Volumetric Imaging and Multi-Angle Illumination for Dense Sprays Characterization

Chad M. Sipperley¹*, William D. Bachalo¹

1: Artium Technologies, Inc., Sunnyvale, United States of America
*correspondent author: csipperley@artium.com

Abstract Characterization of dense sprays remains one of the challenges of sprays diagnostics. Beam extinction and multiple scattering plague traditional imaging techniques. Advanced techniques under development such as ballistic-and X-ray phase-contrast imaging rely on esoteric illumination sources and/or high-speed detectors. Because both techniques exhibit exceptionally large depths-of-field there is ambiguity in the interpretation of the results.

In this work the authors demonstrate an imaging strategy appropriate for dense sprays utilizing arrays of consumer-grade electronics for both illumination and sensing. Given the preliminary nature of the work the target in question was static but the method is agnostic to motion. The results are not a two-dimensional image of the target but rather a three-dimensional map of all light scattering sources in a volume. Using a novel illumination scheme that actually benefits from multiply-scattered light the authors demonstrate how an array of inexpensive imaging sensors can be utilized to provide microscopic resolution at every location in a macroscopic volume. In fact, under ideal conditions, the resolution of the output can far exceed that of any single sensor. With the current optical configuration this would result in an imaging resolution better than 39 µm in all three dimensions over the entire cylindrical target volume: 135 mm high by 135 mm across – or more than 32x10⁹ possible volume elements.

The authors evaluate the performance of this technique under varying levels of obscuration until an extinction fraction estimated at 99.8%. Though the spatial resolving power of the technique decreases with increasing extinction, the three-dimensional structure of the target was resolvable for all cases.

Introduction

The development of sprays imaging has been the utilization of ever faster illumination sources coupled with ever more capable cameras or sensors. These technological developments have been a response to the challenges of imaging dense sprays, spray formation regions, and sprays that exhibit substantial optical extinction. Initially strobe lamps were superseded by Nd:YAG lasers. But even the few nanoseconds pulse from these lasers is not nearly fast enough to be used as an illumination source for ballistic imaging. The pulse duration is not dictated by the need to “freeze” the motion of the flow field but rather as a requirement of the technique itself. Outside of the optical wavelength regime, X-ray imaging strategies incorporating both absorption tomography and phase-contrast imaging are allowing investigation of flows that would otherwise be optically inaccessible.

As imaging techniques become more advanced their illumination sources become more esoteric and rare – to the limiting case of utilizing a unique facility: the Advanced Photon Source at Argonne National Laboratory (Wang 2008). Along with each advanced source is an advanced sensor. Though the technology of these sources and sensors continues to improve, the relative scarcity of these devices limits the rate at which their performance per cost will increase as compared to, for instance, computer CPU’s or consumer-grade electronics.

In this work the authors propose a novel imaging system intended to characterize the most challenging of spray flows by leveraging the improvements in performance and cost of consumer-grade CMOS sensors most commonly found in cellular phones. Individually, such sensors cannot compete with a scientific-grade camera on any metric except size. However, the low unit cost of these sensors allows the incorporation of dozens if not hundreds of sensors into an imaging array. In aggregate, these sensors can provide the performance necessary for sprays imaging. The acceptable pulse duration of the illumination source will be dictated only by the acceptable motion blur of the target.
Current Techniques

Traditional shadowgraph, ballistic, and X-ray phase contrast imaging all exhibit large depths of field. The resultant image is a superposition of shadows or index of refraction gradients accumulated across the entire spray flow. For sprays that exhibit high optical extinction, the expectation is that most paths across the sprays will intersect with more than one droplet, ligament, or other fluid parcel. The overlapping of features from different locations along the path of the illumination makes interpretation of the results quite challenging (Linne 2012a,b).

Overlapped shadows are not the only challenge to shadowgraph imaging in sprays that exhibit high extinction. Such flows generally exhibit substantial multiple scattering – that is, photons may interact with several gas-liquid interfaces between the source and the imaging sensor. These photons may exit the spray flow at a substantial angle relative to the illumination path. The result is a reduction in the contrast ratio between shadows and background. At the limit of the technique, the background and the shadows will be indistinguishable. Ideally, ballistic imaging can avoid this reduction in contrast ratio. However, the complexity of the source and sensor preclude the use of inexpensive off-the-shelf electronics for this technique.

Dark Field Imaging

Since bright field imaging is incompatible with multiple scattering, dark field imaging must be used to achieve measurements in the densest possible sprays. Dark field imaging is a configuration such that illumination source(s) do not reach the imaging sensor(s) directly in the absence of a scattering source. Unfortunately, dark field imaging has historically had a limitation for imaging droplets, ligaments, and liquid sheets. Whereas a shadowgraph image of a droplet will be a circle outlining the drop, a dark field image will only show the glare spots – one or two bright spots much smaller than the drop. Similarly, ligaments and liquid sheets may appear in an image as thin lines or a series of arcs in a line. Even though the ligament is unbroken only the parts of the surface that have the proper curvature will direct light into the sensor.

One solution to the problem of imaging only the glare spots of the liquid phase is to illuminate the spray field from many possible angles. Each trajectory of the illuminating beams will correspond with its own set of glare spots. Taken as a whole it is possible to illuminate the entire surface of the droplet. Under lighting conditions such as these, secondary scattering of the illumination sources is actually beneficial. Light scattered between the source and the target volume may approach the target region on a new trajectory helping to “fill in” the lighting. Furthermore, the illumination source(s) will cover a large area necessitating focus to the measurement volume. As compared to collimated illumination where shadows may persist through the entire spray, the illumination strategy described here will “wash out” the shadows of objects in their beam paths. Furthermore, since any given region of space will be illuminated from many possible trajectories, a blockage of a portion of the light will not necessarily have a large impact on the scattered signal.

Reduced Depth of Field

The easiest way to reduce the impact of an object partially occluding the view of an imaging target is to reduce the depth of field. The impact of the occluding object will then be spread more diffusely over a larger area on the image. Unfortunately, the depth of field in a sprays application is dictated by the extent of the region of interest. The solution to this dilemma in the proposed imaging scheme is to image onto multiple sensors for a given camera lens by means of a series of partial reflectors. Each sensor is located a different distance from the principal plane of the lens. The result is that each sensor will be in sharp focus at a different location in space. The entire volume is then imaged in sharp focus on at least one sensor in the camera. Figure 1 schematically demonstrates the concept.

The authors believe it is practical to include a dozen or more inexpensive CMOS sensors into a multifocal plane camera. One might fear that splitting the light collected by the lens onto so many sensors will reduce the recorded light to an unworkable degree. However, depth of field is proportional to f/# while light gathering is inverse to the square of f/#. The amount of light incident on each sensor will actually increase by a factor equal to the number of sensors for each lens (neglecting optical losses).

Functionally, this multi-sensor camera is similar to a “lightfield” camera but there is an important difference: the multi-sensor camera will have more resolving power. A lightfield camera extracts depth information by placing a lens array on top of the imaging sensor. Each “lenslet” focuses its sub-array onto a slightly different region of space than the sub-array next to it. The result is a sensor with sharp-focus points distributed throughout a target volume. However, the total number of these points is less than- or equal to the resolution of the sensor (it may be “less than” if the sub-array images are arranged to overlap one another for
In the multi-sensor camera each individual sensor utilizes the full sensor resolution and there may be as many as a dozen or more sensors per camera. Furthermore, the distance between sharp focus fields can easily be adjusted in the multi-sensor camera simply by moving each sensor relative to the front lens. In a lightfield camera the lens array is fixed.

![Diagram showing the difference between a traditional imaging system and a multi-sensor camera system.](image)

**Figure 1.** A traditional imaging system utilizes a single sensor whose depth of field (DoF) covers the entire region of interest (top). A multi-sensor camera system (bottom) would place multiple sensors at varying distances from the lens ($s''$). The sharp focus distance for each sensor ($s'$) would then vary for each sensor according to the thin lens approximation $1/s' + 1/s'' = 1/f$ where $f$ is the effective focal length of the imaging lens. The reduced DoF of each sensor would be arranged such that every part of the volume is in sharp focus on at least one sensor. The depths of field are drawn without sharp edges as a reminder that the transition from in- to out-of-focus is not instantaneous.

**Volume Imaging Array**

Illuminating a region of a spray over a large solid angle and capturing that light with a multiple depth of field camera begins to form a complete imaging system. Such a system would have a shallow depth of field insofar as occlusion sources outside of the measurement point will rapidly defocus. It would even be possible to extract a limited amount of spatial location along the optical axis simply by recognizing which imaging plane was in sharpest focus for a given object. However, for the proposed imaging technique the multi-sensor camera is only one element of an array.

The final advantage of using an array of inexpensive sensors is the ability to collect at many different angles. Most traditional imaging techniques collect light over a small solid angle. However, light is scattered in all possible directions. Not capturing that light is a loss of information that could otherwise be used in a measurement.

There is an area of active research generically called computational photography that attempts to extract more information from a series of images than would ordinarily be contained in a single image. Commonly the distance along the optical axis of the objects in the image is of interest (the lightfield camera is the result of just such research). Of course, stereoscopic vision systems have been used for this purpose for quite some time. However, the resolving power increases as the number of views increases as well as the total angle between views. The most important aspect of this field for the purposes of this work is simply correlation of multiple images of every region of space in the interrogation region onto multiple sensors.

All of the necessary parts for the proposed imaging system have been described. An illumination source that covers a large solid angle will generate the dark field images on an array of multi-sensor cameras. Processing techniques from computational photography will extract the strength of the light scattered from every location in three-dimensional space within the interrogation region. Figure 2 is a conceptual layout of such an imaging array. The region of interest could be only a millimeter across or could encompass an entire spray flow. The size is simply determined by the focus of the lighting and the camera lenses.
Figure 2. Conceptual illustration of a volume imaging array. Large-angle illumination would be provided by the curved panels (white and blue) arranged to provide reflected and refracted light to each camera over many angles. The cameras are an array of multi-sensor cameras arranged in an arc to provide spatial resolution in three-space. The interrogation region would be in the center of the arcs and could range in size from 1mm across to an entire spray flow.

Proof-of-Concept Hardware

A fully-equipped imaging array with a pulsed illumination source is still only a proposed concept. Therefore, it was impossible to use such an array to determine its own performance. Instead, a static target was imaged from many different orientations at different focal positions in order to simulate the performance of such an array with a single camera. Continuous lighting was provided by approximately 1,200 LEDs arrayed to cover 60% of the possible solid angle around the target volume. In comparison, an f/3 lens would only fill about 0.7% of the solid angle around a target.

A volume imaging array can be configured to image microscopic or macroscopic regions depending on the magnifications of the lenses chosen. The greatest interest for the research sponsor was in imaging a region of 150 mm in characteristic dimension. To accommodate this a lens and camera combination capable of a maximum magnification of 0.11x was chosen resulting in a theoretical pixel resolution of 39 µm and a field of view of 202 mm x 135 mm. No single sensor in a volume array should image the entire volume within its depth of field. Instead, the lens was operated at its widest aperture (f/1.2) resulting in a depth of field of approximately 4.4 mm. However, operating a lens at a faster f/# generally degrades its sharpness. Due to this lens blur and the algorithms to interpolate across the different colors of the Bayer filter on the sensor, 100 µm resolution from this camera/lens combination was the targeted goal under ideal circumstances.

Imaging Target

There are four criteria that the imaging target required: 1) It should be three dimensional in nature. 2) It should be rigid such that rotating the target and imaging it from multiple angles would be equivalent to simultaneously imaging it with multiple cameras. 3) It should be translucent such that light can be both reflected and refracted – similar to liquids in air. 4) It should have details at length scales appropriate to evaluate the resolution of the technique.

To satisfy these criteria a frame holding an array of monofilament lines in tension was constructed. The line is 200 µm in diameter before tensioning. This is of the order of the size of ligaments in sprays and a reasonable target given the 39 µm (theoretical) to 100 µm (practical) resolving capability of the camera/lens combination. The twelve lines were strung from a knot near the top of the frame to a dozen holes in the bottom plate. The bottom holes were arranged in two concentric hexagonal patterns fitting circumscribed circles of 100 mm and 200 mm respectively. Additionally, the two hexagonal patterns were clocked 30 degrees with respect to one another. To these monofilament lines were affixed glass beads 187 µm in size. Figure 3 is
close-up image of the top portion of the imaging target. Note that this image was shot with a higher-magnification lens than was used for the bulk of the proof-of-concept phase.

![Close-up view of the top portion of the imaging target.](image)

**Figure 3.** Close-up view of the top portion of the imaging target. The target is composed of twelve 200µm diameter monofilament strands that spread from a single know into two hexagonal series of holes in the bottom plate. Affixed to the monofilament are 187µm glass beads. This photograph was taken at a higher magnification and with substantially larger depth-of-field than those used for the demonstration of the volumetric imaging technique. Additionally, this photograph is only showing approximately the top 9% of the imaging target.

### Multiple Depth of Field Camera

To simulate the performance of a camera with multiple sensors aligned at varying focal depths a traditional, single-sensor camera was traversed along its optical axis. While the distance from the camera to the focal plane never varied, the region in sharp focus traversed with the camera. This is not exactly the same effect as having multiple sensors behind a single lens. The demonstration configuration exhibits more parallax error than a single camera while each sensor for the multi-sensor camera would have a slightly different magnification. However, the two effects are similar in that objects displaced from the optical axis will image at varying points on the sensor as a function of the displacement from the image plane.

At each angular position of the stage, a series of photos were acquired at varying distances from the target. At the top of the region, the monofilament lines were sufficiently close to obscure those behind if oriented properly. Further down, a line in front cannot entirely block the line in back. Only one line (or part thereof) can be in sharp focus of any given image. The other would be a blur. By placing the resulting image at

![Schematic representation of the image acquisition process.](image)

**Figure 4.** Schematic representation of the image acquisition process. Each plot displays a series of images taken at varying distances from the centerline at a given angle relative to the target (grey on white). The transverse planes (white on black) represent the interpolated values between successive images for a given distance from the “injector.”
the location of the plane of sharp focus a volumetric image was created – interpolating between image planes. Each captured image is normal to the optical axis of the lens. However, interpolation between images can create an image plane normal to the spray axis. Figure 4(a) shows several images shot from a single angle (the stacked images) and two cross-sectional images formed by interpolation – one near the knot of the target and the other further down. Figure 4(b) shows another series of images acquired from a second angle.

Correlated Images

For any plane downstream from the “injector” a planar image may be created from each camera angle after applying the necessary coordinate transformations to convert the image location into the proper XYZ coordinate on the target. Utilizing only a single viewing angle, any given filament can be resolved only as a long streak (as in Figure 4). By correlating multiple images together a more accurate spatial representation of the target is possible. Figure 5(a) shows several such cross sections relative to the imaging target. Figure 5(b) displays details of areas of interest. The correlations in Figure 5(a) were calculated at 3 planes normal to the “injector axis.” Since each filament crosses at a steep angle to these planes there should be a circle of strong correlation at the location where the surface of the lines cut through the plane. The details in Figure 5(b) highlight these regions (as the correlation is near zero away from the lines).

Volume Images

The result of correlating multiple images together is a measure of the strength of the scattering source at that location in three-space. This scattering density function is more similar to CAT scan data than to a two-dimension image. As such, it is possible to compute the value of this density function everywhere in a volume. Figure 6(a) shows a selection of cross sections through the density function in a small region along one of the monofilament lines. By connecting the 50% (orange) contour from one slice to another one may make a surface of uniform density (an isosurface). This surface is shown in Figure 6(b). The bulge in the surface is clearly that of two beads affixed to the monofilament.

Recall that the monofilament is nominally 200 µm in diameter and the glass beads are 187 µm. Figure 6(c) is the subsection of one image corresponding to the surface plot in Figure 6(b). The theoretical resolution of the camera is 39 µm with a goal of a true resolving power of less than half that. As can be seen in this figure, the correlated density function has far more detail than the camera itself can generate in a single image. Correlating images from multiple angles has effectively oversampled the image to a higher resolution. Such a capability could prove valuable outside of dense spray imaging to any industrial application in which the detailed morphology of particle surfaces at microscopic scales is of interest. Of course, values for the correlation coefficient may be measured everywhere in the measurement volume. Figure 7 is a rendering of the 50% isosurface for just the top 25 mm of the “spray” target.

All of these data were acquired at 72 different angles (every 5 degrees) and at 33 different focus positions at each angle for a total of 2,376 separate images of the target. Likely, this number is far beyond the limit of diminishing returns for a volume imaging array. Determining what subset is acceptable for a given performance target would be critical to developing and deploying such an imaging array on a true spray flow.
Figure 6. High-resolution calculation of the scattering density in a small volume. (a) plots three slices through the volume while (b) plots a surface contour at the 50% correlation value between slices 30 microns apart. The monofilament line is clearly resolved as are two glass beads adhered to the surface of the line. (c) is a single image of this region of the target highlighting the raw resolution capability of the camera. Each square represents 39 μm of spatial resolution.

Figure 7. A rendering of the 50% isosurface for the top 25 mm of the 135 mm measurement region. The process in figure XXX is repeated over a larger 3D map. All twelve monofilament strands are resolved as are several of the beads and/or clusters of beads adhered to the surface. The target resolution for the technique was 100 μm. The strands are nominally 200 μm in diameter and the beads are 187 μm.
Obscuration, Extinction, and Multiple Scattering

Correlation of images from multiple angles and at varying focus locations reduces the influence of occlusions, obscuration and out-of-focus objects in the imaging system. No two sensors will receive the same noise sources. Obviously cameras aligned at different angles to the flow will be subject to different noise sources which will not correlate. However, even multiple sensors in the same camera will record the light scattered off the same particles somewhat differently as the distance from the focus plane will be different in each image. The varying degrees of blur for any out-of-focus object will only weakly correlate from one image to the next. However, at some point the error sources will overwhelm the correlated signal. Somewhere between the pristine results in Figures 5-7 and having no signal whatsoever there will be a degradation of the performance of the technique that will manifest itself in a reduction in the resolving power of the array.

Figure 8 is a cross section of the scattering density function at a location of only 2mm from the knot. At this location the monofilament strands are sufficiently close that they can occlude one another from the camera – exacerbated by the fact that the camera angles were chosen to ensure this overlap happened as often as possible. Unlike positions downstream, the lines are close enough that two strands in line can both be close to sharp focus (recall the depth of field is about 4 mm). There has been an obvious impact on the resolving power of the technique as compared to Figure 6. However, it is still possible to clearly discern the location of all twelve strands and to note that the symmetric, concentric hexagonal cross sections measured at lower locations are distorted this close to the knot. In this area the monofilament lines are much closer together than ten times their diameter – a common definition of the threshold between dilute and dense sprays.

![Figure 8.](image)

Figure 8. Plot of the correlation coefficients between images at a distance of 2 mm from the knot in the monofilament lines. In this region the resolving power of the technique is reduced (as compared to Figure 4) due to occlusion effects between lines. Rather than see a steep transition from high correlation to near zero, in the near-knot region of the target the volume in between the strands exhibits a relatively high correlation even though no scattering sources are located in this region. However, judicious selection of an isocontour value would still capture the cross sections of the 12 monofilament strands.

Beyond local obscuration one must also consider extinction and secondary scattering of the target signal. As mentioned earlier in the illumination section, multiple scattering actually benefits this technique. No matter how many times any given photon may interact with the spray it must have hit something last. That is where it will be imaged. However, if there is a substantial amount of spray between the target volume (or if the target volume itself is of sufficiently large extent) then light scattered off target fluid elements may be
lost to secondary scattering before reaching the cameras. The research sponsors were interested in conditions with an extinction of greater than 95%.

In order to simulate this extinction and multiple scattering, a series of stainless steel screens was placed in the region between the camera lens and the target. Each screen is approximately 70% transmissive and they were arranged to fill the void from the camera lens to the measurement volume. From eleven to seventeen screens were placed in series. By geometric arguments this is 98% to 99.8% extinction. To simulate the effect of additional secondary scattering, a series of lights were placed on these screens to overwhelm the signal from the target.

Figure 9 displays a cross section of the density function for varying levels of extinction. The resolving power of the technique clearly diminishes with extinction. Note that the outer 6 strings are more poorly resolved in all cases. Recall that the optical centerline is nearly aligned with the axis of rotation. The interior six strings never move far from the optical axis. The outer strings do pass in front of the optical axis for various rotation angles but travel twice as far from the axis at others. Light passing through a series of screens of finite thickness at an angle will attenuate slightly more than straight on. This is consistent with more poorly resolved exterior features of the target volume.

![Figure 9](image.png)

Figure 9. Impact of obscuration and multiple scattering on the resolving power of the volume imaging technique: Cross sections taken at $z = 20$ mm from the “injector.” (a) 0%, (b) 98%, (c) 99%, (d) 99.8%.
Finally, Figure 10 is a rendering of isosurface of the correlation coefficient for the top 25 mm of the target at 98% extinction. Though this case is not as smooth or as detailed as the unobscured rendering in Figure 7, the 12 individual monofilament lines and attached glass beads are all resolvable – at least in the “far field” region away from the knot and converged monofilament lines.

![98% Beam Extinction](image)

**Figure 10.** Rendering of the isosurface of the 50% correlation coefficient for the 98% obscuration case. Only the top 25 mm of the target are represented here but such data exists in the entire 135 mm long domain. Note that even at 98% obscuration (well beyond the 95% extinction goal of the research sponsors) the details of the target are well resolved.

### Illumination

All of the development reported here was done with continuous lighting provided by a large number of LEDs. For measurements in a true spray environment the lighting must pulse in order to prevent motion blur of the objects. One cannot expect to use the exposure control of consumer-grade CMOS cameras for this purpose. If one were to image a spray of the size demonstrated here with a maximum velocity of 100 m/s and an acceptable blur of 1 pixel’s resolution (39 µm) the illumination pulse need only be 390 ns or shorter. That’s well within the range of an array of pulsed LEDs. In fact, within the authors’ company an array of LEDs has been developed that can generate 20 ns pulses that reach steady-state intensities. At such short pulse durations the total energy output of each LED is miniscule. However, the need to have large arrays of LEDs to provide enough light for imaging purposes also meets the need to illuminate over a large solid angle. A fully-deployed volume imaging array may have over 100,000 LEDs.

One advantage of using consumer-grade CMOS sensors is the availability of sensors with Bayer filters attached. If one has an illumination array with individual red, green, and blue LEDs it would be possible to image the flow field three times over as short an interval as desired. This would allow for measurements of droplet, group, and surface velocities. Color separation combined with frame straddling could potentially yield 6 unique volume images of the spray to characterize the flow evolution over a short time period.

For microscopic imaging goals even 20 ns LED pulses may prove too long to freeze the motion. In such situations traditional pulsed lasers may satisfy the illumination requirements. Likely the laser(s) would be diverged through a negative lens and then reflected off a concave diffusing surface that redirects the light.
into the measurement volume. Nothing presented herein precludes the use of fast, high-power lasers. The only requirement is that the laser pulses be fast enough to freeze motion at the desired length scale.

**Conclusion**

The authors have proposed a novel technique to image dense sprays and demonstrated a proof-of-concept on a representative target. The proposed volumetric imaging technique utilizes a large number of inexpensive, consumer-grade CMOS sensors as well as large arrays of pulsed LEDs to produce a three-dimensional map of all light scattering sources in the interrogation region. Proof-of-concept results show that it is possible to exceed the sensor resolution in the final results throughout the measurement volume as well continue to acquire useful data beyond 98% obscuration – perhaps as far as 99.8%. With no obscuration the surface of the target could be resolved at better than 39 μm in all three dimensions throughout the 150 mm cylindrical region. As obscuration was increased to 98% very little detail was lost. As obscuration was increased to 99.8% great detail was lost but the features of the target – on the order of 200 μm in characteristic dimension – were still resolvable.

**Acknowledgements**

The authors would like to thank Wright Patterson Air Force Base for the generous funding of this research under SBIR topic AF112-167; Proposal award F2-6694.

**References**

