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13. ABSTRACT (Maximum 200 words)
The Colorado School of Mines (CSM) has developed a technique (called ballistic imaging) for single-shot imaging of the near-field primary breakup region of a diesel spray. Ballistic imaging is a non-intrusive optical measurement technique that produces line-of-sight integrated images. These images represent the underlying spray structure in spite of the droplet cloud which surrounds the interior of the spray. Single shot ballistic imaging relies on an ultra-fast optical “switch;” the optical switch is used to discriminate between ballistic and non-ballistic photons. Note that the ballistic photons contain the “image” information which appears as a range of extinction levels across the imaging beam. This technique has been applied to the breakup region of a high pressure turbulent water jet and to a high pressure diesel spray directed into the ambient environment. Results from the diesel injection indicate harmonic structure at the spray periphery and downstream voids that possibly are formed due to entrainment. Current work is focussed on using this technique with a non-regeneratively amplified laser system (i.e. with a significantly cheaper and more reliable laser system) and on applying the measurement to a diesel spray at diesel relevant conditions using the high temperature and pressure diesel spray facility at CSM.

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(1) Foreword - none 

(2) Table of Contents 

<table>
<thead>
<tr>
<th>Table of Contents</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure List</td>
<td>2</td>
</tr>
<tr>
<td>Statement of Problem Studied</td>
<td>3</td>
</tr>
<tr>
<td>Summary of Most Important Results</td>
<td>4</td>
</tr>
<tr>
<td>Important Results: Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Important Results: Overview of Results</td>
<td>5</td>
</tr>
<tr>
<td>Important Results: Background on Time-Gated Ballistic Imaging</td>
<td>6</td>
</tr>
<tr>
<td>Important Results: Discussion of Ballistic Imaging Results</td>
<td>9</td>
</tr>
<tr>
<td>Important Results: Recent Results: Ballistic Imaging with the Continuum Leopard and Image Processing</td>
<td>10</td>
</tr>
<tr>
<td>Important Results: Imaging of Breakup Dynamics</td>
<td>12</td>
</tr>
<tr>
<td>Important Results: Conclusions</td>
<td>13</td>
</tr>
<tr>
<td>Publication List</td>
<td>14</td>
</tr>
<tr>
<td>Scientific Personnel</td>
<td>15</td>
</tr>
<tr>
<td>Report of Inventions</td>
<td>15</td>
</tr>
<tr>
<td>Bibliography</td>
<td>15</td>
</tr>
</tbody>
</table>

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### Figure List

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ballistic image of the fully developed spray.</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Volume fraction measurements within a diesel spray.</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Geometric schematic of ballistic imaging</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Layout of OKE-switched ballistic imaging system at CSM.</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Ballistic images for early times in the spray.</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Ballistic images acquired with the Continuum leopard.</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>Image of the spray that does not include the time gate</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Zoomed in image of the diesel jet.</td>
<td>11</td>
</tr>
<tr>
<td>9</td>
<td>Images of the diesel jet at various distances from the injector tip.</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Droplet images with velocity vectors. Droplet diameter is on the order of 500 µm.</td>
<td>13</td>
</tr>
</tbody>
</table>
(4) Statement of the problem studied

Diesel sprays and their properties are critical to the emission, ignition, and efficiency performance of all diesel engines. Therefore, sophisticated diesel engine design and analysis models must use an accurate description of the spray and its performance. Unfortunately, the spray breakup process is poorly understood and is influenced by factors such as cavitation, liquid turbulence, and aerodynamic shear. Compounding the problem of uncertain spray breakup physics, is the difficulty of making measurements of the breakup process. These measurements are difficult due to the optical density of the region near the injector tip. A technique known as ballistic imaging has been applied within this work to produce images of the spray breakup region.

Ballistic imaging is a non-intrusive optical measurement technique capable of producing line-of-sight integrated images for highly scattering systems. At the Colorado School of Mines, this technique has been developed with a focus on investigations of the near-field spray-break-up region of diesel sprays. Single shot ballistic imaging relies on a combination of an ultra-fast laser pulse and an ultra-fast optical “switch;” the optical switch is used to discriminate between ballistic and non-ballistic photons and results to-date include diesel injection with injection pressures of 100 MPa (14,000 psi) through an on-axis, single orifice (155 microns) nozzle. These results indicate harmonic structure at the spray periphery and downstream voids that possibly are formed due to entrainment. In addition, we have demonstrated ballistic imaging with a significantly cheaper and more reliable laser system to enable dissemination of the measurement technique throughout the scientific community.
(5) Summary of Most Important Results

Introduction
Within this ARO-supported program, the Colorado School of Mines (CSM) has developed a technique for imaging the near-field, very high liquid volume fraction region in the primary breakup region of a diesel spray which is at the injector outlet. Experimental efforts to date have been for a realistic diesel injection system (a Lucas nozzle mounted in a Sturman Injection system) into the ambient atmosphere. The long-term goal is to perform these measurements under operating temperatures and pressures typical of a diesel engine for a realistic combusting spray. In parallel with this effort, CSM has continued to develop and implement infrared based droplet size and volume fractions for diesel sprays.

Further improvements in diesel engines will be achieved by development of more sophisticated computational design tools, and these must include high quality submodels for injection, breakup, and evaporation. Development of such generalized submodels requires a fundamental understanding of each process. Our goal has been (and is) to contribute to the understanding of the primary breakup zone by producing images of this flowfield under realistic conditions and by acquiring quantitative droplet size and volume fraction near the breakup region. CSM is uniquely positioned to produce the measurements at diesel-like conditions using a high pressure and temperature diesel spray combustion facility.

The team working on this project includes Prof. Mark Linne (specializing in ballistic imaging), Prof. Terry Parker (specializing in diesel sprays and scattering/extinction measurement in sprays as well as ballistic imaging), and three graduate students (M. Paciaroni, Ph.D. 2003, T.D. Hall, M.S. 2004, and E. Brooke Walters, Ph.D. candidate). The early part of the program (described in interim progress reports) focused upon optimization of single-shot ballistic imaging for transient diesel spray studies, reported on initial ballistic imaging results to a steady water jet and finally reported on a diesel spray issuing into a one atmosphere ambient surrounding. For the overall contract we can report the following accomplishments:

- Publications:
  - Six Archival Journal publications
  - Eight Conference Presentations
  - Four invited presentations

- Technical Accomplishments:
  - Developed a single shot ballistic imaging system based upon a laser system capable of a 1 mJ, 150 fs pulse
  - Applied this ballistic imaging system to a steady, high pressure water jet
  - Applied this ballistic imaging system to a realistic diesel injection system spraying into the ambient environment.
  - Augmented an existing diesel spray test facility to allow operation at conditions up to 30 atm. The overall facility capability is 30 atm., 1000 K, with a production-like diesel engine spray system.

• Work that is still in progress:
  - Optimization of the ballistic imaging system to a new, more powerful and reliable laser system (Continuum Leopard). This conversion required a complete redesign of the optical delivery system for both the image and gate pulse. We are pleased to report that we have acquired ballistic images of the diesel spray with this system and we believe that this is the first of its kind. The ballistic images acquired used a time gate that is dramatically shorter than the parent laser pulse.
  - Acquisition of ballistic images at conditions similar to those in an engine.

• Work in parallel with the ballistic imaging work at CSM has produced:
  - Two-dimensional “movies” of the diesel spray system.
  - An assessment of the multiple scattering interferences that ultimately limit the application of infrared scattering sizing methods to the spray outlet and breakup region.

Overview of Results

Figure 1 highlights results from this work and shows a ballistic image from the injector during the steady spray operation. Figure 2 illustrates infrared scattering results (“movie” results were also produced and can be found at http://egweb.mines.edu/T Parker-Primary/Diesel%20Spray%20Movies/diesel_spray.htm) and shows the spatially resolved volume fraction for a spray into the ambient environment as well as for a combusting spray. Note that these results start 15 mm from the injector tip. Multiple scattering analyses done by Prof. Parker indicate that accurate measurements can be performed within the combusting spray 10 mm from the spray tip. Regions closer to the spray tip are as yet unexplored with this technique.

As a long term goal, we will apply the ballistic imaging diagnostic to an optically accessible diesel engine simulator used for spray studies at CSM. Finally, we will apply infrared scattering measurements, with multiple scattering corrections, to produce quantitative droplet size and volume fraction measurements as close to the primary spray breakup zone as possible. There is thus a logical evolution from diagnostics development to application, with an emphasis upon the fluid mechanics and development of the spray.

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In what follows, we provide a brief description of ballistic imaging (for readers that are unfamiliar with the technique), and then present and discuss important results from the overall effort. Publications generated by this work have appropriately disseminated results to the scientific community.

**Background on Time-Gated Ballistic Imaging**

The very small amount of light transmitted through turbid material is separated into three components: ballistic, snake and diffuse. Upon exiting the medium, a resultant pulse is typically orders of magnitude longer in time and much weaker than the input pulse. A small group of photons, called “ballistic photons,” propagate directly through the material with no scattering. These photons traverse the shortest path and are the first to exit the material. The second group of photons, called “snake photons,” will be forward scattered minimally and remain within a small forward-directed solid angle. These photons will traverse a slightly longer path and will exit the material just after the ballistic photons. The remaining diffuse photons are scattered quite severely into a large solid angle, take the longest path, and are the last group of photons to exit the material. Figure 3 provides a schematic description of these photons.

Due to their undisturbed path, ballistic photons retain an undistorted image of structures that may be embedded within the turbid material. If used in a shadowgram arrangement, the ballistic photons can provide diffraction-limited imaging of these structures. In contrast, diffuse photons retain no memory of the structure within the material. If allowed to participate in the formation of an image, the various paths these multiply scattered photons take through the material will cause each image point they form to appear as if it came from an entirely different part of the object, and this will degrade resolution. Unfortunately, diffuse photons are the most numerous when light is transmitted through highly scattering media. The problem of obtaining a high-resolution image through highly scattering materials is thus a matter of separating and eliminating the diffuse light from the ballistic and snake light. This can be done using discrimination methods that make use of the properties that are retained by the ballistic and snake light, but are lost in multiple scattering events. The direction and polarization taken by
transmitted light, together with exit time, can help to segregate diffuse photons from the imaging photons. This is done in this work via spatial filtering (to select the light exiting at narrow scattering angles) and polarizers, together with time gating. In time gating, a very fast shutter (an optical Kerr effect (OKE) gate\textsuperscript{4}) is used to select just the leading edge containing ballistic and snake photons.

The fluid structures imaged by the ballistic photons fall within the geometric imaging domain. Under normal imaging (i.e. non-ballistic) circumstances, the smallest scale that would be observable would approach the diffraction limit (depending of course upon the optics used in the experiment). As described in more detail elsewhere,\textsuperscript{5} system development work has demonstrated that we can routinely achieve a single-frame spatial resolution around 40-50 µm in scattering environments characteristic of diesel sprays. Among the sprays we have studied, atomizing diesel fuel sprays are the most highly attenuating. This figure of merit (spatial resolution of 40-50 µm) is an approximation to the FWHM of the point spread function (PSF) for the entire optical system. The PSF is a continuous function, meaning that features smaller than the quoted FWHM do not suddenly become invisible. They are certainly detectable, but with reduced image contrast (i.e. with more blur). As features grow successively smaller, image contrast can become eroded to the point where one can comfortably label the feature as "not visible", but it is a continuous progression from what could be called clearly visible to what could be called invisible.

The time-gated ballistic imaging instrument used for initial experiments at CSM is shown in Figure 4. A 1-kHz repetition rate Spectra-Physics Spitfire Ti:Sapphire regenerative amplifier, seeded with a Spectra-Physics Tsunami Ti:Sapphire mode-locked laser, generates 80 fs, 1mJ pulses centered in wavelength at ~800 nm. The linearly polarized beam is split into OKE gating and imaging beams; 30% of the optical power is used as the imaging beam while the remaining power is used to create the OKE time gate. A DURIP award has been used to replace the regeneratively amplified Spectra-Physics laser

\textbf{Figure 3a. Geometric schematic of ballistic imaging.}  
\textbf{Figure 3b. Time-domain schematic of ballistic imaging with a short pulse.}


system with a single, turn key laser system. This new laser system is quite reliable and easy to operate. However, the change in lasers has required a complete redesign of the optics required for the measurement.

Referring to Fig. 4, the polarization state of the imaging beam is first linearized with a polarizer, because the OKE gate relies upon polarization switching, and then the polarization is rotated 45°. The imaging beam is then time delayed using an adjustable length delay arm that allows one to control the delay between the arrival of the switching and imaging pulses at the OKE gate, for optimum time gating. The imaging beam then passes through an optics train consisting of a telescope (with spatial filter) that controls the imaging beam size at the object, a system to relay the beam through the OKE switch, and a combined spatial filter/telescope for imaging onto a display screen. This optical system was designed and optimized using OSLO®, a commercial ray-trace code. By careful choice of available optics, we have ensured that the optical train itself is diffraction limited; there are no spurious aberrations or distortions introduced by the imaging optics themselves. The OKE gate depends on a pair of polarizers with orthogonal polarization states; the CS₂ Kerr cell is placed between the polarizers. When the switching beam is not present, the image beam passes through the Kerr cell with no change in polarization state and is blocked by the second polarizer. However, the applied electric field from the switching beam produces birefringence in the CS₂ which in turn rotates the polarization state of the image beam. Thus, the application of the switching beam produces a transient polarization rotation in the applied imaging beam. Careful timing of switching and image beam arrival along with a design that produces an effective ½ wave plate at full intensity for the switching beam produces a high speed optical “switch.” This OKE induced birefringence (or switching time) is limited by either the duration of the laser pulse or the molecular response time of the Kerr medium, whichever is longer. For work with the Continuum Leopard, careful relative timing between image and probe beams is required to produce an appropriately short time gate.

Past the OKE gate, the image is relayed to a display screen and the image is captured by a Roper

![Figure 4. Layout of OKE-switched ballistic imaging system at CSM.](image)
Scientific Cascade 650 CCD camera equipped with on-chip multiplication gain.

**Discussion of Ballistic Imaging Results**

The spray studied here was produced by a Sturman® diesel fuel injector, which has the capability for multiple injections in a single diesel combustion event. The results presented in this paper were acquired using an on axis, single hole (155 μm) in the injector nozzle. Both commercial diesel fuel and dodecane were evaluated, and the jet issued into still air at ambient conditions (0.8 atm. and approximately 300 K) and injection pressure was 100 MPa.

An example ballistic image of the diesel spray was previously introduced as Fig. 1 and the height of the displayed area depicts roughly 3.5 mm in the object plane. As one examines the images, it must be remembered that they are based upon extinction across the spray field; the ballistic aspect of the measurement simply removes multiply scattered light so that an “image” may be formed. In the image, dark areas represent regions of high extinction levels and light areas represent little or no extinction. The light areas clearly represent regions of gas; interpretation of the regions that are dark is more difficult due to the column integrated nature of the measurement and the fact that either liquid or high volume fraction regions of droplets can both be highly attenuating. The jet itself is quite distinct from the surrounding gas and illustrates a highly structured edge. Clearly the jet is mixing vigorously on the edges and shows features such as voids and periodic structures. One must be careful when interpreting the images because small variations in adjacent regions may simply be due to noise and/or diffraction effects. However, when somewhat organized structures appear at the jet edge and these structures are of significant scale that simple diffraction cannot explain them, one must conclude that the likelihood of the structures in the overall image simply being noise is quite small. The very near nozzle region of these images at this point in time cannot be interpreted due to the very large optical depth at the outlet so that the combination of noise, diffraction, and size make quantitative interpretation difficult.

![Figure 5. Ballistic images for early times in the spray. Times noted are the image acquisition times after start of injection.](image)
The development of the central jet region at the beginning of an injection event was observed by collecting a series of images of the region surrounding spray tip, for increasing times after the start of injection. Representative images are contained in Figure 5. The very early liquid stream develops a roll-up as it encounters the air, and in some cases this roll-up is penetrated by the oncoming liquid stream as it builds momentum.

These images show that we have proven the ability of OKE-gated ballistic imaging to acquire high-resolution, two-dimensional, single-shot images of the spray breakup region at the nozzle outlet of a transient atomizing diesel spray injected into ambient air. Voids are observed, as are spatially periodic structures. The jet itself appears to consist of a high momentum, high liquid volume fraction (or pure liquid) region that is vigorously mixing with the surrounding fluid.

**Recent Results: Ballistic imaging with the Continuum Leopard and Imaging processing**

Fig. 6 shows the initial time gated ballistic images taken with the Continuum Leopard laser system. Although we are still improving image quality in the system, these images are very promising. Features at the edge of the spray are apparent with the characteristic fluctuations and voids that are present in the time gated ballistic images typical of the images taken with the spectra physics laser system. Noise in these images is from a combination of the beam and the scattered light from the optical kerr cell. Improvements in beam quality are ongoing, scattered light from the kerr cell will be avoided when we move to a cell switched by the fundamental laser wavelength (1.06 μm instead of 532 nm), and intensity variations in the image will be partially removed by image processing which accounts for local beam intensity changes. Overall, we are quite pleased with this result as it demonstrates that the Continuum Leopard can be used in ballistic imaging experiments.

Further work with the continuum Leopard has focused on improving imaging performance and on image processing. This work has proceeded without the OKE time gate so the images are ballistic due to spatial rejection of non-ballistic photons; however, the temporal rejection of photons is not present in these images.

**Figure 6. Ballistic images acquired with the Continuum leopard. Note the periodic structures at the spray edge.**

10
Figure 7 is an image of the Sturman Injector spray showing approximately 7.5 mm of the spray; note that this image has been processed to remove the background signal and adjusted for the laser intensity fluctuations across the beam. Both intensity fluctuations and the camera background were quantified by acquiring multiple frames of data (typically 30). Background signal was acquired by operating the camera with the laser off; laser intensity variations were quantified by acquiring multiple images of the beam with the no spray. The color scale on this image is from 0 to 1.0 and is defined as the background subtracted signal at a pixel divided by the background subtracted signal at the same pixel when no spray is present (essentially the image shows the fraction of the original laser intensity that is present at a particular pixel). Image quality is limited for this system by the camera resolution (full frame 653x492 pixels). However, laser intensity fluctuations across the frame are significant and the software correction is working well, as evidenced by the relative uniformity of the field where no spray is present. A special note on the injector tip is in order; laser intensities were acquired with the injector in position. Thus, the signal within the injector tip is not terribly meaningful.

Figure 7. Image of the spray that does not include the time gate, note that resolution is limited by the camera, not by the optical system. The far right side of the image shows significant noise due to intensity falloff of the beam. The scale is fractional intensity with 1.0 being no attenuation of the laser and 0.0 total attenuation of the laser.

Figure 8. Zoomed in image of the diesel jet. Image on the left is fractional intensity. Image on the right has been filtered with 3x3 box filter. Scale is the fractional intensity of the laser.
Figure 8 shows a smaller field of view for the same spray. In this case the resolution is not limited by the camera array and the image is much sharper. As in other images, as the jet moves away from the orifice, undulations in the interface from the surrounding gas and the jet fluid become more pronounced. Fig. 9 shows a series of images similar to those in Fig. 8 but offset from the injector tip. The interface between jet fluid and surrounding gas becomes much more structured as the fluid moves downstream. The addition of a time gate should improve the image information in this interface region.

**Imaging of breakup dynamics**

In a recent collaboration with Air Force Labs, we have demonstrated that a ballistic imaging instrument can be modified to detect the velocity of both the liquid-gas interface of a spray core, and the velocity of primary droplets stripped from the core. Moreover, a simple extension would make it possible to provide images of the force vectors that act to break apart intact liquid features in sprays.

In order to demonstrate velocity imaging, a flow system used for liquid jet in cross-flow research was adapted by shutting off the gas flow and reducing the liquid flow. This generated a steady sequence of falling droplets. This enabled the 1-kHz laser system to illuminate droplet image pairs with sufficient time resolution between successive images. Sprays will require greater than 1-kHz repetition rates, but such laser systems and cameras are commercially available. The image pairs used for this
proof-of-concept were acquired using an interline transfer CCD capable of storing two images spaced as little as 2 µs apart. To extract velocity, pairs of ballistic images taken at times $t_1$ and $t_2$ are analyzed via noise reduction and correlation algorithms. An example image is shown in Figure 10.

If one could obtain at least three or four images taken at sufficiently short intervals, it would be possible to apply a similar method to mitigate uncertainties and to obtain acceleration vectors.

![Image 1](image1.jpg) ![Image 2](image2.jpg)

**Figure 10.** Droplet images with velocity vectors. Droplet diameter is on the order of 500 µm.

Laser systems with the appropriate speed are commercially available, and four images can be acquired with two double image cameras suitably aligned with each other. Other components of the instrument (e.g. the OKE gate) are not rate limiting.

From acceleration data, given some knowledge about the composition of the liquid and gas under observation, one could determine forces acting on the features tracked by our method. This capability can, for the first time, resolve unambiguously the dynamics that break apart the liquid core in the near field.

**Conclusions**

This ARO supported program has been focused on production of diagnostics capable of monitoring processes in diesel sprays. Ballistic imaging has been applied to a realistic diesel spray providing the first of their kind pictures of the break up region in a diesel jet. In addition, ballistic imaging has been demonstrated with a simple to use laser system (the Continuum Leopard); this facilitates the dissemination of the technique to other laboratories. Finally, the ballistic imaging instrument has been used to produce images of the breakup dynamics between droplets.
(6) Publication List

(a) Papers published in peer reviewed journals


(b) Papers published in conference proceedings

(c) Presentations not including a publication


(7) Scientific Personnel and degrees earned

Professor Mark Linne
Professor Terry Parker
Dr. Megan Paciaroni (Ph.D. degree earned during the project)
Mr. Tyler Hall (M.S. degree earned during the project)
Ms. E. Brooke Walters (currently in the Ph.D. program)

(8) Report of Inventions

None

(9) Bibliography

References included as footnotes within the text

(10) Appendices

None