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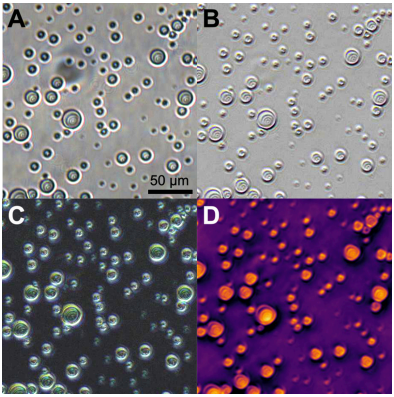
WELCOME TO WARP

HIGHLIGHTS:

- WARP - the Wavefront Angle Retrieval Process – is a proprietary method for quantifying the optical phase shift by an object.
- Simple, fast and precise maps of phase, refractive index, and/or geometry with microscopic resolutions over mm-sized fields of view.
- Richer, more reliable data via simultaneous imaging with DIC, phase contrast, scattering amplitude and bright-field contrast modes in full RGB color.

WARP is the Wavefront Angle Retrieval Process. It measures the angular deflection of light waves using an optical filter placed in the infinity plane of the imaging system. This optical filter introduces a mathematically-defined attenuation pattern that modulates the image contrast in a manner correlated with the scattering angle of the light.[1] Each WARP measurement involves acquiring four images at unique filter positions. The Z1 system then analytically determines the angular components (horizontal and vertical) of the light being scattered by the sample.

WARP is also a quantitative phase imaging (QPI) method.[2] The scattering angle of the light wave transmitted by the sample also has a straightforward derivative-integral relationship to the phase. Hence, measuring the wavefront angle also provides the optical phase shift (i.e. the speeding up or slowing down of the light) due to the sample. Combined with the intensity recorded by these four images, WARP measures the perturbation of the wavefront by the sample in its entirety.



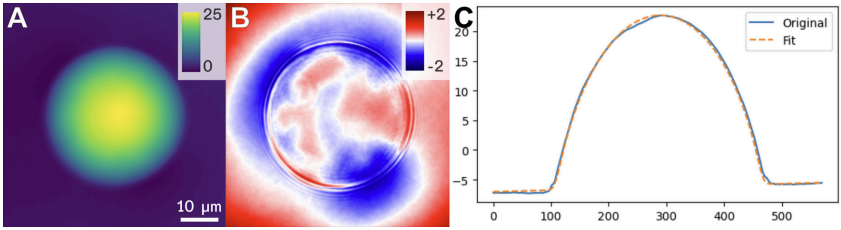
Contrast multiplexing with WARP: Measuring the entire wavefront (amplitude and phase) provides substantially more information about the sample, as well as the ability to reconstruct multiple contrast modes from a single exposure. Shown here (for a sample of biocondensate droplets) are: A) brightfield, B) DIC, C) scattering angle magnitude (GAMP) and D) quantitative phase.

Sample credit: R. Nørrild & A. Büll, DTU

What could I do with WARP? Microscopic phase maps like those produced by WARP are particularly well-suited to the study of microscopic physical phenomena because they reveal everything that affects the transmission of light through the sample: from shape and thickness to molecular concentration and nanoscale structural heterogeneity. Compared to traditional QPI techniques, such as digital holography or interferometry, WARP offers some key advantages:

- **It eliminates the need for beam-splitting optics**, making the system mechanically and thermally robust with no need for vibration isolation.
- **It operates under white-light (i.e. incoherent) illumination**, providing full colour (RGB) imaging and enabling the analysis of chromatic dispersion – something not possible with monochromatic laser-based systems.
- **WARP's analytical phase retrieval method makes no assumptions** about sample thickness, geometry or content, while avoiding the heavy computational burden and uncertainty inherent in numerical phase reconstruction.

Collectively, these features let the ClairSci Z1 rapidly and reproducibly generate quantitative, full-color phase maps across any optically-transparent (or semi-transparent) type of sample. For highly heterogeneous samples, such as protein aggregates or biomolecular condensates[3], a broader array of phenomena can then be studied within a single imaging session, without needing to reconfigure the system or resort to using multiple instruments.



Multi-spectral phase calibration of a 40µm polystyrene sphere: Depicting: A) a raw phase maps of a 40µm diameter polystyrene sphere, B) the residual after numerical fitting of this raw data, and C) a cross-section comparing the data and analytical fitting

Precision is everything. WARP is a quantitative characterization method and as such every Z1 microscope is subject to rigorous qualification and calibration processes:

- Spatial resolution is measured using Fourier Ring Correlation[4] based on a calibrated standardised test sample. The system magnification is then calibrated based on this measurement.
- Spectral resolution is measured via a second calibrated standardized testing sample to ensure the illumination and sampling wavelengths are consistent, and to calibrate the phase measurements to these measured wavelengths (rather than just the assumed wavelengths).
- Phase resolution is measured using calibrated polymer microspheres with a known and consistent refractive index. The spheres are quantitatively fit and the entire imaging system qualified based on the fitting residuals.

These testing results are contained within a calibration report distributed with every new Z1, guaranteeing accuracy, precision, repeatability and traceability.

References:

1. H. Simons, M. Beltran, Light-field imaging based on tilt-aberration. European Patent 23708404.1A (2023)
2. Y. Park et al, Quantitative phase imaging in biomedicine, Nature Photonics **12**, 578-89 (2018)
3. P.M. McCall et al., Nature Chemistry (2025)
4. B. Rieger et al., Optics Express **32**, 12, 21767-82 (2024)

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