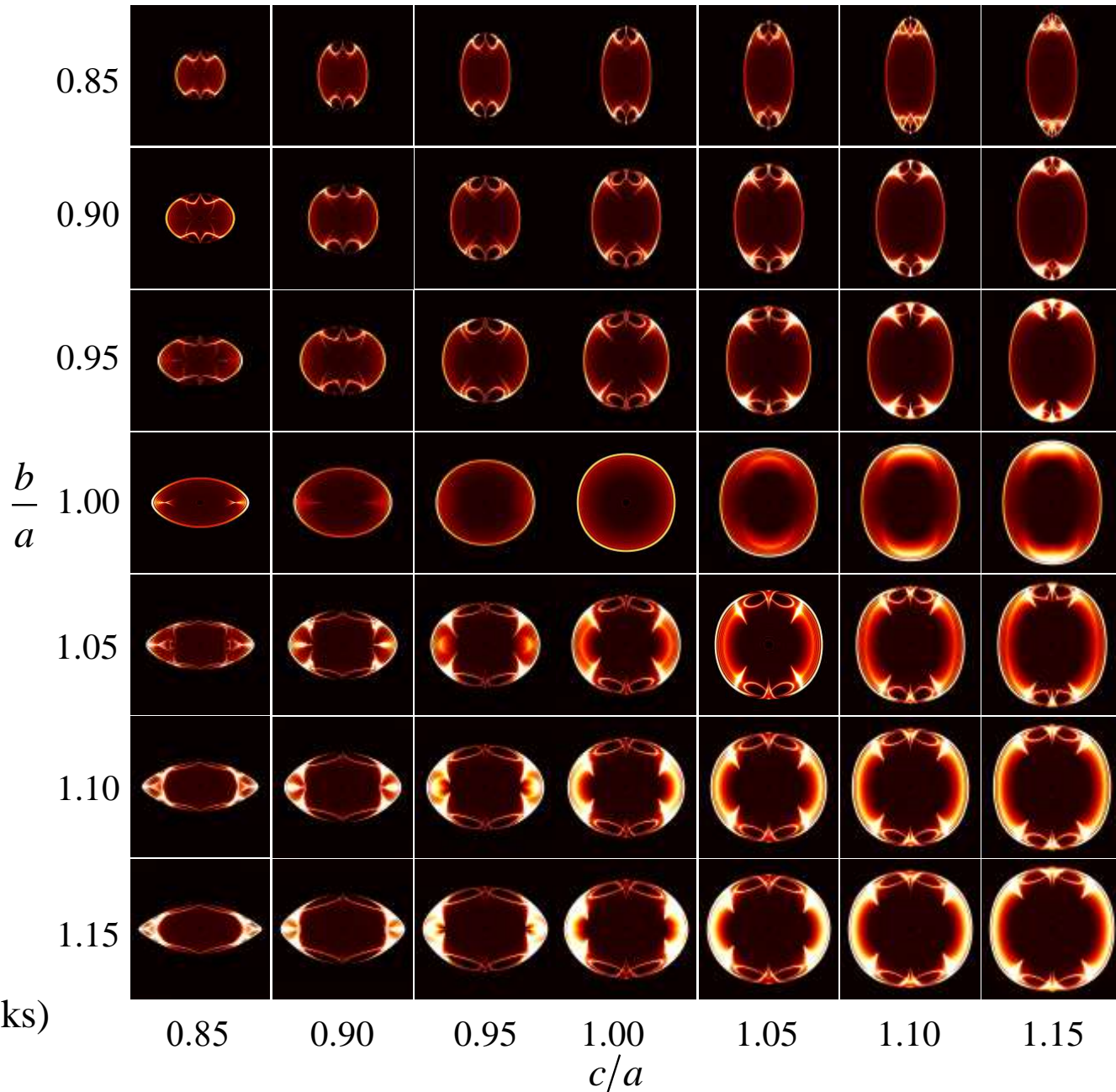


Fig. 8. Generalized rainbow patterns of triaxial ellipsoidal drops
simulated by the VCRM3D

(To be published...)

An example of application

Challenges faced in measuring the 3D geometric shape of non-spherical droplets.

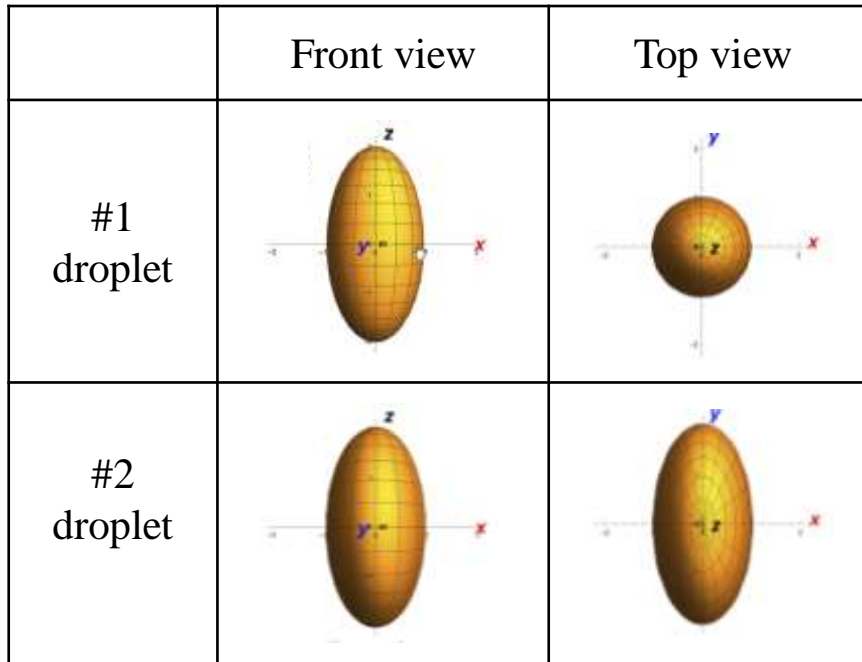
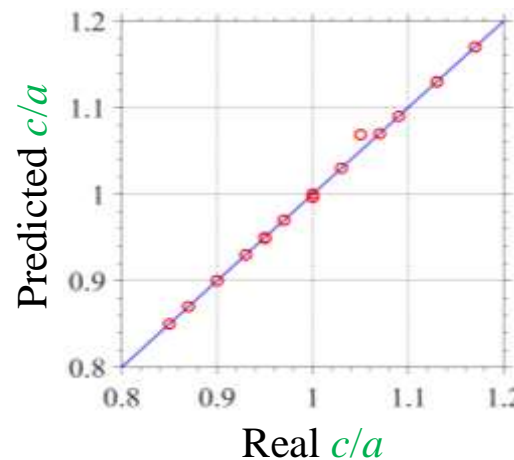
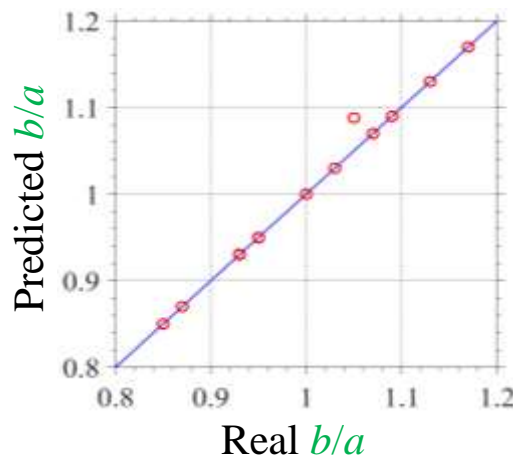
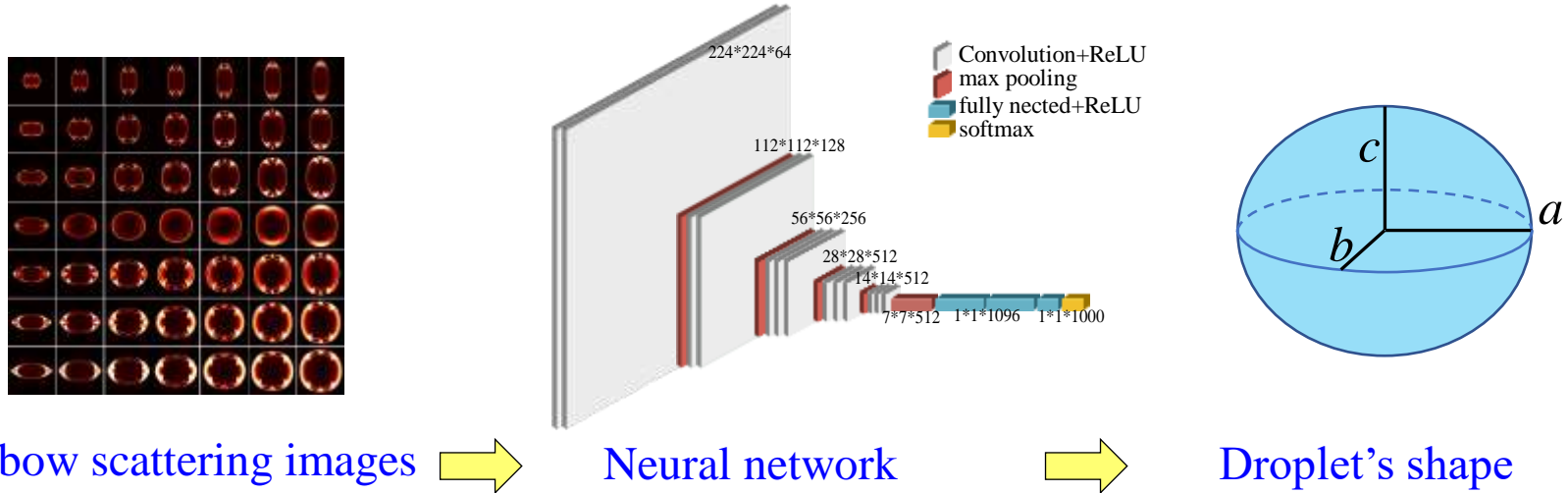


Fig. 9. The shapes of two non-spherical droplets from different perspectives [1].

Obtaining the 3D shape of non-spherical droplets generally requires synchronous photography technology from multiple angles, which is difficult to operate and incurs high costs.

[1] M. Agrawal et al., “Experimental investigation of a nonspherical water droplet falling in air,” *Physics of Fluids* 32, 112105 (2020).

An example of application



Accuracy $\geq 98\%$

(To be published...)

Fig. 10. Accuracy of neural network for predicting the aspect ratios (b/a and c/a) of ellipsoidal droplets by their rainbow scattering patterns.

Summary

- Simulation for the **generalized rainbow patterns** of ellipsoidal droplets has been achieved with VCRM3D.
- The **proposed method has been validated** numerically and experimentally.
- The feasibility of **using generalized rainbows assisted with neural network to acquire the shapes of nonspherical droplets** has been proven.



Thanks for your attention!

Qingwei DUAN^{1,2}, Fabrice R.A. ONOFRI³, Xiang'e HAN¹, and Kuanfang REN^{1,2}

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²CORIA-UMR 6614, Normandie Université, CNRS, 76801 Saint-Etienne du Rouvray, France

³Aix-Marseille Université, CNRS, IUSTI, UMR 7343, 13453 Marseille, France

Emails to qwduan@xidian.edu.cn, fabrice.onofri@univ-amu.fr,
xehan@mail.xidian.edu.cn and fang.ren@coria.fr

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