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RPPR Final Report
as of 02-Jan-2019

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Major Goals: In short, this project addresses the inverse problem in electromagnetic scattering, and the work conducted constitutes a form of its "solution." Using digital holography, the goals of this project are to complete several experiments intended to image micron-sized aerosol particles in situ while also measuring scattering observables, including the scattering pattern, extinction cross section, and the Stokes parameters around the backward direction. The imaging aspect of this work could have substantial value as a front-end discriminator on single-particle analyzers, which is a highly desirable capability for WMD/BW detection. More broadly, the ability to unambiguously correlate a particle's image with, e.g., its scattering pattern, is the first of its kind and will enable the validation and improvement of existing scattering-only methods developed by others in this field. The specific goals are as follows:

1) Single-particle extinction measurement: The first phase of work involves demonstrating that the single-particle extinction cross section, Cext, can be extracted from a measured digital contrast hologram. The work begins with spherical calibration-particles where the extracted Cext can be directly compared to Mie theory. Once this validation step is completed, the study is extended to particles of increasingly more complex morphology.

2) Scattering pattern extraction: A concept proposed to extract far-field scattering patterns is tested. The effort will begin with spherical calibration particles to enable direct comparison of the patterns to Mie theory for validation purposes. Next is an effort to perform the pattern extraction on complex shaped particles and compare to studies in the literature where, e.g., forward-scattering measurements have attempted to size such particles.

3) Backscatter polarimetry: An experiment will be undertaken to measure the polarization state (Stokes parameters) of the light backscattered by a particle simultaneous with the holographic imaging. Again, the study will begin with calibration particles to facilitate a direct comparison with the Stokes parameters from Mie theory. Next, the study will consider aggregate, mineral dust, and urban aerosol particles. Specific focus will be given to aggregate particles like BG clusters to establish whether the technique can differentiate between cluster and solid nonspherical particles as predicted. This phase will conclude with all the characterization concepts (extinction, scattering pattern, and polarimetry) implemented simultaneously. The goal here is twofold: First, to investigate what new features of a complex particle can be resolved as compared to existing scattering-only techniques. Second, to explore the diagnostic potential of these simultaneous measurements to differentiate between particle classes of interest in BW-agent detection, e.g., biological vs. inorganic.

Accomplishments: 1) Major Activities: From 2015-2016, the first of several planned experiments was completed demonstrating the ability to simultaneously measure the light-scattering pattern and the holographic image of a single, immobile microparticle. This effort relates to goal 2. Yet, an important next step was to demonstrate that the concept would also work for free-flowing aerosol particles. During 2016-2017, an experiment was constructed to show this ability and was successful on the full range of aerosol particles intended. A publication resulted in Nature Scientific Reports. We also developed a method to render 3D forms of single particles from their holograms. This work was mostly successful and lead to a publication. The 3D imaging showed a degree of geometrical perturbation from an unknown origin. A large-scale super-computer based computational study was completed with the Mississippi State University High Performance Computing facility to show that the idea to extract extinction cross sections from a hologram is not limited to spherical particles only. This effort was remarkably successful showing that the cross section for particles could be consistently extracted from the holograms with less than 10% error (and often <5% error) over nearly five orders of magnitude in the cross section value. Moreover, the extraction concept was validated through use of laboratory measured holograms. The work resulted in several publications. I also moved from MSU to KSU in 2016, re-established the laboratory, and began training new students and two postdocs.

2) Specific Objectives: Regarding the initial laboratory experiments, the primary objective was to show proof-of-principle results demonstrating that a color CCD sensor, spatial filtering, and multi-wavelength illumination can be used to image a stationary, fixed particle while also measuring the scattering pattern. For short, I will call this experiment “color holography” in the following. We validated the concept using spherical calibration-particles with comparison to Mie theory. Following this, a broader selection of particles were studied that were more representative of coarse-mode, i.e., super-micron, particles. Next, the same method was applied to free-flowing aerosol particle to show the intended ability for in situ aerosol characterization. These efforts were completed in 2018. The computational study on extinction cross-section extraction was ultimately intended to motivate an experiment to prove its validity, which was finished in late 2017.

3) Significant Results: The color holography experiment was a success for both stationary, fixed particles and truly free-flowing aerosols. The important result boils down to what one could call a laboratory-based solution to the long-standing “inverse problem” in electromagnetic scattering. A negative outcome was that the color sensor chosen for the experiment did not have sufficient dynamic range to yield optimum-quality holographic images and several options to correct this were identified. The extinction cross-section extraction study proves the new ability to extract cross section directly from the hologram. That is significant because it relieves one from the need to make additional measurements to obtain the cross section, i.e., is automatically provided by the hologram yielding the particle image. As such, instrumentation designed to sense or characterize super-micron aerosol particles may now be much more compact and simple than would have been the case previously.

4) Key Outcomes: The key outcome is the first-ever laboratory-based solution to the inverse problem on free-flowing aerosol particles, which satisfies the intent of the original proposal. This is an important advance in the field as evidenced by the interest it has received at scientific meetings and the Nat. Sci. Rep. publication. There is now a wide scope of work that this achievement has opened-up and we hope to pursue this in future work. The computational groundwork for goal 1 – cross section extraction - has been completed and validated experimentally with positive outcomes.

Training Opportunities: A graduate student at Mississippi State University, Dr. Nava Subedi, was supported in this award period. Nava gained experience in optical physics through assisting with the experimental set-up and execution of the color holography experiment. Dr. Subedi graduated with his Ph.D. through this support. Another graduate student, Mr. Peter Anderson, was also supported and trained in the same skills as Dr. Subedi.

Results Dissemination: Nine publications resulted form this project and many presentations were given at national and international scientific meetings and university seminars. These publications and presentations were the main route for dissemination of this work. Please see the products section for a list.

Honors and Awards: PI Dr. Matthew Berg was named a Senior Member of the Optical Society of America this year. Research stemming from this project was featured as a Quick Study in the March 2018 issue of the Physics Today magazine.

Protocol Activity Status:

Technology Transfer: A patent disclosure was presented to the Inventions Evaluation Committee at Army RDE Comm titled," Methods and Apparatuses for Contact-Free Holographic Imaging of Aerosol Particles." To my knowledge, it remains under evaluation. I have an ongoing collaboration with Dr. Somnath Sengupta from Energetics Technology Center, Inc., which is an Army contractor tasked with finding licensees for existing Army patents. This effort relates to a 2014 Army-owned patent where I was a co-inventor, but has much technical overlap with this award's research.

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Peter Anderson
Person Months Worked: 12.00 **Funding Support:**
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Other Collaborators:

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Authors: Nava Subedi
Acknowledged Federal Support: **Y**

WEBSITES:

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Date Received: 16-Aug-2017
Title: Berg Research at Kansas State University
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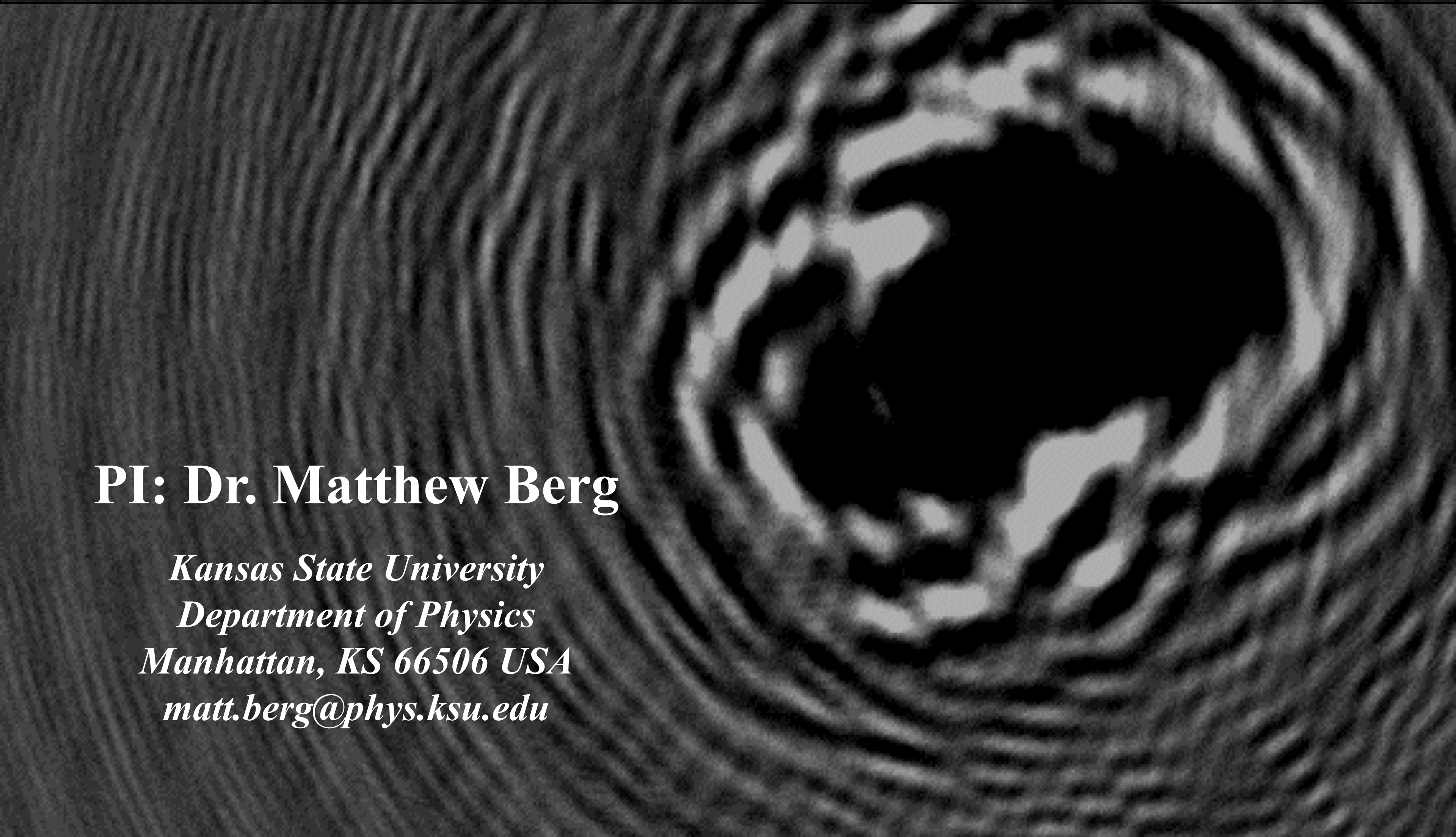
RPPR Final Report
as of 02-Jan-2019

Extracting Scattering Observables from Digital Holograms: Application to Aerosol Particle Characterization



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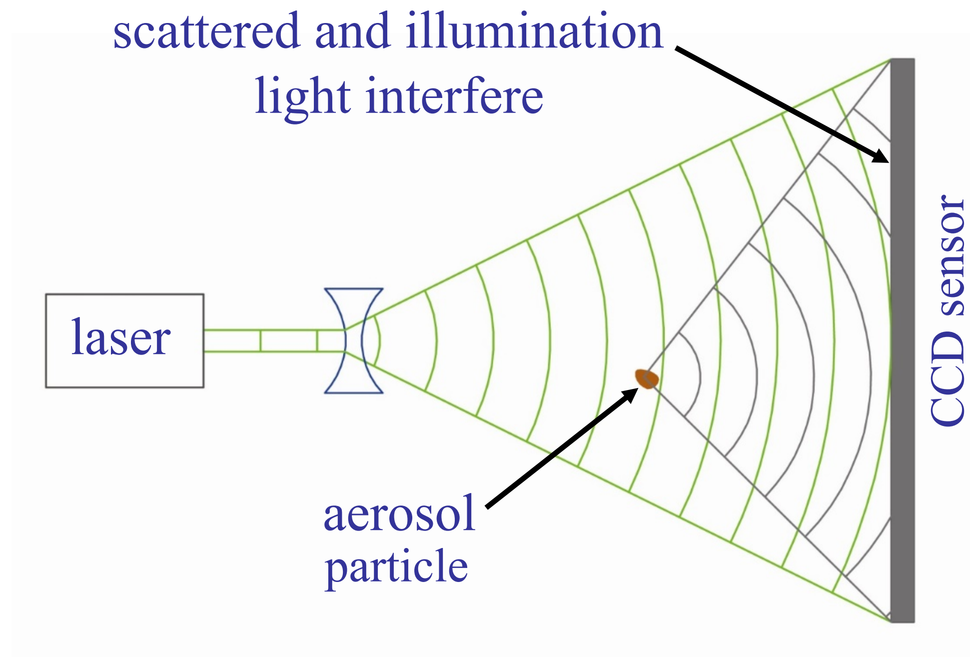
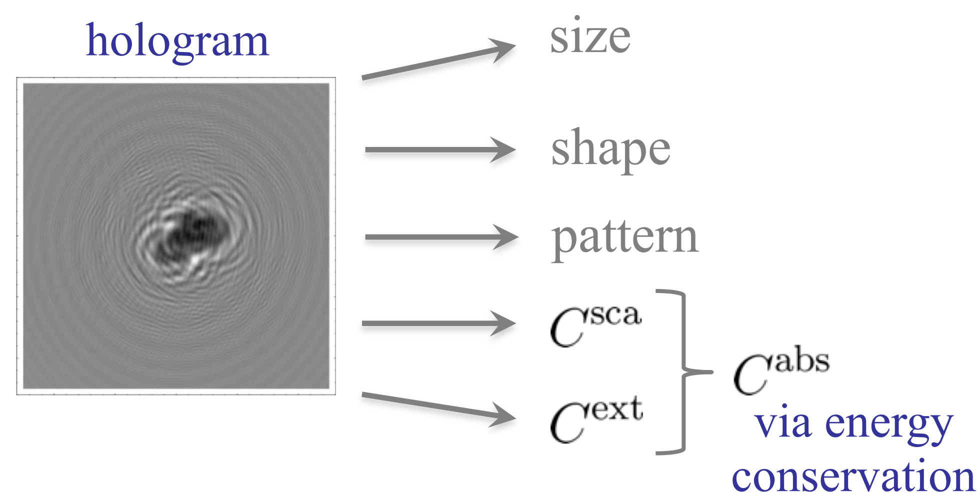
Concept Overview

- An aerosol particle is illuminated by a triggered optical pulse, producing a hologram on a CCD sensor.



- Objective: Extract particle shape, size, scattering pattern, and optical cross sections from measured hologram.



Approach

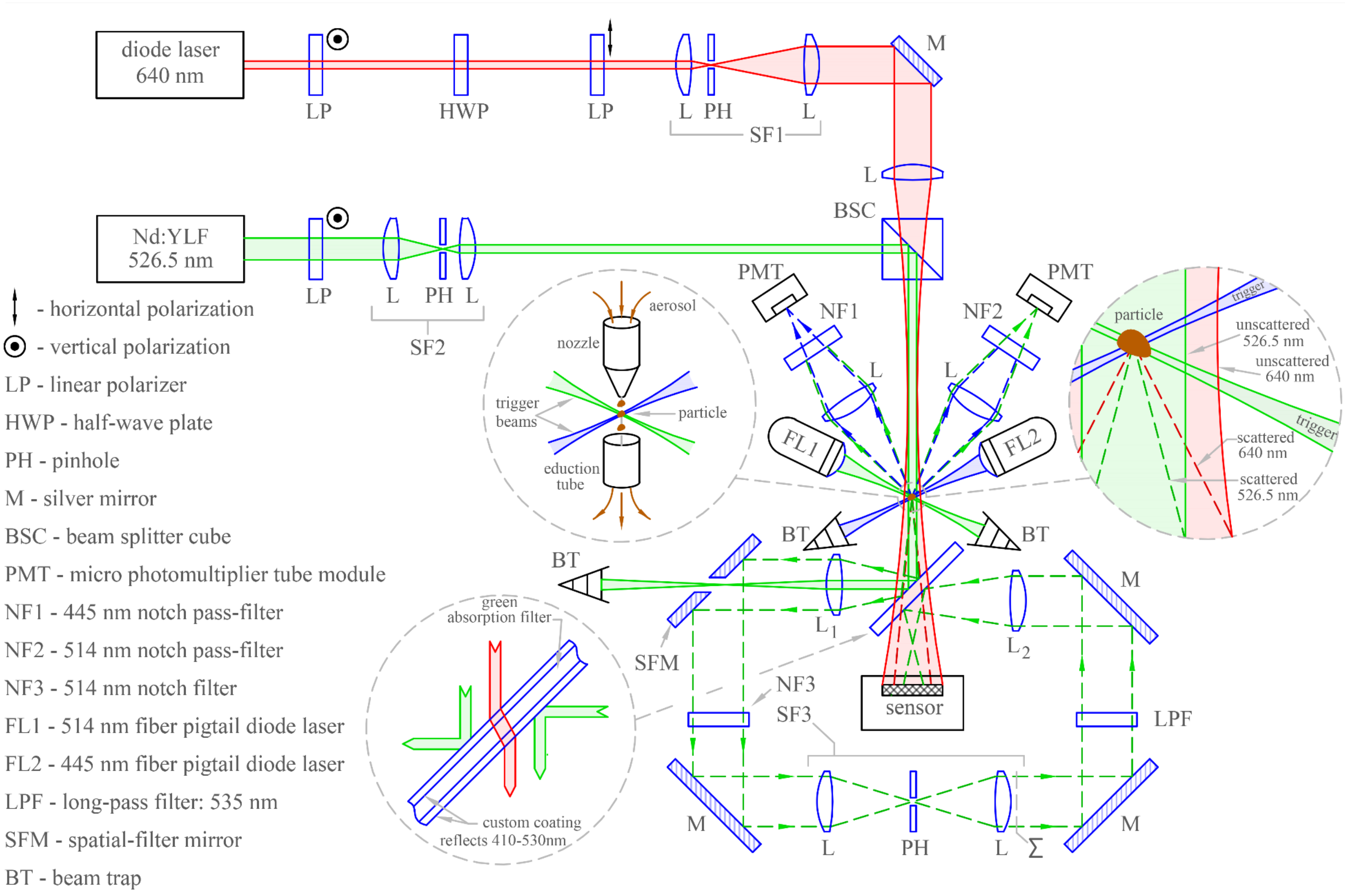
- Employ crossed-beam optical trigger to sense presence of aerosol particles free-flowing in a sample stream.

- Trigger used to queue two laser pulses at different wavelengths, "red" (640 nm) and "green" (526.5 nm), which illuminate particle.

- Color CCD sensor records hologram in red channel and 2D scattering pattern in green channel *simultaneously*.

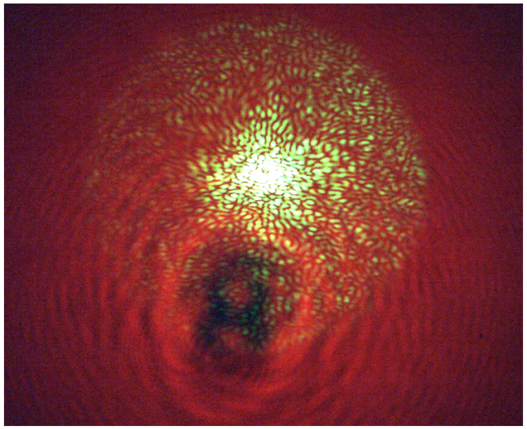
- From hologram, particle shape and size is rendered.

Proof of Principle Demonstration



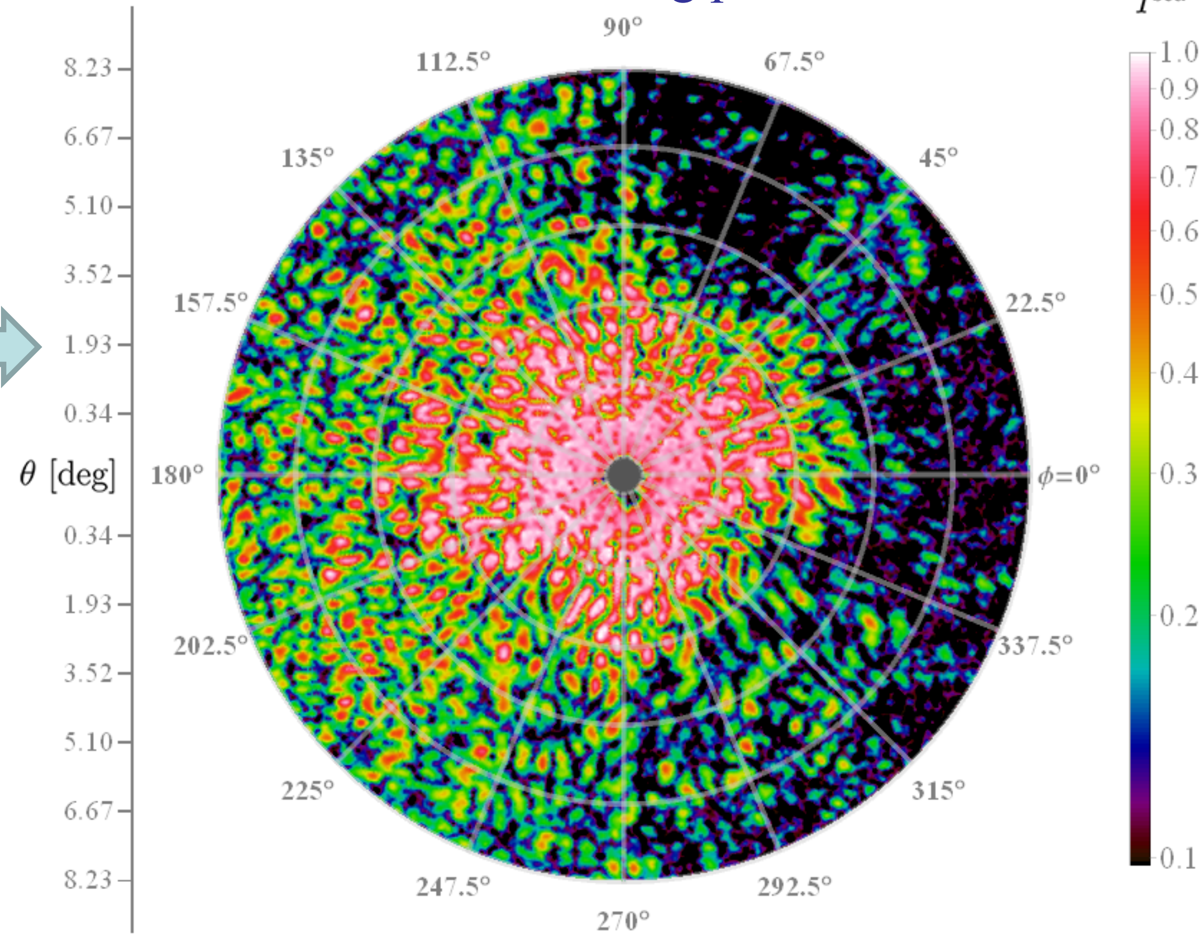
Initial Results

raw sensor data



particle image

2D scattering pattern



Particle shape and size can be unambiguously associated with scattering pattern: solves classic inverse problem w.r.t. shape analysis.