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14. ABSTRACT This final report covers the research activities supported by grant 59999-EV-YIP. In addition to launching the PI's new research program at MSU, three graduate and five undergraduate students were supported, nine peer-reviewed journal articles were published, and 20 presentations at professional meetings were given. Several major research discoveries were made including a relationship between an aerosol particle's hologram and its extinction cross section, and a computational demonstration that holographic interferometry can resolve aerosol particle size resolution.					
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Report Title

Final Report: Digital Holographic Interferometry for Airborne Particle Characterization

ABSTRACT

This final report covers the research activities supported by grant 59999-EV-YIP. In addition to launching the PI's new research program at MSU, three graduate and five undergraduate students were supported, nine peer-reviewed journal articles were published, and 20 presentations at professional meetings were given. Several major research discoveries were made including a relationship between an aerosol particle's hologram and its extinction cross section, and a computational demonstration that holographic interferometry can resolve aerosol particle size evolution.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Talk: A new method to measure the extinction cross section using digital holography, American Association for Aerosol Research, Orlando, FL (2014).
2. Invited talk: Electromagnetic Scattering by Particles: Applications in Atmospheric and Energy Science, Center d'Energétique et de Thermique de Lyon, Lyon, France (2014).
3. Talk: Particle characterization with digital holography, 10th International Conference on Laser-Light and Interactions With Particles, Marseille, France (2014).
4. Invited talk: Measuring the extinction cross section using digital holography, Asia Oceania Geosciences Society meeting, Sapporo, Japan, 2014.
5. Talk: Holographic Interferometry and polarimetry for aerosol particle characterization, Bioaerosols: Characterization and Environmental Impact, Austin, TX (2014) [organizer and conference chair].
6. Invited talk: Holographic Interferometry and polarimetry for aerosol particle characterization, Optical Characterization of Atmospheric Aerosols workshop, Smolenice, Slovak Republic (2013).
7. Poster: Digital Holographic Imaging of Aerosol Particles In-Flight, American Association for Aerosol Research, Portland, OR (2013).
8. Invited talk: A new concept for single-particle material characterization, International Symposium on Atmospheric Light Scattering and Remote Sensing, Nagoya, Japan (2013) [session chair].
9. Talk: A new concept for single-particle material characterization, Electromagnetic & Light Scattering XIV, Lille, France (2013).
10. Invited seminar speaker: Digital holographic imaging of aerosol particles in flight, Texas A&M University, College Station, TX (2013).
11. Poster: Particle-Assisted light concentration for solar concentration, Optical Society of America; Optics and Photonics Congress on Energy and the Environment, Eindhoven, The Netherlands (2012).
12. Poster: Power-law patterns in electromagnetic scattering for nonspherical particles, American Association for Aerosol Research, Minneapolis, MN (2012).
13. Talk: Electromagnetic scattering from nonspherical particles, Mississippi State University, Graduate Student Physics Association seminar (2011).
14. Invited talk: Digital holographic imaging of aerosol particles in flight, U.S. Naval Research Laboratory, Washington, D.C. (2011).
15. Talk: The cause of characteristic lengths in scattering curves, Electromagnetic & Light Scattering XIII, Taormina, Italy (2011) [Young Scientist Award].
16. Invited talk: Digital holographic Imaging of aerosol particles in flight, American Association for Aerosol Research meeting, Orlando, FL (2011).
17. Poster: Digital holographic imaging of aerosol particles in-flight, American Association for Aerosol Research meeting, Portland, OR (2011).
18. Talk: Digital holographic imaging of aerosol particles in-flight, Mississippi State University, Society of Physics Students seminar (2011).
19. Poster: Digital holographic imaging of aerosol particles in flight, Chemical and Biological Defense Science & Technology meeting, Orlando, FL (2010).
20. Talk: Reflection symmetry of a sphere's internal field and its consequences on scattering: Behavior of the Stokes parameters, NATO Advanced Science Institute on Special Detection Technique (Polarimetry) and Remote Sensing, Kyiv, Ukraine (2010).

Number of Presentations: 20.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

03/19/2015 12.00 R. Ceolato, N. Riviere, M. J. Berg, B. Biscans. Electromagnetic Scattering from Aggregates Embedded in Absorbing Media, Progress In Electromagnetics Research Symposium Proceedings. , . : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
03/19/2015	5.00 Matthew J. Berg, Nava R. Subedi. Holographic Interferometry for Aerosol Particle Characterization, Journal of Quantitative Spectroscopy & Radiative Transfer (04 2014)
03/19/2015	6.00 Jing Wen, Matthew J. Berg, Matthew Steed. Scattering-based solar light collector, Journal of Renewable ans Sustainable Energy (01 2014)
03/19/2015	7.00 Matthew J. Berg, Christopher M. Sorensen. Internal fields of soot fractal aggregates , Journal of the Optical Society of America A (05 2013)
03/19/2015	10.00 Matthew J. Berg, Gorden Videen. Concepts in Electromagnetic Scattering for Particulate-Systems Characterization, Journal of Quantitative Spectroscopy & Radiative Transfer (04 2013)
03/19/2015	11.00 Romain Ceolato, Matthew J. Berg, Nicolas Riviere. Spectral and angular light-scattering from silica fractal aggregates, Journal of Quantitative Spectroscopy & Radiative Transfer (11 2012)
03/19/2015	8.00 Nava R. Subedi, Nicholas B. Fowler, Matthew J. Berg. Backscatter digital holography of microparticles, Optics Express (03 2013)
03/19/2015	9.00 Matthew J. Berg. Power-law patterns in electromagnetic scattering: A selected review and recent progress, Journal of Quantitative Spectroscopy & Radiative Transfer (01 2012)
08/28/2014	3.00 Matthew J. Berg, Nava Subedi. Holographic interferometry for aerosol particle characterization, Journal of Quantitative Spectroscopy and Radiative Transfer (04 2014)
08/28/2014	4.00 Nava R. Subedi, Peter A. Anderson, Matthew J. Berg, Nicholas B. Fowler. Using holography to measure extinction, Optics Letters (accepted) (05 2014)
TOTAL:	9

Number of Manuscripts:

Books

Received Book

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Young Scientist Award, presented by the Journal of Quantitative Spectroscopy & Radiative Transfer at the Electromagnetic & Light Scattering XIII conference in Taormina, Italy (2011).

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Nava Subedi	0.33	
Jehan Seneviratne	0.33	
Jing Wen	0.33	
FTE Equivalent:	0.99	
Total Number:	3	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Matthew J. Berg	0.10	
FTE Equivalent:	0.10	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Paul White	1.00	Physics
Thomas Bunch	1.00	Computer Science
FTE Equivalent:	2.00	
Total Number:	2	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 5.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 4.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 1.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 4.00

Names of Personnel receiving masters degrees

<u>NAME</u>	
Nava Subedi	
Jehan Seneviratne	
Total Number:	2

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Visited Droplet Measurement Technologies, Inc. in Boulder, CO, to meet with staff scientists and engineers. The purpose of this meeting was to initiate a cooperative effort between DMT, Inc. and MSU to commercialize my recent patent through a proposal to the Department of Energy's SBIR/STTR program.

Final report:

DIGITAL HOLOGRAPHIC INTERFEROMETRY FOR AIRBORNE PARTICLE CHARACTERIZATION

Matthew J. Berg
Mississippi State University
Department of Physics & Astronomy

ABSTRACT

This final report covers the research activities supported by grant 59999-EV-YIP. In addition to launching the PI's new research program at MSU, three graduate and five undergraduate students were supported, nine peer-reviewed journal articles were published, and 20 presentations at professional meetings were given. Several major research discoveries were made including a relationship between an aerosol particle's hologram and its extinction cross section, and a computational demonstration that holographic interferometry can resolve aerosol particle size evolution.

LABORATORY INFRASTRUCTURE AND EDUCATIONAL ACHIEVEMENTS

The first major accomplishment of this work was to establish a new electromagnetic laboratory for the PI and launch his research program in holography applied to aerosol characterization. This was achieved through the Young Investigator Program (YIP) and supplements from the Defense University Research Instrumentation Program (DURIP) during the project's second term. Equipment obtained with this support includes, e.g., UV and visible diode-pumped Nd:YLF Q-switch lasers from Photonics Industries, an optics table, optical elements with associated hardware, electronic instrumentation, large-format CCD sensor, and a custom-made airtight aerosol cell, see Fig. 1. As the laboratory grew, the PI recruited graduate students to undertake research projects related to the YIP proposal. During the summer term, the PI also recruited and supported undergraduate students to work with the graduate students through yearly supplements from the Undergraduate Research Apprenticeship Program. Several of these students later joined the graduate program at MSU.

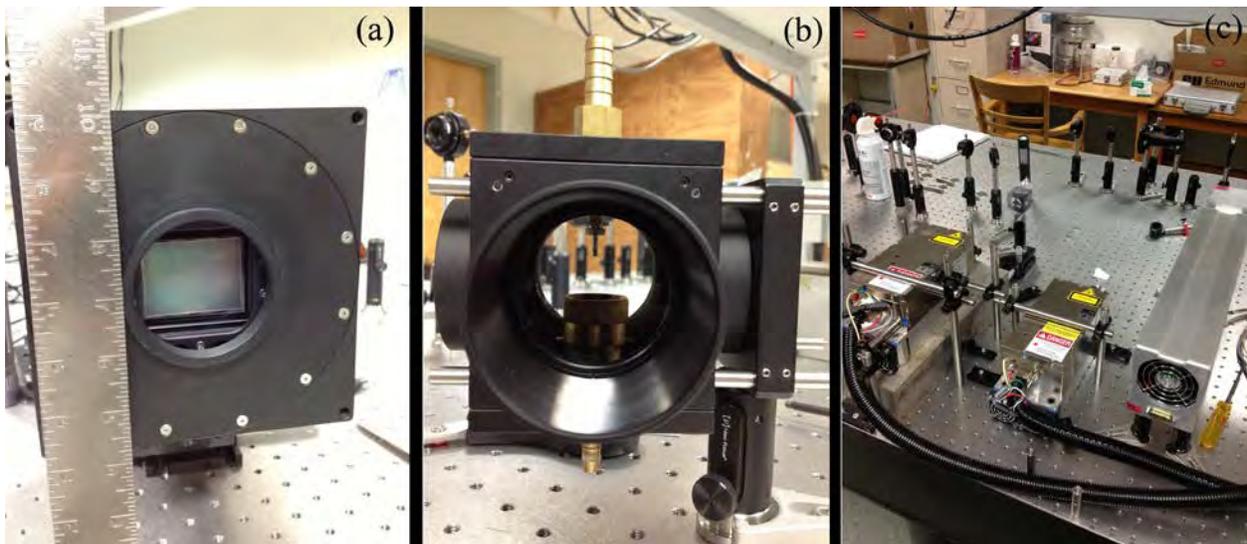


Figure 1: Large-format CCD sensor (a), air-tight aerosol cell (b), and the new lasers.

RESEARCH ACHIEVEMENTS

The research objectives of the original YIP proposal were pursued through multiple laboratory and computational investigations over the duration of the grant. Major achievements were reported in a total of nine peer-reviewed journal publications and described in presentations at national and international meetings and workshops, including twenty presentations in all. These presentations were highly valuable to the progression of the work as input and advice from the PI's colleagues in the community strongly affected how various technical problems were addressed. In what follows, a brief description of the major research achievements is given. More detailed descriptions can be found in the published journal articles.

BACKSCATTER DIGITAL HOLOGRAPHY

First developed was a method for digital holographic imaging of particles using their *backscattered* light, as opposed to the forward scattered light pursued previously. This effort was motivated by the potential practical applications for stand-off aerosol characterization. In short the optical arrangement, which was a Michelson-interferometer-like setup, used a beamsplitter to direct a particle's back scattered light onto a CCD sensor. Combination with the retro-reflected incident wave across the sensor produced a hologram, from which a particle image was obtained following the same computational process as with the forward scattering technique, see Fig. 2. This imaging was, overall, successful and resulted in a paper published in *Optics Express*. Another motivation for this work was to determine if such holograms could resolve the surface structure of *opaque* particles. Unfortunately, this question could not be answered at the time since the resolution of the images was too coarse to make such an assessment. However, the large-format CCD sensor obtained through DURIP support following these experiments could provide the needed resolution and such is part of ongoing work. Also notable here is that the work was partly performed by a former URAP student, Mr. Nicholas Fowler, who enjoyed his previous URAP experience enough to return for a second summer to help complete the work. His contribution was acknowledged in the publication.

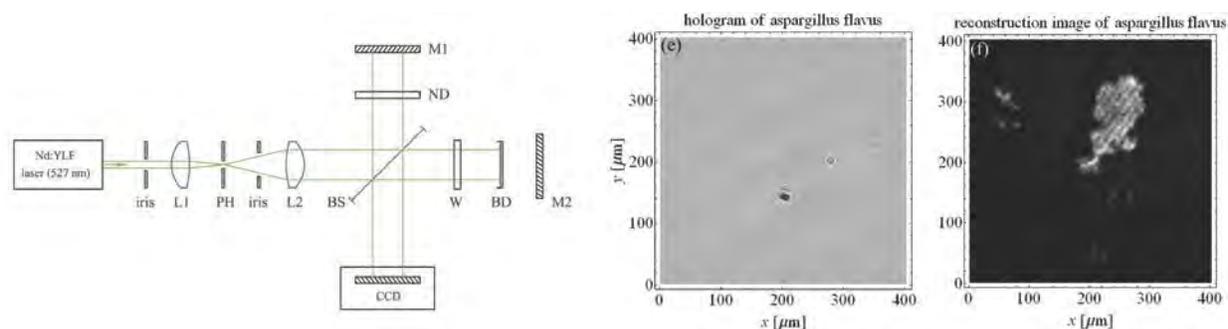


Figure 2: Diagram (left) of the experimental arrangement used to demonstrate backscatter digital holography of fixed microparticles. The images to the right show an example of a backscatter contrast hologram along with the reconstructed image. The particles in this case are *Aspergillus flavus* spore clusters.

HOLOGRAPHY INTERFEROMETRY

A major objective of this project was to investigate the possibility of holographic interferometry to infer material-dependent properties of aerosol particles. To this end, a computational study was first undertaken wherein the concept was tested for a spherical particle undergoing expansion. Initially, it was believed that the concept would readily work on aerosol particles in the laboratory and no serious computational work was planned. However, following multiple

discussions with colleagues at professional meetings, the feasibility of the concept became less obvious, and so, the computational study was justified.

First, to describe the concept, consider the illumination of a particle *twice* and allow the sensor to record a double exposure consisting of the two contrast holograms, I_1^{con} and I_2^{con} . For example, these illumination stages could be laser pulses timed to illuminate a particle at stages during its expansion or contraction. To better understand what this double-exposed hologram represents, suppose that the particle is actually in exactly the same physical state during each of these illuminations, i.e., has not changed in size. In this case, the holograms will be the same and application of the Fresnel-Kirchhoff (FK) diffraction integral will yield two overlapping, identical images. However, if the particle's state changes between the pulses, the holograms will then differ. Applying the FK integral in this case will yield two reconstructed waves, K_1 and K_2 , that differ in amplitude and *phase*. Thus, these waves will interfere, and the absolute square $|K_1 + K_2|^2$ will yield a particle image superimposed with interference fringes. The fringes are then a direct consequence of the change in the particle's state occurring between the first and second illumination.

To test this concept, an expanding spherical particle is considered. This permits the use of Mie theory to generate the *exact* scattered fields from which a contrast hologram can be produced. To do this, a simulation was developed in the C++ language following the Mie theory derivation outlined in the resulting *JQSRT* article. Verification of the code is done by comparing the far-field scattered intensity patterns for a variety of spheres of different size and refractive index to that produced by the widely used BHMIE code, which is also given in the paper. The simulation considers the particle with two sizes; R_1 and R_2 where $R_2 > R_1$ and the same refractive index $m = 1.33 + 0.05i$. Here, the scattered electric \mathbf{E}^{sca} and magnetic \mathbf{B}^{sca} fields are computed at each pixel in the hologram sensor, which resides in the particle's far-field zone. These fields are then superposed with the incident plane wave, \mathbf{E}^{inc} and \mathbf{B}^{inc} . From this, the time-averaged Poynting is calculated and the component directed *into* the sensor is assigned to each pixel. Thus, the two contrast holograms I_1^{con} and I_2^{con} are generated corresponding to the particle sizes, R_1 and R_2 , respectively. These holograms are then superposed to yield the final double-exposed hologram, $I_{\text{tot}}^{\text{con}}$. To this the FK integral is applied to render an image of the particle as $|K^{\text{tot}}|^2$. Figure 3 shows how a change in the particle size, i.e., ΔR , appears in the fringe structure in the cross section taken through the reconstructed.

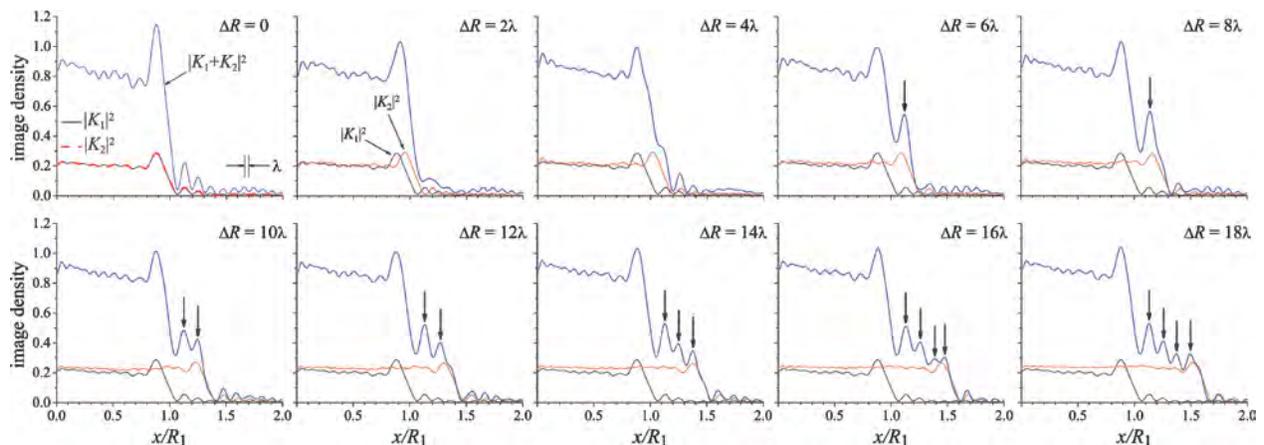


Figure 3: Evolution of the interference fringe-structure in the reconstructed image for an expanding particle.

Figure 4, however, shows how this change in particle size is expressed in the two-dimensional, silhouette-like reconstructed images. Here, the particle's two sizes are $R_1 = 27\lambda$ and $R_2 = 47\lambda$, where λ is the wavelength of the incident light. The first two columns in the figure display the contrast hologram for each state, I_1^{con} and I_2^{con} , along with their reconstructed images, shown below. As expected, the images for each state are silhouettes with radii R_1 and R_2 . For the state-2 reconstruction, the dashed white-outline denotes the size of the particle in state-1 for reference. Surrounding each of these silhouettes are faint rings. These are due to the out-of-focus twin image that is always present with the in-line geometry used. The last column in Fig. 4 shows the double-exposed hologram $I_{\text{tot}}^{\text{con}}$ and its image reconstruction, $|K^{\text{tot}}|^2$. One can see a prominent, dark inner-disk surrounded by an annular region with lighter fringes. Here, the dashed circles denote the R_1 and R_2 particle sizes, and thus, the width of the region between them corresponds to the change in particle's size $\Delta R = R_2 - R_1$.

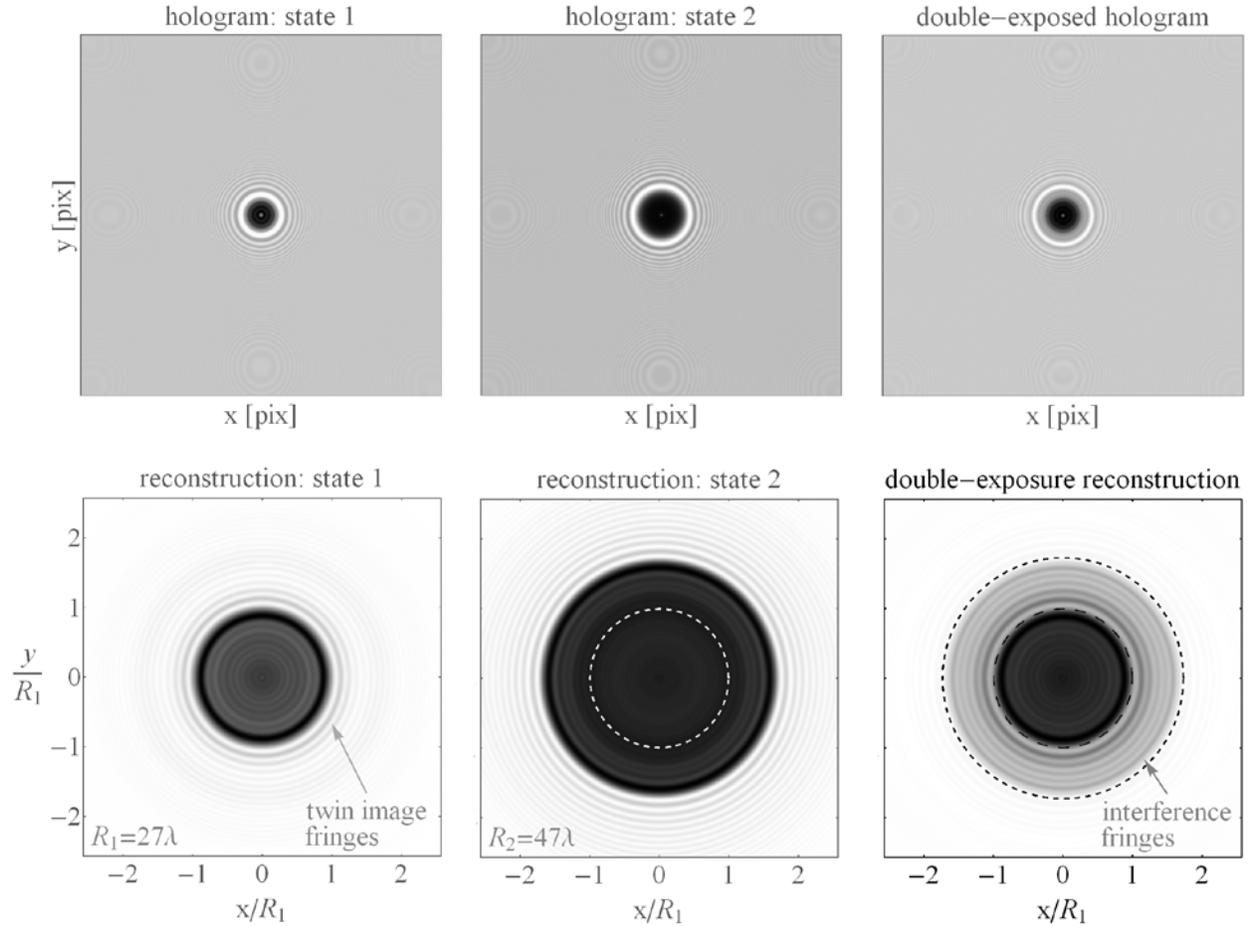


Figure 4: Demonstration of holographic interferometry for a single expanding particle. The top row shows, respectively, the contrast holograms for the particle in state-1 I_1^{con} , state-2 I_2^{con} , and the double-exposed hologram $I_{\text{tot}}^{\text{con}}$. The bottom row shows the corresponding reconstructed particle-images obtained by applying the FK integral. The particle's refractive index is $m = 1.33 + 0.05i$, and in state-1 has size $R_1 = 27\lambda$ while state-2 has size $R_2 = 47\lambda$.

As Fig. 1 demonstrates, the change in size of the expanding particle can be determined from either the number of interference fringes in the “overlap” region of the image or from the size of this region itself. Thus, this computational effort validates the basic concept proposed for this project and is reported in more detail in the paper.

EXTINCTION CROSS-SECTION EXTRACTION

Extinction is a ubiquitous phenomenon that describes the attenuation of light traversing a medium due to scattering and absorption, and the ability to accurately measure the extinction cross section C^{ext} is important in many applications, including aerosol characterization. An important new development in this project was to show that C^{ext} can be measured by recording the interference energy-flow due to a particle's scattered light interfering with the incident light across a detector's surface, i.e., from the hologram.

To present the concept, consider a single spherical particle in vacuum illuminated by a linearly polarized plane wave traveling in vacuum along the z -axis, which will approximate a collimated laser beam. To see how extinction comes about, Poynting's theorem is applied to the volume defined by a deformed spherical surface consisting of component surfaces S_1 and S_2 shown in Fig. 5 below.

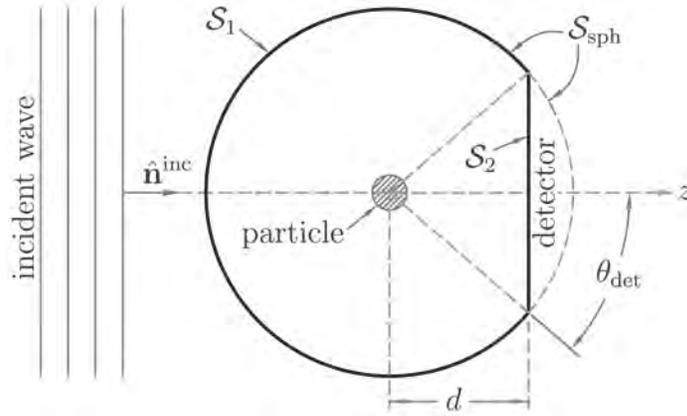


Figure 5: Sketch of the spherical surface S_{sph} and composite surface $S_1 \cup S_2$ in relation to the particle and incident wave. Here, S_2 is coincident with the surface of the detector used to record the particle's hologram.

Using the divergence theorem, the volume integral in Poynting's theorem can be transferred into surface integrals over S_1 and S_2 , giving

$$W^{\text{abs}} = - \left\{ \int_{S_1} \langle \mathbf{S} \rangle \cdot \hat{\mathbf{r}} da + \int_{S_2} \langle \mathbf{S} \rangle \cdot \hat{\mathbf{z}} da \right\}, \quad \text{Eq. (1)}$$

where W^{abs} is the power absorbed by the particle and $\langle \mathbf{S} \rangle$ is the time-averaged Poynting vector. From Eq. (1), the following quantities are defined:

$$I_0^{\text{det}} = \int_{S_2} \langle \mathbf{S}^{\text{inc}} \rangle \cdot \hat{\mathbf{z}} da \quad \text{and} \quad I^{\text{det}} = \int_{S_2} \langle \mathbf{S} \rangle \cdot \hat{\mathbf{z}} da, \quad \text{Eq. (2)}$$

which, respectively, represent the holograms received by the detector without and with the particle present. In Eq. (2), \mathbf{S}^{inc} is the energy flow of the incident wave. Taking the difference of these two measurements with Eq. (1) in mind gives

$$I_0^{\text{det}} - I^{\text{det}} = W^{\text{abs}} + \int_{S_1} \langle \mathbf{S}^{\text{ext}} \rangle \cdot \hat{\mathbf{r}} da, \quad \text{Eq. (3)}$$

where \mathbf{S}^{ext} is the energy flow due to the interference between the incident and scattered waves. Lastly, we define

$$C^{\text{ext}} = f(\theta_{\text{det}}) + \delta(\theta_{\text{det}}) \quad \text{Eq. (4)}$$

where

$$f(\theta_{\text{det}}) = \frac{1}{I_{\text{inc}}} [I_{\text{o}}^{\text{det}}(\theta_{\text{det}}) - I^{\text{det}}(\theta_{\text{det}})] \quad \text{Eq. (5)}$$

and

$$\delta(\theta_{\text{det}}) = \frac{1}{I_{\text{inc}}} \int_{S_1} \langle \mathbf{S}^{\text{ext}} \rangle \cdot \hat{\mathbf{r}} da \quad \text{Eq. (6)}$$

where I^{inc} is the incident light intensity and θ_{det} is the angular size of the integration surface S_1 on the detector.

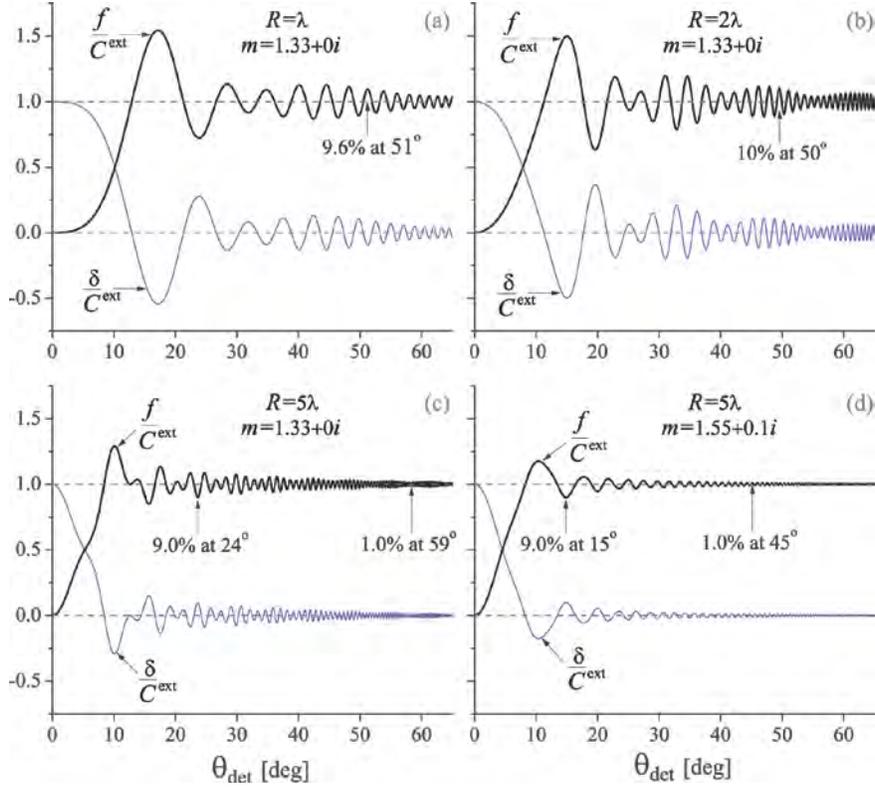


Figure 6: Behavior of the f and δ curves of Eqs. (5) and (6) as a function of θ_{det} . Plots (a)–(c) show the curves for nonabsorbing spheres with $m = 1.33 + 0i$ and $R = \lambda$, 2λ , and 5λ , respectively, whereas the sphere in plot (d) is absorbing with $m = 1.55 + 0.1i$ and $R = 5\lambda$. Also shown are the points along the f curve, after which its error in approximating C^{ext} drops below 10% (all plots) and 1% in plots (c) and (d).

What remains to be seen is exactly how this extinction behavior is related to holography. To explain this, consider a Gabor-type, or in-line, holographic arrangement intended to image a single particle. Here, a laser beam directly illuminates a position-sensitive detector facing the oncoming light, i.e., what is shown in Fig. 5. If a particle is introduced into the beam, the light scattered will interfere with the incident light and produce a fringe pattern across the detector. This interference pattern constitutes a digital hologram from which an image of the particle can be computationally reconstructed by applying the FK integral. The results in Fig. 6 show that by simply integrating the contrast hologram from the forward-direction out one can get an estimate for C^{ext} . The accuracy of the estimate will depend on the particle size to wavelength ratio and the angular size of the detector, but as shown in Fig. 6, this estimate can be within several-percent error from the true cross section value. Thus, from a single contrast-hologram measurement, it is possible to extract an unambiguous image of the particle *simultaneous* with a

measurement of its extinction cross section. Further detail of this technique are given in paper published in *Optics Letters*.

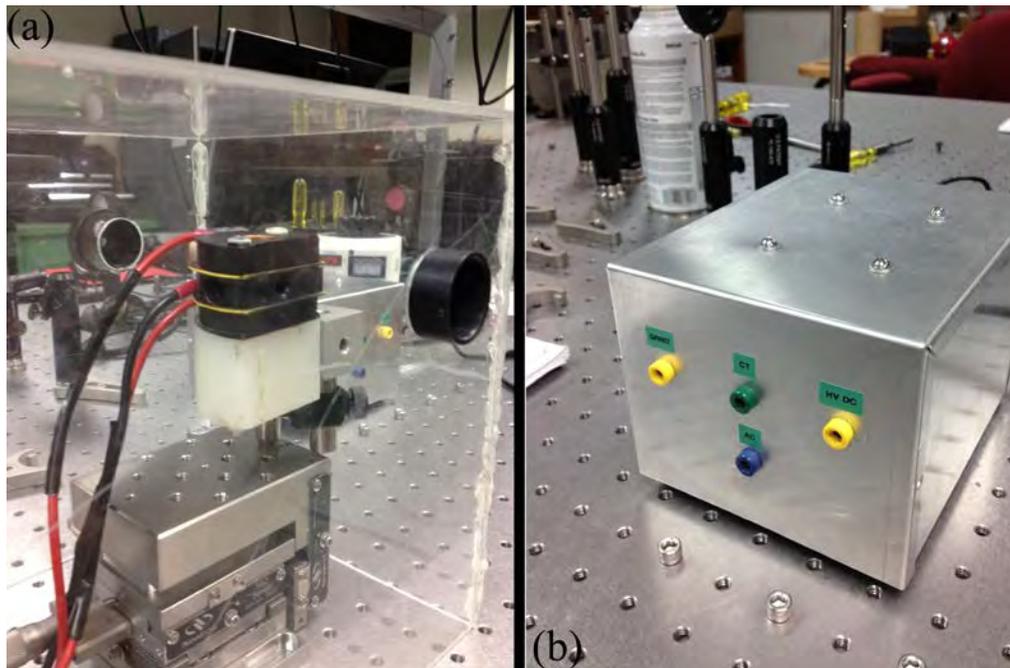


Figure 7: Spherical void electrodynamic levitator trap (a) and high-voltage power supply (b).

To test this concept in the laboratory, the students used a Spherical Void Electrodynamic Levitator (SVEL) to collect a digital hologram of a single glass microbeads suspended in the trap, see Fig. 7. Then, an integral of the hologram from the point corresponding to the optical center of the incident beam was performed to yield an estimate for the cross section of the trapped particle. The outcome of this work is still not clear due to the difficulty of trapping only a single particle in the SVEL. However, work with this experiment is ongoing and is being extended to other particle types that may be easier to handle. Once the experiment can be completed, a follow-up to the *Optics Letter* published on the concept will be produced that describes the experimental tests.