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Direct retroreflective laser strobography shadowgraphs

Destin Sandlin

DIRECT RETROREFLECTIVE LASER STROBOGRAPHY SHADOWGRAPHS

by

DESTIN SANDLIN

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
in
The Department of Mechanical and Aerospace Engineering
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

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Submitted by Destin Wilson Sandlin in partial fulfillment of the requirements for the degree of Master of Science in Engineering in Aerospace Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Engineering in Aerospace Engineering.

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ABSTRACT

School of Graduate Studies
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Name of Candidate	Destin Wilson Sandlin		
Title	Direct Retroreflective Laser Strobography Shadowgraphs		

High speed imagery is an important tool used in the study of ballistic events. Here, a unique retroreflective photography method is reported which uses a pulsed laser to capture images at very high speed. The technique yields schlieren-like images which allow operators to visualize flow fields and fast moving fragments. The laser is diverged and illuminates an area of interest being observed by the camera on a coincident axis with that of the laser. If properly set up, this technique allows for the visualization of gaseous disturbances, as well as the ability to see through fire. The system successfully recorded the shock wave structure around a bullet travelling 365 meters per second, covering a field of 50cm by 28cm with only .54 µJ of laser energy. The system also recorded the mechanical interaction between a bullet traveling at 365 meters per second striking a target within an intense flame. Different strengths and weaknesses of this method are described, and suggestions are made for possible future areas of research.

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Note*: *Patent paperwork has been submitted by the author (Destin Sandlin) to claim certain techniques and hardware described in this document as intellectual property.

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4. Bill Vining is internationally recognized as an expert in the field of high speed photography and optics. He currently serves as the lead of the US. Army's Redstone Test Center's Photographic Instrumentation Group operating at Redstone Arsenal, AL. He is an active member of the Range Commanders Council Optical Systems Group. He is well known in the high speed camera community as an experienced and knowledgable authority on the operation of high speed imagers. His skills have taken him all over the world to collect high speed imagery and data products on the launch and flight characteristics of missiles and weapon systems. Bill is an expert Bee farmer and is known to grown the hottest chile peppers known since the dawn of time. A patient co-worker, Bill gracefully served as mentor to the author for this effort.

5. Dr. Gary Settles is a Distinguished Professor of Mechanical Engineering at the Pennsylvania State University. He established the Penn State Gas Dynamics lab, which is well known for its work in gaseous flow fields. He has expertise in Gas Dynamics, Flow Visualization, Nozzle Design, Materials Processing, and Industrial Applications. He is a fantastic writer who is recognized as an international expert in Schlierent type techniques. He is currently pioneering efforts to create large scale shadowgraph and schlieren techniques. He is also authored the book "Schlieren and Shadowgraph Techniques, which was published

in 2001 and reprinted in 2006. An accomlished researcher and author in his own right, Dr. Settles is always quick to give credit to those who came before him and perfected the methods and mechanisms which allow him to accomplish new feats in his research.

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CHAPTER ONE

INTRODUCTION

Ballistic events are over in the blink of an eye. For over a hundred years now, humans have been trying to unravel the mysteries of all kinds of events they interact with on a daily basis using the technological miracle of high speed imagery. Several events such as rain drops splashing in a puddle, heat rising from a candle, or a horse galloping have all intrigued men for years. All these things appear to the casual observer as a normal, casual interaction of matter with the forces and environment around it. Invariably, whenever a seemingly simple event is characterized by high speed photography, the incredible complexities created into nature are revealed. When these complexities are studied and understood, man's understanding of how to manipulate the world around him is increased. This paper describes in detail the history of high speed photography and offers a new approach to image high speed events and the structure of the flow field around them.

A firm knowledge of not only the "how" but the "why" of high speed photography is used as a foundation to create a new type of high speed photography which utilizes lasers to create a collimated, coherent light source for imaging high speed objects and phenomena, and the flow field around them. This new method has unique capabilities allowing it to image objects and flow field information inside of a large explosive event. These new qualities make it an important tool which scientists may use

to augment traditional research methods such as wind tunnels, high speed imagery, flash x-ray imaging, rocket plume studies, and many more.

CHAPTER TWO

EARLY EFFORTS IN HIGH SPEED IMAGERY

Several men have devoted their lives to the advancement of high speed photography technology. These giants paved the way for today's scientists and engineers to make huge discoveries which improve the lives of the entire human race. The efforts which led to these discoveries were often more simple challenges rather than lofty noble causes.

2.1 Eadweard Muybridge, Early Efforts in High Speed Imagery

The story of high speed photography begins as many great technical advancements in human history do. Two egotistical men decided to settle a longstanding bet to determine who was right. The Governor of California decided to employ a man to determine if, in fact, all four of a horse's feet are off the ground at one time. Eadweard Muybridge was the first known person to use high speed photography to investigate a motion problem with high speed photography. He set several cameras up to determine if a horse's legs were all off of the ground at one time. Muybridge set up several cameras along the path of the horse's transit. He pulled a thread across the lane the horse was to run down and triggered each camera as the thread corresponding to its location tripped[1]. The result is the now famous moving image of a horse running. Thus began an entire field of scientific study.

2.2 Arthur Mason Worthington

Arthur Mason Worthington began to conduct scientific experiments which utilized an arc flash to expose a film slide.[2] This method was quite ingenious because it did not require the scientist to precisely time a very rapid shutter mechanism (most of which tended to have repeatability issues). As long as some type of electrical contact could be cleverly devised into the experiment, a precisely timed photograph was possible. He devised, along with a team of knowledgeable individuals, very ingenious ways of creating hardware which would create high intensity flash arcs at the exact desired moment in time he wanted. Figure 2.1 shows one such apparatus. Worthington opened his discourse by describing the idea of focusing on a drop of water splashing as crazy. He said this belief must be removed because a simple splash reveals several fundamentals about the behaviors of fluids.

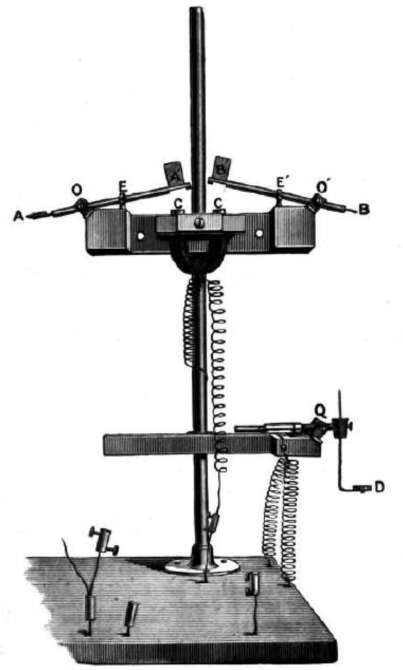


Figure 2.1. Worthington's device used to time an arc with the collision of a water drop.[2]

Initially, Worthington setup his machine simply as a method used to illuminate a droplet impacting a glass surface. The spark was generated by pulling a large conductor out of a pool of mercury. The flash occurred at the moment the conductor broke the surface of the mercury. The voltage used for the spark was created by a Ruhmkorff's induction coil. The first high speed images were created by creating an extremely bright short duration flash which an observer would then take note of. He would then draw exactly what he saw. The figures listed in Figure 2.2 show the obervations which were drawn by the observer. They proved to be remarkably accurate, even though they were hand drawn.

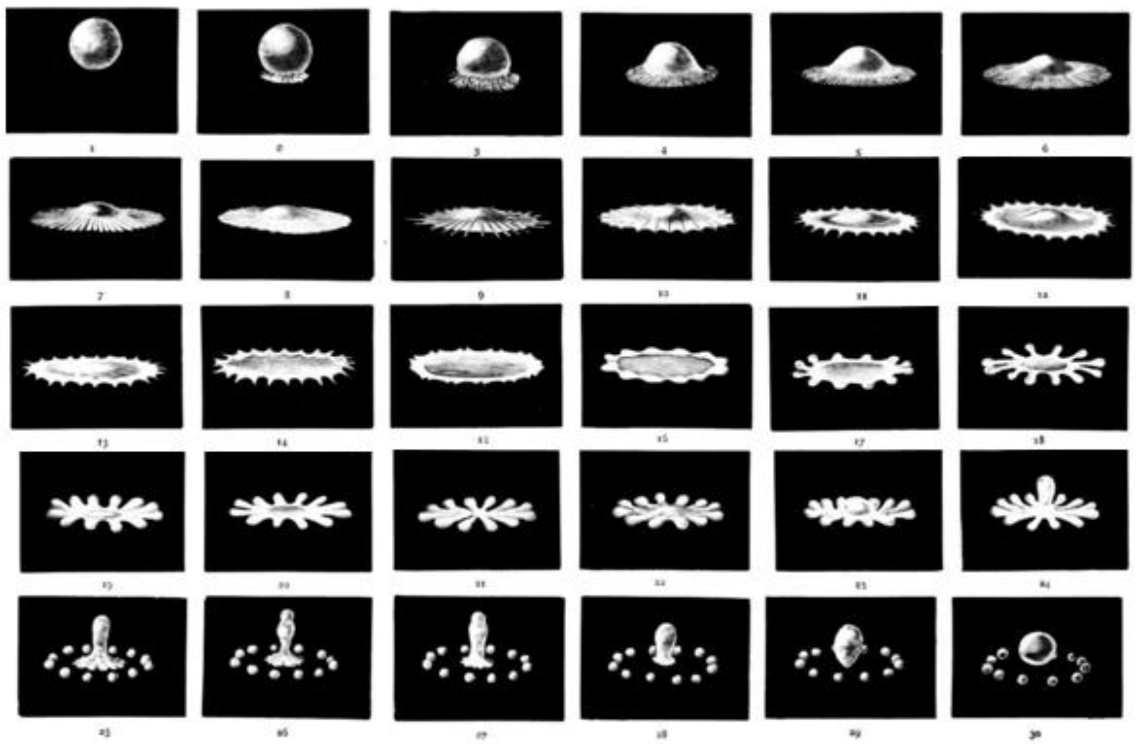


Figure 2.2. Hand drawn sketches of water droplet impacts.[2]

Worthington then moved on to creating high speed photos of the same event. Special plates were made to capture the exposures. He was able to use his methods to successfully and repetitively capture an image of a liquid splashing as it impacted a flat surface. Figure 2.3 is one of his now famous photos captured using this method. Worthington presented his findings in May 1894 at the *Discourse delivered at the Royal*

Institution of Great Britain.[3] His findings were then published by a company called "Society for Promoting Christian Knowledge."

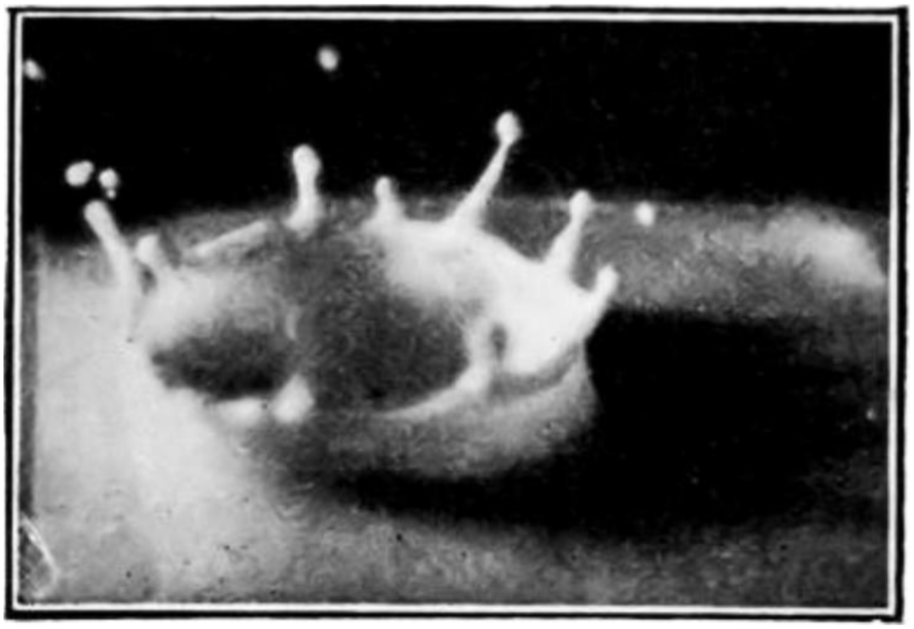


Figure 2.3. Worthington's famous splash photograph[3].

2.3 Doctor Harold Edgerton, A Revolution in High Speed Imagery

The next significant advancements in the art of high speed photography came with the inventions of the Flash lamp and the stroboscope by Dr. Harold Edgerton.[4] His research at the Massachusetts Institute of Technology started with an investigation into flashes which never ended. Even into his 80s, "Doc" Edgerton was still performing useful scientific experiments.

2.3.1 Flash Sources For High Speed Photography

The electronic flash tube consists of a glass or quartz tube wth a cathode and an anode mounted internally. The basic circuit consists of a battery source and a chargng crcuit. The charging capacitor is usually very large. The flash tube has a trigger electrode mounted externally on the glass tube which is electrfied in order to fre the energy of the capacitor across the anode and the cathode. No flament exsts inside the tube, only a gas, usually Xenon. The pressure of the gas inside the flash tube and the distance between the two electrodes determines the breakdown voltage.

When a capacitor is hooked up directly to the electrodes of a flash lamp, nothng happens because current s not flowing. A trigger voltage is necessary to start the discharge. This is accomplished by wrapping a wire around the outside of the tube, and providing a voltage spike along this "trigger wire."

2.3.2 Why Xenon?

Doc Edgerton devoted much of his lifetime to the investigation of the Xenon Flash Lamp. Xenon is often used as the fill gas of choice because it s very efficient in terms of how much energy it converts to light. Also the light emitted by Xenon similar to daylight.[5] The ionization of Neon produces mostly red light. The ionization of Argon produces mostly blue light. One might wonder "Why several gasses cannot simply be added together to simply arrive at whatever color gas is desired?" Simply put, gasses cannot simply be combined like paint from a "spectral palette". The gas with the lowest ionization potential will be excited first, and will dominate the light signature produced

by the lamp[4]. For example, Edgerton specifically discovered that the ionization potential for Argon is much lower than that of Neon. Argon ionizes at 15.69 Volts compared to 21.47 volts for neon. Likewise a mixture of Xenon and krypton will tend to reflect more of the spectral distribution of Xenon, because it's ionization energy is lower.

Xenon's ionization potential is 12.08 Volts, while Krypton's ionization potential is 13.94 Volts. Figure 2.4 shows the spectral outputs of several different types of gasses while used in similar flash tubes. Notice by comparing the bottom two spectral distribution graphs that Xenon is closest to sunlight in spectral output.

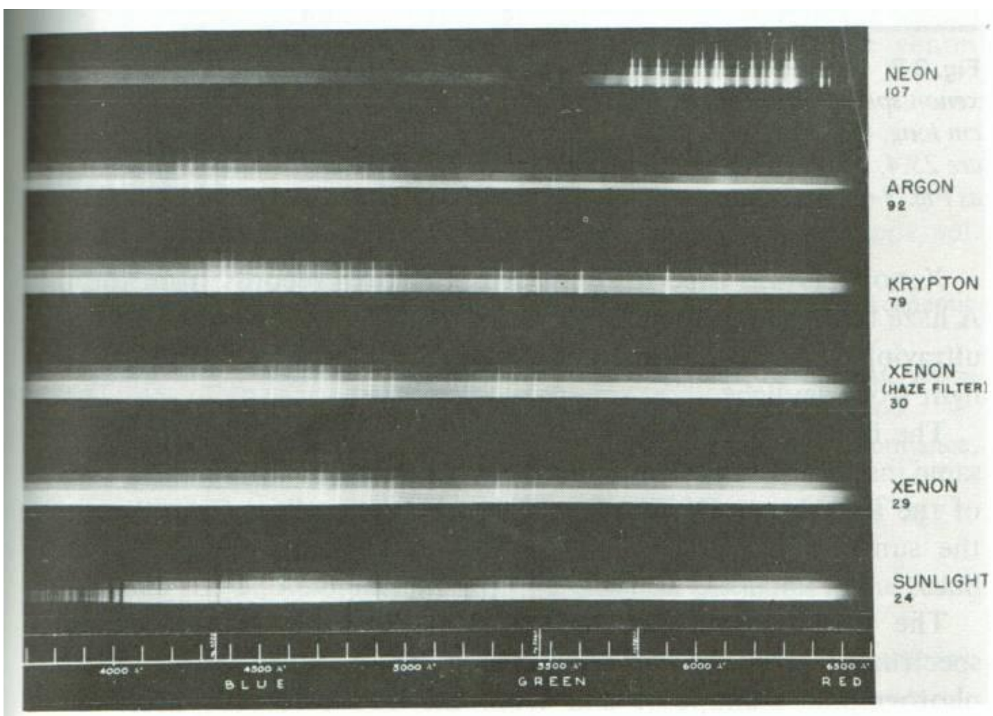


Figure 2.4. The Spectral output of several types of gases used in flash lamps as compared to sunlight.[5]

2.4 Stopping the Hands of Time

Two of the major elements which must be controlled when taking high speed photography are the exposure time and the light used to expose the image. Xenon Flash Bulbs are well suited for providing lots of light, but unfortunately for anything travelling at a significant velocity, the duration is too long to significantly "stop" the motion. Xenon flash tubes are great for illuminating, but they exhibit a relatively long "die off" period during which the light trails off. This makes xenon tubes not ideal for extremely fast moving objects due to motion blur. The flash performance is measured by quantifying the time and intensity of the light emitted from it. The duration is measured from 1/3 peak to peak, and the intensity is measured with a special meter called an Integrating light meter. The velocity of the subject must be known to determine an appropriate exposure time as calculated in Equation 2.1.

$$Time_{RequiredExposure}(t) = \frac{d}{v}\,\mathrm{sec} \tag{2.1}$$

Using this equation, *d* is the blur distance due to motion and *v* is the velocity of the subject. Time t is the exposure time. The sensitivity of the film or media must be considered when taking a photo to make sure the exposure is correct. Multiple exposures may be taken on the same photo by using several flashes timed well with a flash system.

Using this equation, it is clear to see that for very high speed events such as flying birds and bullets the xenon flash bulb is not fast enough to capture an image without

significant motion blur. Their flash durations are normally on the order of tens of microseconds. In order to accomplish a crisp image an arc flash lamp capable of a microsecond duration flash must be used. Edgerton defines “short” flash durations as any flash that is less that 1 μsec. The three things that are required for a fast flash circuit are: small inductance on discharge circuit, damped circuit oscillations, and quenched gas discharge.

Edgerton developed a flash method which utilizes an open air spark gap is enclosed in a glass tube for the protection of the user. This method is called “guided air spark” and consists of an arc on an internal quartz rod is typically 1 inch or so in length. The capacitors used to charge the circuit are usually quite large. Figure 2.5 from Edgerton’s book “*Electronic Flash, Strobe*”[6] shows the arrangement of the electrodes positioned inside a quartz tube. The “stinger” is used to initiate and guide the ionization of the air between the two electrodes.

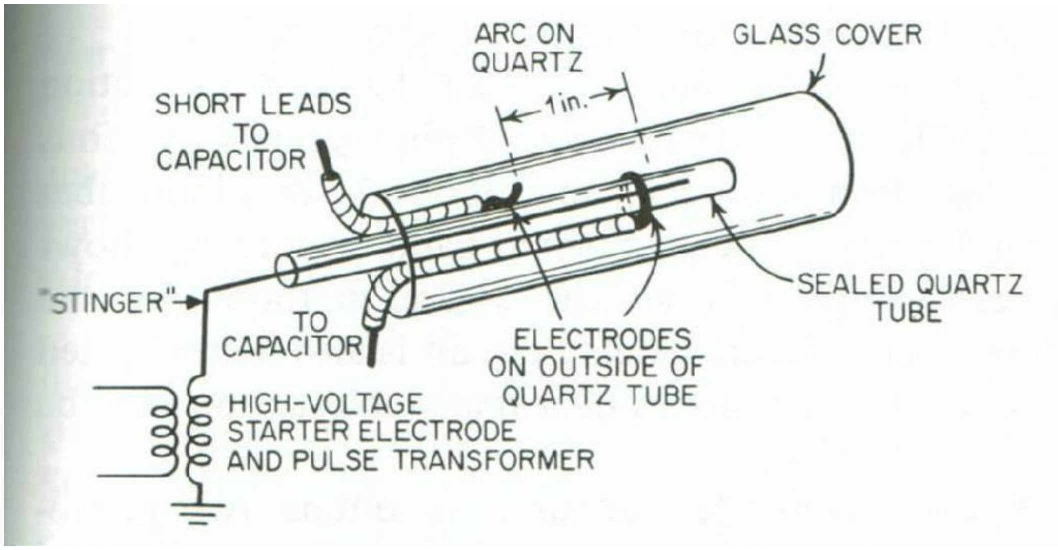


Figure 2.5. The air spark flash used for sub microsecond high speed photography.[6]

Some important facts about this type of flash

- Great care must be given to the design of the capacitor circuit for the electric discharge for an arc flash.
- Inductance is the enemy in a flash circuit.
- The voltages necessary for such a circuit are extremely dangerous, even lethal.
- The configuration of the spark gap is very important in terms of how the light is distributed.
- A point source spark is ideal for creating a shadow source.
- The energies involved in creating this type of flash often mean the flash tube will be very fragile, both electrically and mechanically.

Edgerton and two graduate students, Kenneth Germeshausen and Herbert Grier formed a company known as "EG&G." Together they acted as technical consultants and developers of high speed photography equipment. Edgerton describes the science behind the EG&G Microflash type 549. The flash tube for this device consists of an open air

spark gap triggered by a "stinger"[5] high voltage wire which is used to initiate the ionization of the gas. The gas which is ionized is air at atmospheric pressure. The author describes this as favorable because the air ionization has a nice red color to it. The 1/3 peak power flash duration for this type of flash is approximately .4 μsec, which indicates very little afterglow.[6]

The proliferation of modern digital camera equipment has rendered much of the hard preparation work which used to be associated with high speed photography obsolete. Now, a photographer can simply test an exposure with a flash quickly to see what type of settings should be used on the camera. The pioneers in the art of high speed photography were advanced technical scientists at the cutting edge of technology. One example of this is the lack of need for an integrated light meter for modern photography. For little to no cost a test photograph can be made to determine proper exposure levels. The challenge then becomes resolving the most effective way to trigger one's flash equipment accurately and repeatedly.

2.5 Camera, Action, LIGHTS!

There are several methods to trigger a stroboscopic flash or a single flash for high speed photography. Electronic methods are preferred over mechanical methods due to the quick response of electronic circuits. Ideally the room's light will be controlled in a way such that the shutter can remain open the entire duration of the test. The light source provided will then be all that is given to expose the photography.[7]

Elimination of variables is the single most important factor to a successful high speed photography setup. Electrical, chemical, optical, mechanical, and acoustic factors must all be considered when taking a photograph.

Van Veen[1] states that electronic triggering is preferred over mechanical triggering. This makes sense because often the repeatability of electronics is an order of magnitude above that of mechanical devices. Also, if an object like an electromechanical solenoid is used the phase/energy level of the supplied electricity is important for repeatability. For example, if a battery is used to activate a solenoid valve, energy is used. The battery will then have less energy to provide to the solenoid the next time it is activated. One way to get around this issue is to provide some sort of voltage regulating circuit in series with the power supply in order to regulate a consistent energy source for your electromechanical device.

Another example of a mechanical issue with an electronic setup is present when mircrophone triggers are used. Position of a microphone is also a very important consideration due to the time required for sound to travel from the energy source to the microphone. This is basically an acoustic delay. This should also be factored into the equation. An electronic signal such as an optical breakscreen would be preferred due to the fact that light travels so much faster than sound. Figure 2.6 below shows a simple setup used to collect images of a bullet in flight.

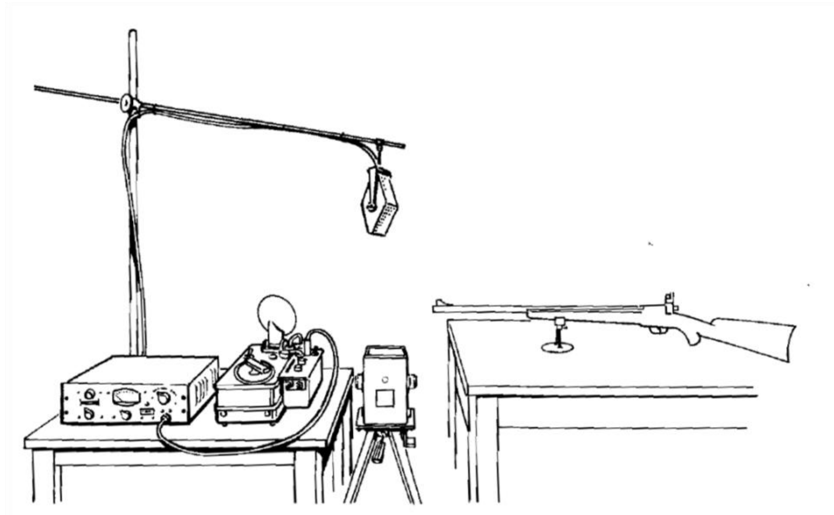


Figure 2.6. A simple high speed flash setup triggered by a microphone.[7]

Four physical attributes must be synchronized for an ideal high speed photograph:

- Motion to be photographed
- Contact action or signal generation
- Stroboscopic flash
- Camera Shutter.

2.6 Migration to Digital Storage Media

High speed image sequences have been used for over a century to analyze moving events. Basically, the exposure of image sequences is similar to high speed photography methods for still imagery, except repeated in series. Because so many images are produced with video systems, the storage media of these images has been the subject of much investigation throughout the years.

The first video cameras were created after invention of paper roll film. Subsequently, celluloid backed film furthered the proliferation of video and 46 frames

per second video was achieved.[8] Parisians created a camera with claw mechanism around 1895, ushering in the era of rolls of film. One may be shocked to know that by marrying up the spark method with a drum camera 100,000 frames per second “video” was achieved in the early 1900s![8] Rotating prism/shuttered cameras which distribute an image across a synchronized film strip are capable of 10,000 frames per second. The FASTAX and HYCAM are examples of this.

Almost a century later, technological developments began to usher in alternatives to film media for storage. As photography approached the digital horizon, Fuller[8] provided a paper in the mid-late 90’s describing a history of film high speed cameras and what the digital horizon looked like. Fuller writes “At the present time film still holds a premier place for resolution and framing rate capabilities in the cine region, but electronic image capture methods, including video systems, are becoming more and more widespread in the study of motion analysis.” He notes that the digital camera technology of the day was advancing so fast it was difficult for an individual to stay well versed in the current state of the art.

A device called an “Image Orthicon Tube” was the first generation of image sensor. The photons create “electrons which are attracted towards a positively biased wire mesh target.” This energy is converted to a digital signal. The Orthicon tube was very sensitive due to a natural gain effect caused. Figure 2.7 shows a schematic diagram of an Image Orthicon Tube.

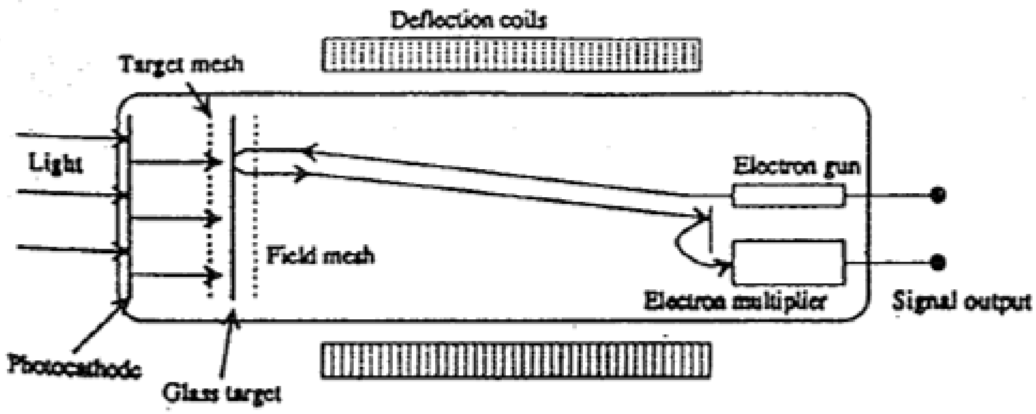


Figure 2.7. Schematic diagram of an Image Orthicon Tube.[8]

The Vidicon Tube uses a photo-electrode conductor instead of a wire mesh. A pattern of charges are formed on the back of a surface, creating a semi-conductive compound only a few microns thick. This is placed "on a thin transparent metallic film which acts as an electrode to channel the electrical charges." The most popular chemical photo-conductive compound used is antimony trisulphide. Lead Monoxide is also used on a different kind of tube called a plumbicon. Figure 2.8 shows the schematic diagram of a Vidicon Tube.

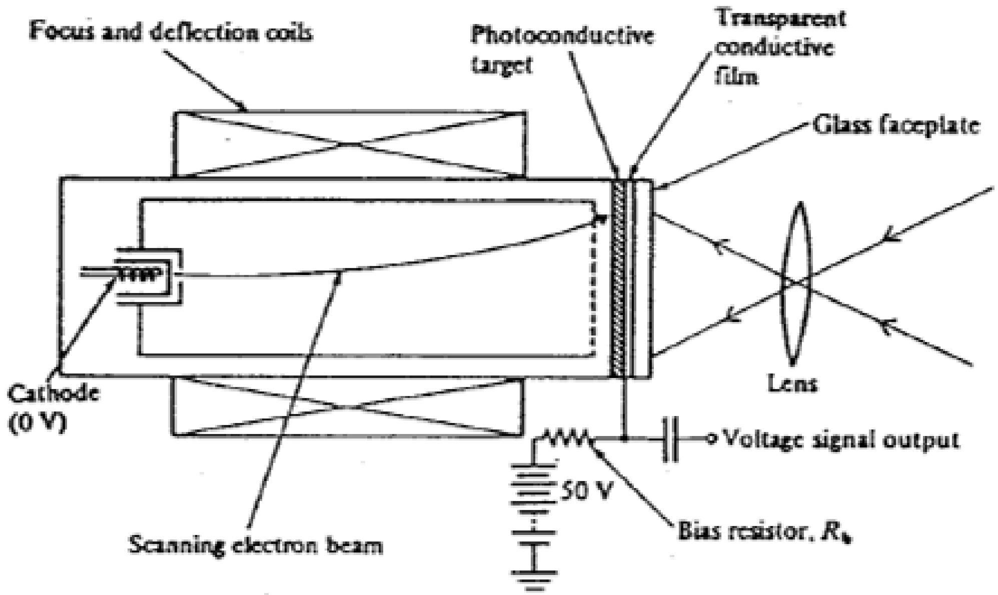


Figure 2.8. Schematic diagram of a Vidicon Tube.[8]

The Charge Couple Device (CCD) was created in the early 70's. Basically, several hundred sensors are stacked next to each other in a grid pattern. Each individual "photosite" has an associated voltage corresponding with its light level. This can be integrated together through use of an image intensifier and assembled through a video amplifier to create a moving image. Another modern sensor is a type of active pixel sensor known as a "CMOS chip." Modern digital imaging equipment typically use either a CCD device or a CMOS chip.

2.7 Modern Digital Photography Using Old Timing Methods

The invention of the digital camera, and its availability to the common consumer has truly been a revolution in photography. With a little motivation and algebra, most people are capable of producing photos of high speed events on their own. Figure 2.9 and Figure 2.10 are photographs made by the author. A .22 caliber rifle has been fired into a small rectangular prism of room temperature butter.

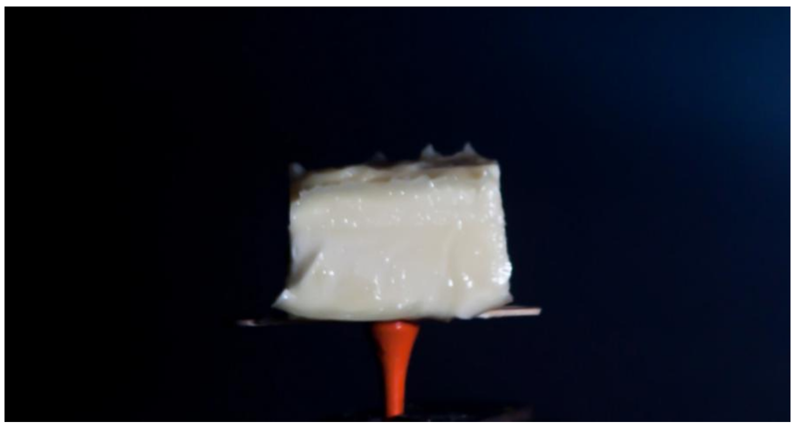


Figure 2.9. Room temperature butter resting on a tongue depressor balanced on a golf tee.

Figure 2.10. Room temperature butter resting on a tongue depressor balanced on a golf tee penetrated by a bullet fired from a .22 caliber rifle. The flash was triggered by a microphone.

CHAPTER THREE

DIFFERENT METHODS USED FOR HIGH SPEED PHOTOGRAPHY

Dozens of innovative methods have been developed for high speed photography by combining old and new technologies. This chapter takes an in depth look at several of these methods

3.1 Synchro-Ballistic Photography

Once again, high speed photography advanced in the investigation of horses. Critchfield[8] describes the use of a streak camera to capture several different types of imagery. The same technology which was used to image the finish line in a horse race is used to capture extremely high velocity events such as shaped charge jets formation characteristics through different media. Critchfield describes the use of a slit and moving film to create an image of a horse on the finish line.[9] The general way this type of camera works is to move the film behind a lens at the same velocity of the photograph subject of interest. The light is passed through a small slit, so only one plane is visible at any time. If the film is moving slower than the horse as it passes the plane, the horse would be compressed in length. If the film was moving faster than the horse, the horse would appear to be quite long. Ideally, the velocity of both the horse and the film must be synchronized. Figure 3.1 shows the simplest synchro-ballistic imager configuration.

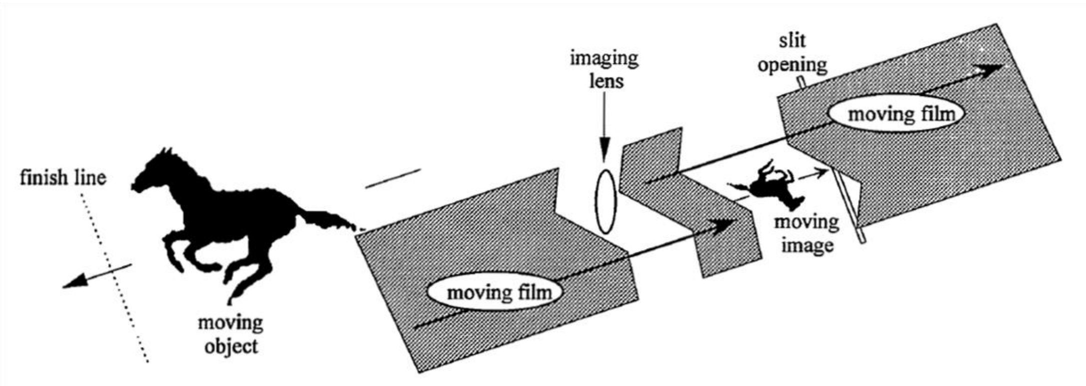


Figure 3.1. Synchro-ballistic photography as illustrated by Critchfield.[9]

Critchfield goes on to describe in detail the use of this technology to capture a viper warhead shaped charge jet as it forms in both a vacuum and in air, as well as the wave front velocity of several types of explosive.

Several limitations exist with Synchro-ballistic photography. Film must be moving at the same velocity of the subject. If film is moving slower, the image will be compressed. If film is moving faster, the image will be expanded. The front of the subject and the rear of the subject are imaged at different times. This method does not represent a "snapshot." Instead, the front of the projectile and the back of the projectile are imaged at different points in time. Depth of field cannot be adjusted during the image.

3.2 High Speed Imaging using Lasers as a Light Source

Lasers are a fast but controllable way to illuminate an area. Another huge advantage to lasers is the fact they are coherent (same wavelength). Even welding may be studied by using laser illumination and filtering of the extra light emitted. Pulsing methods are used to control the duration of a laser pulse down to a time as small as a few femtoseconds. This eliminates the problems described earlier with a "decay time" associated with arc flashes. The duration of the pulse needed depends on the size of the object being imaged as well as its velocity. For purposes of crisp photography, the Equation 3.1 is used:

$$t \leq \frac{d}{10v} \quad , \tag{3.1}$$

Where t is pulse duration, d is the linear dimension of the object, and v is the velocity of the object. Laser Illumination makes the exposure time of the camera irrelevant. The pulse duration of the laser itself determines the exposure of the image. Lasers may be used in conjunction with any high speed camera to boost the performance of the camera. Limitations do exist, but only for extreme circumstances. Lasers "eliminate motion blur, light inaccessible regions, slice through complex three-dimensional flow structures, see through explosions, arcs, and flames, and make quantitative measurements of velocity and particle/droplet size, temporal and spatial distributions."[10] Figure 3.2 shows a sequence of images collected with laser illumination.

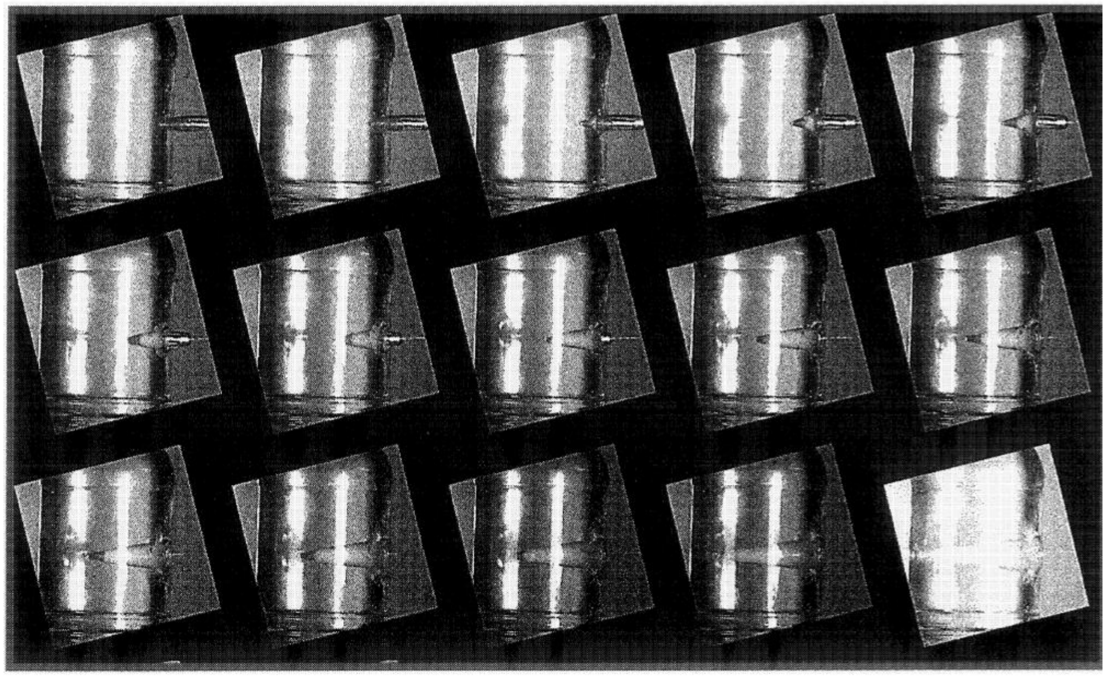


Figure 3.2. A 7.62mm bullet entering a water jug illuminated by a laser[11].

Laser illumination is especially useful for the study of sprays for metered dose inhalers for treatment of asthma. Droplet size, velocity, duration turbulence, spray pattern and plume angle can all be measured. Diode lasers are the systems of choice due to their relatively inexpensive costs. High speed cameras are capable of framing as many as 25 million frames per second, however lasers having enough power to provide light for these images are very difficult to achieve. Figure 3.3 shows a high speed image of a spray nozzle imaged with a laser.

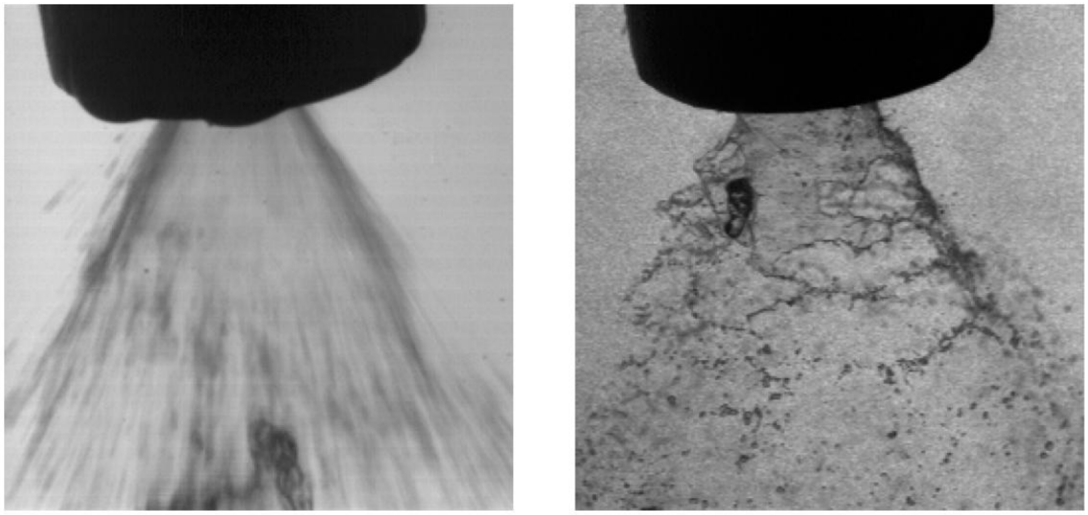


Figure 3.3. Spray nozzle illuminated by traditional methods (left) and a laser (right).[10]

3.3 Schlieren High Speed Photography

Schlieren is a German word meaning "streak". Several types of Schlieren photography exist. Dr. Gary Settles of Penn State University[12] has experimented with several different methods used to capture high speed imagery of ballistic events using this type of photography. He is currently recognized as a subject matter expert on the art.

3.4 Traditional Schlieren

A simple Schlieren system uses A collimated lens is used to make sure all light rays are parallel. The image produced through the lens is projected onto a viewing screen. This image is projected upside down. Transparent schlieren objects are not imaged until a knife edge is added at the focus point of the second lens. When a point source light is used there is no need to focus the image because there can be no existence

of an umbral shadow due to source width. In reality, it is impossible to get a true point source light. Figure 3.4 shows the setup of a traditional Schlieren system.

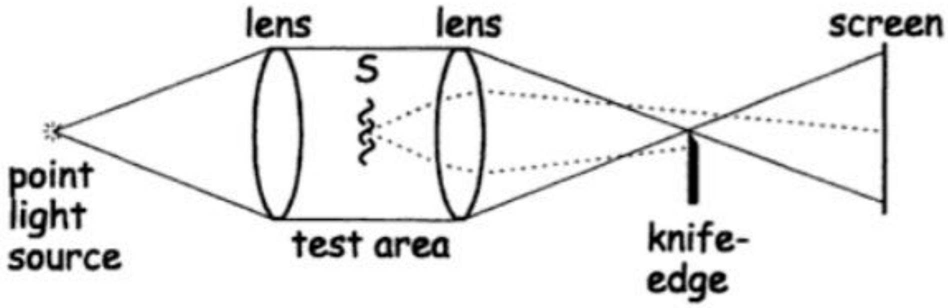


Figure 3.4. Traditional Schlieren photographic setup, as described by Dr. Settles.[13]

The position of the knife edge determines if the image will be "brightfield or darkfield in the language of microscopy." If brightfield is desired, the knife-edge should be positioned "just prior to blocking the image of the source point." The addition of a transparent subject to the area between the two lenses distorts the light rays, causing disturbances in the uniformity of the image. For an extended light source Schlieren system, the "amount of knife-edge cutoff of the undisturbed composite source image sets the background level of illuminance in the image on the viewing screen. Different types of cutoffs can be used to produce Schlieren images. Vertical cutoffs, horizontal cutoffs, and circular cutoffs can all be used.

3.5 Background Oriented Schlieren

Another type of Schlieren Photography used by Dr. Settles is known as "Background Oriented Schlieren" photography. Settles uses the lens-and-grid schlieren optical arrangement to generate large scale schlieren images.[12] The claims of this method are fundamentally different from Toepler's method which expands the beam from a small light source.

The method created by Dr. Settles is not limited by the size of the lens aperture. The size of the image is limited by the background grid source and the "axial distance available in which to set up the optical train." High speed digital videography was used to record Schlieren images using this method. The exposure time used in the tests was 5 microseconds. The weapons used in the test were a Remington 30-06 rifle and Smith & Wesson .44 magnum. Triggering was accomplished by setting up a microphone and an electronic delay circuit in the line to the light source. Figure 3.5 shows the method used by Dr. Settles to accomplish background oriented Schlieren photography. Note the grid drawn onto the backdrop of the test subject. As the light is refracted or "bent" the lines no longer appear clearly. The lines appear more densely, and therefore darker to the camera. This phenomenon allows for shock waves to be observed.

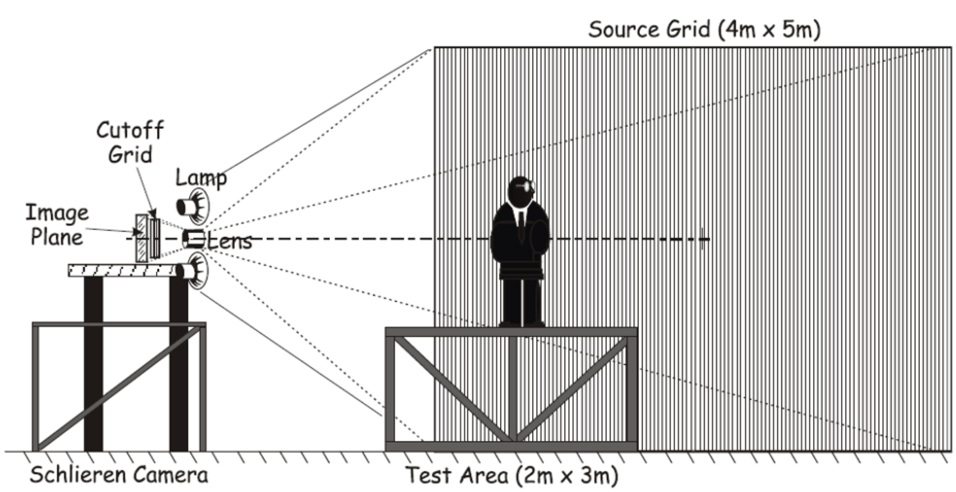


Figure 3.5. Typical large-scale Background oriented Schlieren photography.[12]

This method has a serious advantage in that it is capable of capturing images of test subjects which are very large in physical size. Figure 3.6 shows photographs of gun shots. The disturbances in the air indicate the shock waves created by the weapon.

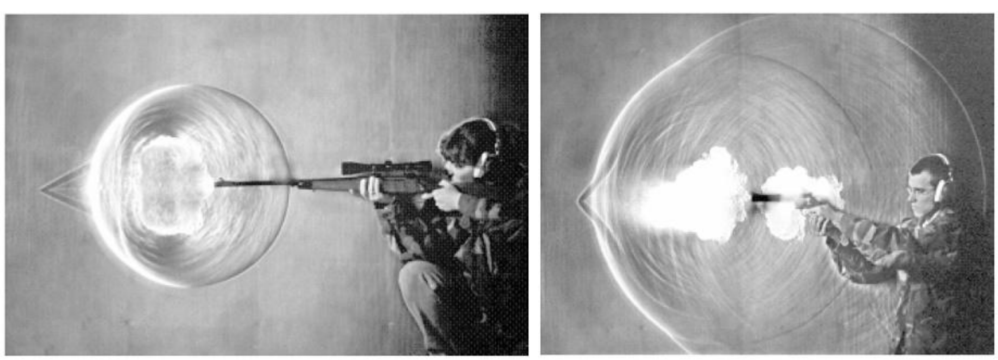


Figure 3.6. Images taken by Dr. Settles which shot the shock waves generated by a 30-06 rifle and a 44 magnum revolver. [12]

This type of testing must be accomplished indoors where light can be controlled or outdoors at night. Performing this type of test may be very costly but ultimately very useful in the study of safety for soldiers. Primary shock waves aren't the concern for soldier hearing damage. Secondary shock waves are most likely what will cause damage to a soldier's ears. This type of photography combined with high speed methods will be very useful in determining how to best design a weapon system for use by friendly forces.

3.6 Hand Held Schlieren

Traditional Shadowgraphy/Schlieren photography involves a very complex lens setup with many different variables to control. Traditional schlieren involve several lenses or reflective surfaces which are hard to setup. Collimated illumination is required. The setups are usually bulky, expensive, and mostly constrained to laboratory environments.

A team has developed a technique called "Light Field Background Oriented Schlieren Photography" (LFBOS).[14] The devices used to capture the images are called "Light field probes." "When included into the background of the scene, these probes allow otherwise invisible optical properties to be photographed." This method employs the use of a lenslet or lenticular array to capture the refraction of light in both positional space as well as angular space.

Background Oriented Schlieren images are created by observing "a planar high-frequency background through a refractive medium."[14] Background Oriented Schlieren

requires the background to the diffuse or photo-consistent. Background Oriented Schlieren only provides 3 dimensions of light refraction information. Light Field Background Oriented Schlieren “employs a background probe, but rather than coding only two dimensions, we can encode up to four dimensions of the light field. By four dimensions, the author is taking into account angular variation in the light. Figure 3.7 shows an example of mixing fluids as viewed through a lenticular array.

Figure 3.7. Mixing fluid viewed through a lenslet array.[14]

Although a great method to perform Schlieren photography, LFBOS still has significant limitations. The size of the lenslet array limits the test subjects which may be analyzed. Printing methods must be very advanced to display the images captured.

Angular resolution is difficult due to the lenslet arrays used. Spatial Resolution and angular resolution are tradeoffs. This method has not currently been tested with high speed imagery, but doing so would be a rather easy task.

3.7 Shadowgraphy

Shadowgraphy has been used for hundreds of years to analyze fluids. Robert Hooke first performed data analysis using this technique to observe fluid dynamics using the sun and a white surface on which a shadow was cast.[15] Dr. Settles rightly gives Doc Edgerton the credit he deserves by referencing traditional direct shadowgraphy as "Edgerton shadowgraphy."[15]

3.8 Large Scale Shadowgraphy

Dr. Settles has demonstrated this photography technique and its applications in the study of ballistics and explosives for homeland defense purposes.[16] A test was performed on the ULD-3 passenger luggage container. Different explosive charge locations were used. Optical shadowgraphy system and high speed cameras were used to record shock wave phenomena after detonation. The shadowgraph system consisted of a 5 meter square retroreflective screen illuminated by a 1 kW concentrated arc lamp. Figure 3.8 shows a series of photographs from Dr. Settles's full scale luggage container test.

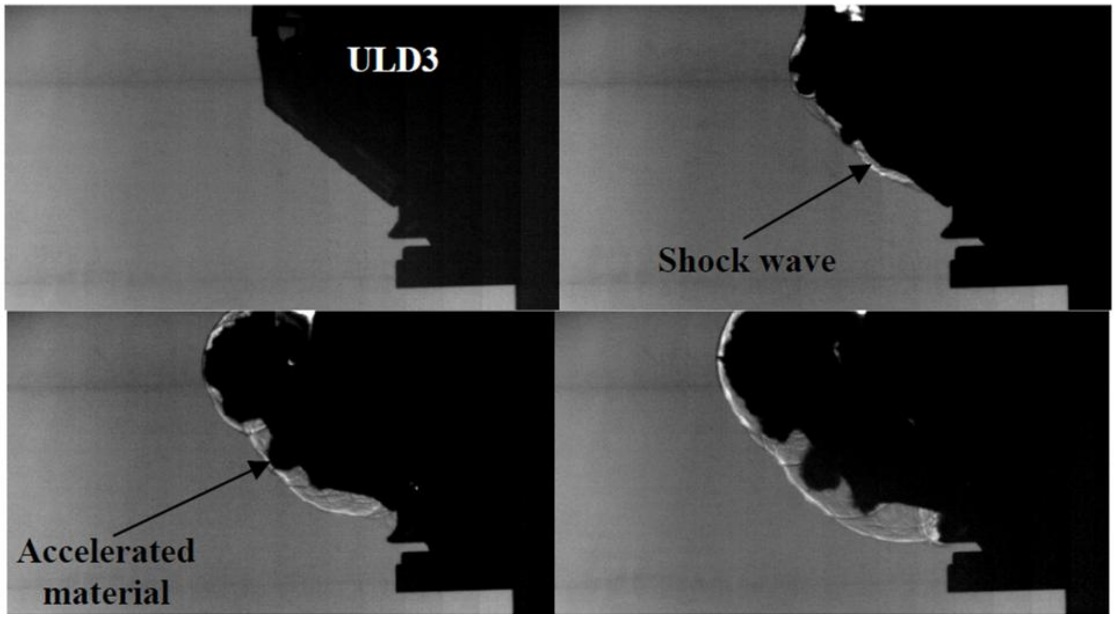


Figure 3.8. Full scale luggage container under explosive test.[16]

This method may also be used to demonstrate the way which shock waves propagate through buildings or other structures. Figure 3.9 below shows a test involving the detonation of a small amount of TATP explosive in a simulated room. The shadowgraphy clearly shows the shock wave travelling down a hall and into adjacent rooms. This type of photography provides a much clearer description of what happens to the flow field than a pressure transducer only solution could provide.

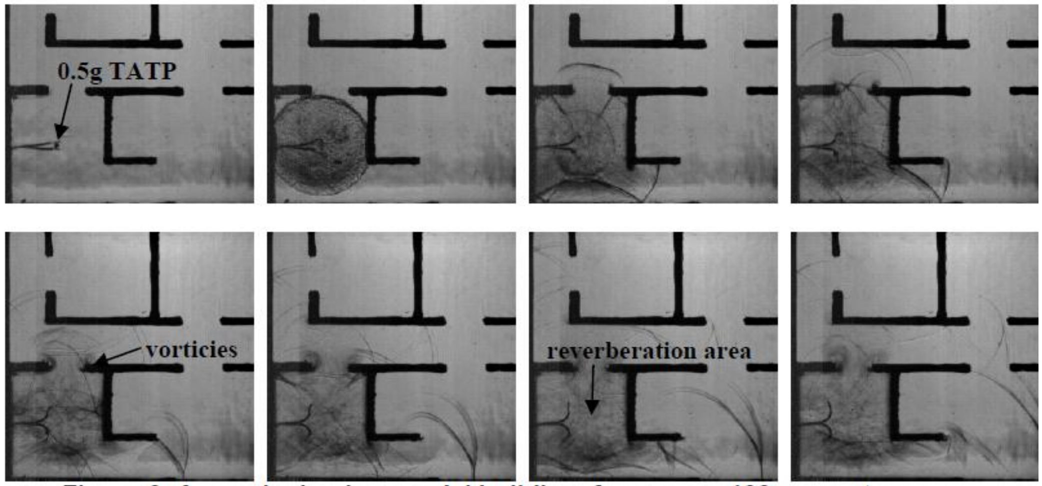


Figure 3.9. A shock wave travels to adjacent rooms from a small detonation in the room on the bottom left corner. [16]

3.9 Retroreflective Shadowgraphy

Dr. Harold Edgerton developed retroreflective shadowgraphy in his lab at the Massachusetts Institute of Technology. Figure 3.10 Edgerton retroreflective shadowgraphy as described by Settles.[15] Figure 3.10 shows his technique. Dr. Settles rightly gives Doc Edgerton the credit he deserves by referencing traditional direct shadowgraphy as “Edgerton shadowgraphy.”[15] Settles’s document on the subject describes how traditional shadowgraphy is performed in the “Edgerton” manner.

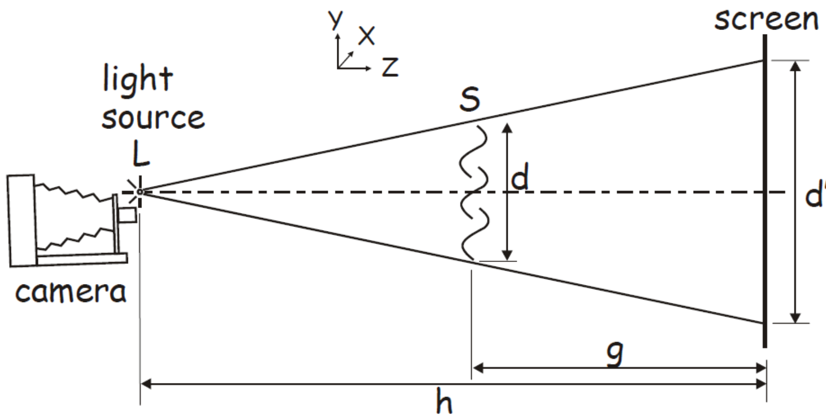


Figure 3.10. Edgerton retroreflective shadowgraphy as described by Settles.[15]

Dr. Settles advanced the retroreflective shadowgraphy methods used by Dr. Harold Edgerton by eliminating the shadow doubling which occurs during illumination of the retroreflective screen by an offset light source. He accomplishes this by using a light source that is focused down to a 3mm circle and then focused on the mirror which is glued at a 45 degree angle onto the lens cover.[15] This type of shadowgraphy seems to be very nice because no double shadows are created The amount of energy used for the light source may be of importance depending on the type of imaging equipment used. Alignment of the camera and light source is very important. Figure 3.11 shows the angled mirror which reflects the collimated light source onto the retro reflective screen. The advantage of the light source bouncing directly off the lens is that the light reflects directly back to the lens of the camera, eliminating any double shadow.

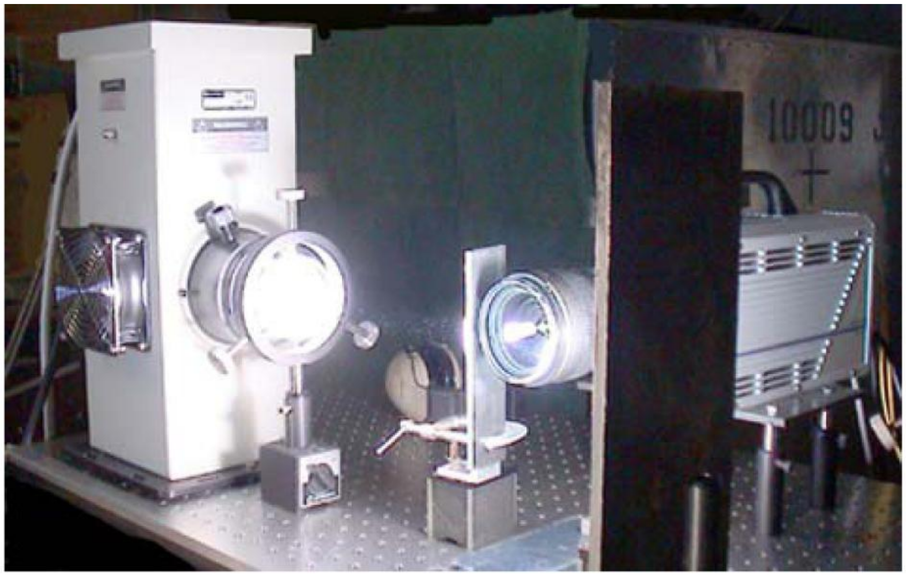


Figure 3.11. Direct light source bouncing off of mirror on a camera lens. [15]

Although a huge leap forward for shadowgraphy, there are still a few limitations in this setup. The light source used was a continuous direct source 1000W lamp. The light source is focused down to a 3mm circle and then focused on the front surface 45 degree mirror wedge which is glued onto a filter.

CHAPTER FOUR

COMBINING METHODS TO PRODUCE NEW RESULTS

One problem with the current state of the art of high speed photography is the cost of equipment. New novel methods should be explored which utilize off the shelf components which are relatively cost effective. Clever arrangements of off the shelf components can yield amazing photography. Knowledge of the fundamentals of high speed photography coupled with these clever arrangements can yield very amazing results.

4.1 Laser Strobography + Shadowgraphy = Laser Strobographic Shadowgraphs

Typically high speed photography involves a very expensive setup using a precisely aligned high cost light source. The Council of Scientific and Industrial Research in India came up with a way to use a series of precisely controlled lasers to accomplish shadowgraphy photography without the use of highly expensive light sources. [17] They used lasers which were precisely controlled to illuminate a bullet at the exact desired moment. These lasers beams were expanded and fired sequentially as the bullet passed the area of interest. Although the array is quite large, the relative cost is extremely low. Flash lasers are relatively inexpensive, and the type of camera used only depended on simple 400 ASA film.

Elegant and simple methods were used to perform this test. The lasers are pulsed with a computer which controls the timing precisely to ensure each camera is exposed at the exact moment the projectile passes the camera. The arrangement of the lasers and cameras are shown below in Figure 4.1.

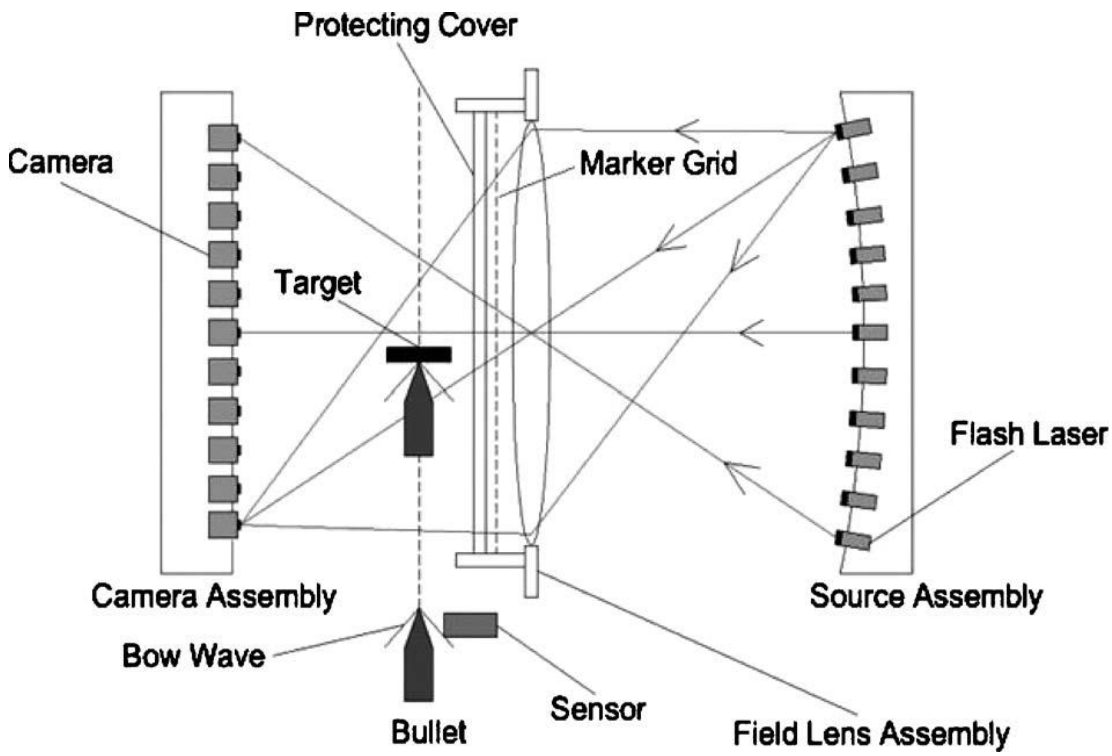


Figure 4.1. Setup for direct laser strobography shadowgraphs.[17]

Images captured using this method are shown in Figure 4.2. Notice the shock wave on the front of the bullet.

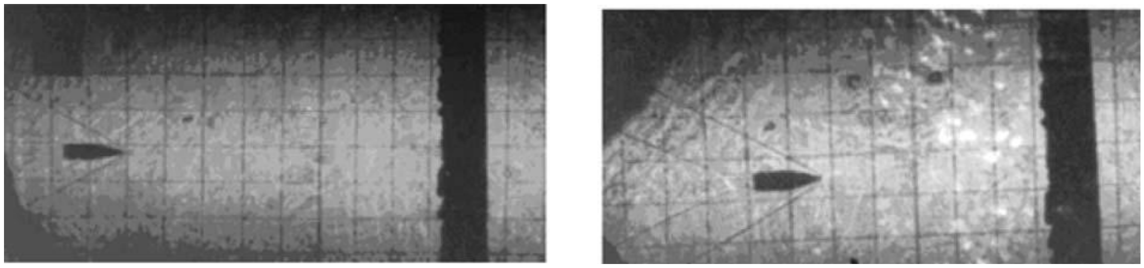


Figure 4.2. Direct laser strobographs produced with a shadowgraphy method.[17]

The same type of test could easily be accomplished with a series of digital cameras. The Protecting cover (Shown in Figure 4.1) used simply provides a contrast for the bullet to pass through. This should make for a very interesting experiment in the lab. The power output of the laser doesn't seem to be extremely critical. The duration of the laser pulse seems to be extremely critical. This can be controlled through a system similar to the one the team built by hand, or an off the shelf pulse generator could be used to create images similar to these. Quantum Composers in Bozeman Montana manufactures pulse generators which are well suited for this type of application.

4.2 Other Considerations

The ability to filter out certain colors of light is a very serious advantage when performing certain types of high speed photography. For example, ultra high speed camera techniques often employ lasers which can be used to brightly illuminate a surface. Ambient light caused by impact dynamics or energy release often produce light. If this created light can be filtered out, the subject being observed can be more closely watched without being disturbed by a nonessential flash of light. This method was employed by

Lawrence Livermore National Labs (LLNL) with their 8 Laser Ruby illumination system used for ultra high speed photography.[18] Below in Figure 4.3 is an example of a transmittance/ diffuse density curve for a particular filter. Notice the properties are a function of wavelength.

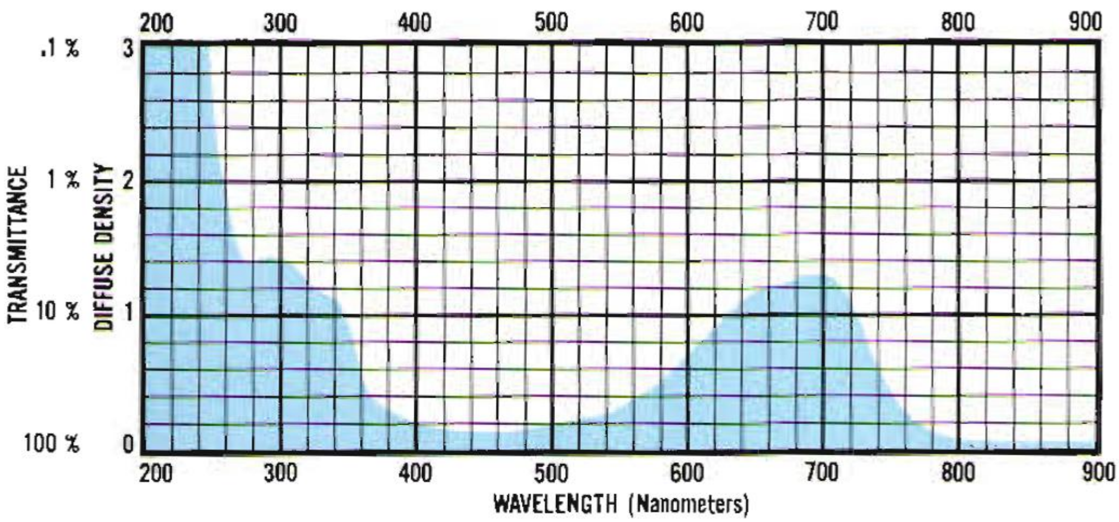


Figure 4.3. Example of a filter which subtracts out certain wavelengths of light.[18]

A common problem when filming an explosive or energetic event is the spillover of extra light which is undesired. Figure 4.4 below is an image of a bullet striking a set of matches (Sandlin). Notice the flame up of each individual match is still present even though it may have happened well after the event occurred. This is a serious flaw in a setup for some high speed imagery applications.

Figure 4.4. Bullet Striking a set of matches.

One high speed video application which this would be a negative affect for is warhead detonation. If fragmentation particles are to be observed, the extra light generated by the explosive event is undesirable. The clever use of laser illumination and a filter of the proper wavelength would allow a high speed camera to “see through” the bright flash of the warhead detonation.

CHAPTER FIVE

CREATING A NEW, UNIQUE METHOD

Existing high speed photography methods used to visualize flow fields are extremely expensive and complicated to setup. Can a method be developed which uses less energy, costs less money, and requires less time to install at a facility?

5.1 Solution Developed to Create Extremely Low Energy, Safe Method

After a thorough analysis of all of the state of the art methods of high speed photography, one particular gap in the technology seems to exist. After reading the article “Multiple-laser flash shadowgraphy system for terminal studies of small-caliber projectiles,”[17] and “Full-Scale High-Speed “Edgerton” Retroreflective Shadowgraphy of Explosions and Gunshots,”[15] it has been determined that the two methods could easily be combined to create a new form of photography. The author (Sandlin) claims to be the rightful inventor of this method. The method is called “Direct Retroreflective Laser Strobographic Shadowgraphy”. The method will employ principles used by both The Council of Scientific and Industrial Research in India and Dr. Gary Settles at the Pennsylvania Gas Dynamics Research Lab.

This method employs the use of Settle’s direct retroreflective technique employed with laser illumination instead of a direct collimated xenon arc lamp source. This has several advantages. The collimated source is quite expensive as well as power hungry.

Pulsed lasers require less power and are easier to control with solid state electronics. The laser electronics are fundamentally more robust (both electrically and mechanically). The implementation of a laser diffuser instead of highly precise optical lenses used to focus the beam down to reflect off of the mirrored wedge is a much simpler solution. Also, the cost of power driving components as well as the laser diode is over one hundred times more cost efficient than a continuous Xenon arc source. Figure 5.1 shows a diagram describing the exact method proposed.

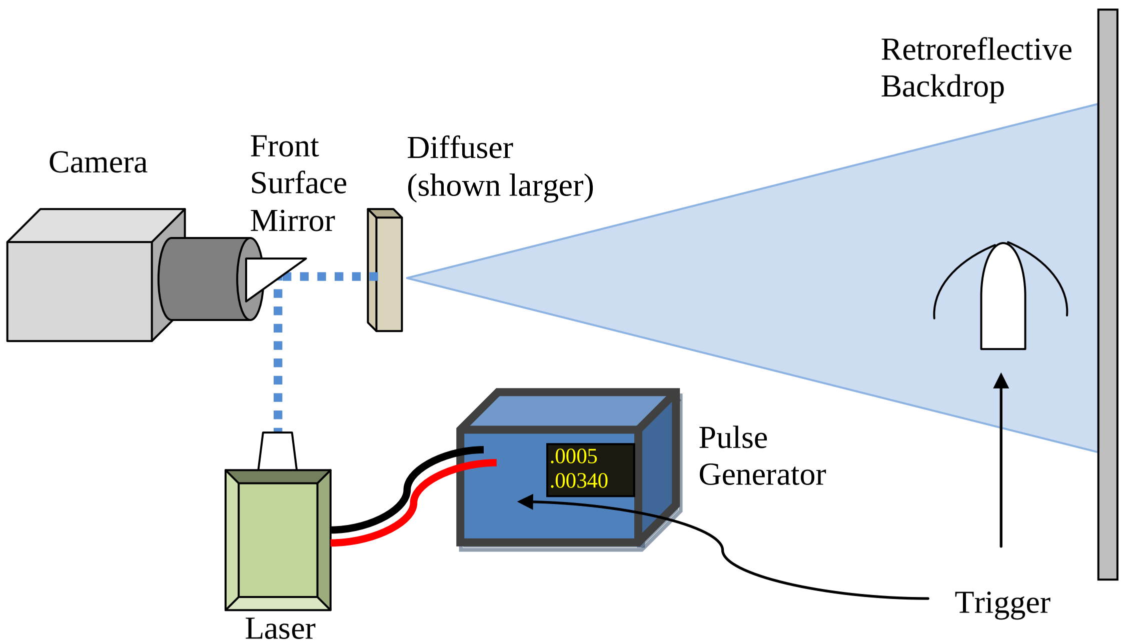


Figure 1. Method for performing Direct Retroreflective Laser Strobography Shadowgraphs.

This figure is not drawn to scale. The distance between the bullet flight line and the retroreflective screen should be roughly equal to the distance between the flight line and the camera.

Jenoptik is a Huntsville based company which provides diffractive laser diffusers for several applications. “A Diffractive diffuser is a type of diffractive optic that can take a laser beam and redistribute the light into virtually any pattern desired. These types of optics are used when the light source is monochromatic. Diffusers have a tightly controlled angle providing high efficiency. They are not sensitive to alignment and do not affect the polarization of the input beam.”[19] A diffuser may be used to spread the laser beam out to a desired area. For the purpose of this experiment a divergence lens is used to spread the laser beam.

The retroreflective backdrop is simply a Scotchlite™ material which reflects the laser light back to the camera lens. The absence of light when shadowed by the item of interest created a shadowgraph located on the Scotchlite™ screen itself. Therefore, the camera is focused on the screen.

Quantum Composers Inc. Bozeman Montanna provided a four channel model 9520 Pulse Generator for use as a controller to pulse a visible laser for imaging. The technical specification sheet for the 9524 states, “The model 9520 series heightens the capabilities of pulse generation and digital delay to new levels. Cost effective, yet extremely capable, this instrument provides solutions to generate and synchronize multiple pulses and triggers for a wide variety of applications from simple to complex. The 9520 Series is the only multi-channel pulse generator to permit differing rates for all the channels using new Clock- Divider functions, and provides up to eight independent digitally controlled channels with width, delay, rate, and amplitude control on each output.” Figure 5.2 below shows the Quantum Composer Model 9528, 8 channel pulse

generator which can be controlled to a resolution of 25 picoseconds. For this proof of concept research the model number 9524 has been acquired. The model 9524 is only capable of four channels of output data.

Figure 5.2. Quantum Composer Model 9528 Pulse Generator, capable of 25 picosecond resolution.

The ability of the Quantum unit to control a visible laser is simple to demonstrate by controlling a MOSFET circuit to control a standard laser pointer power supply. Direct control of the laser in either a pulse width modulation or a single pulse mode is easily achieved through the menu functions. A Digital Selective Lense Reflex (DSLR) camera may also been wired up to another channel on the pulse generator to time the camera

shutter. The laser channel is triggered at a certain delay time after the camera is triggered. This enables the user to put the camera on the fastest shutter setting and fire a quick laser pulse at the precise instant the shutter is open. This reduces noise on the sensor, thereby making a clearer picture. This method could be employed for an extremely cost efficient setup.

The demostrated method for this project illuminates an area roughly 25 cm x 1m area with the absolute minimum pulse necessary to obtain an image. This pulse is synchronized with a high speed digital video camera to capture not only a single image, but an image sequence.

CHAPTER SIX

DEMONSTRATION OF METHOD AND DISCUSSION OF RESULTS

The retroreflective laser method described above was setup with a few variations. As predicted, the shock waves on the front of the bullet were clearly visible. Both aNikon 40D DSLR camera and a Phantom V10 camera on loan from Vision Research (an Ametek company) was used. The Phantom allows not only for single images to be captured, but image sequences. Instead of an RGB laser (as desired), a 1800mW blue 445nm blue laser diode was used. A power controller was devised so the blue laser could be fired in very small pulses controllable via a TTL trigger input. Figure 6.1 shows a shadowgraph taken with this setup.

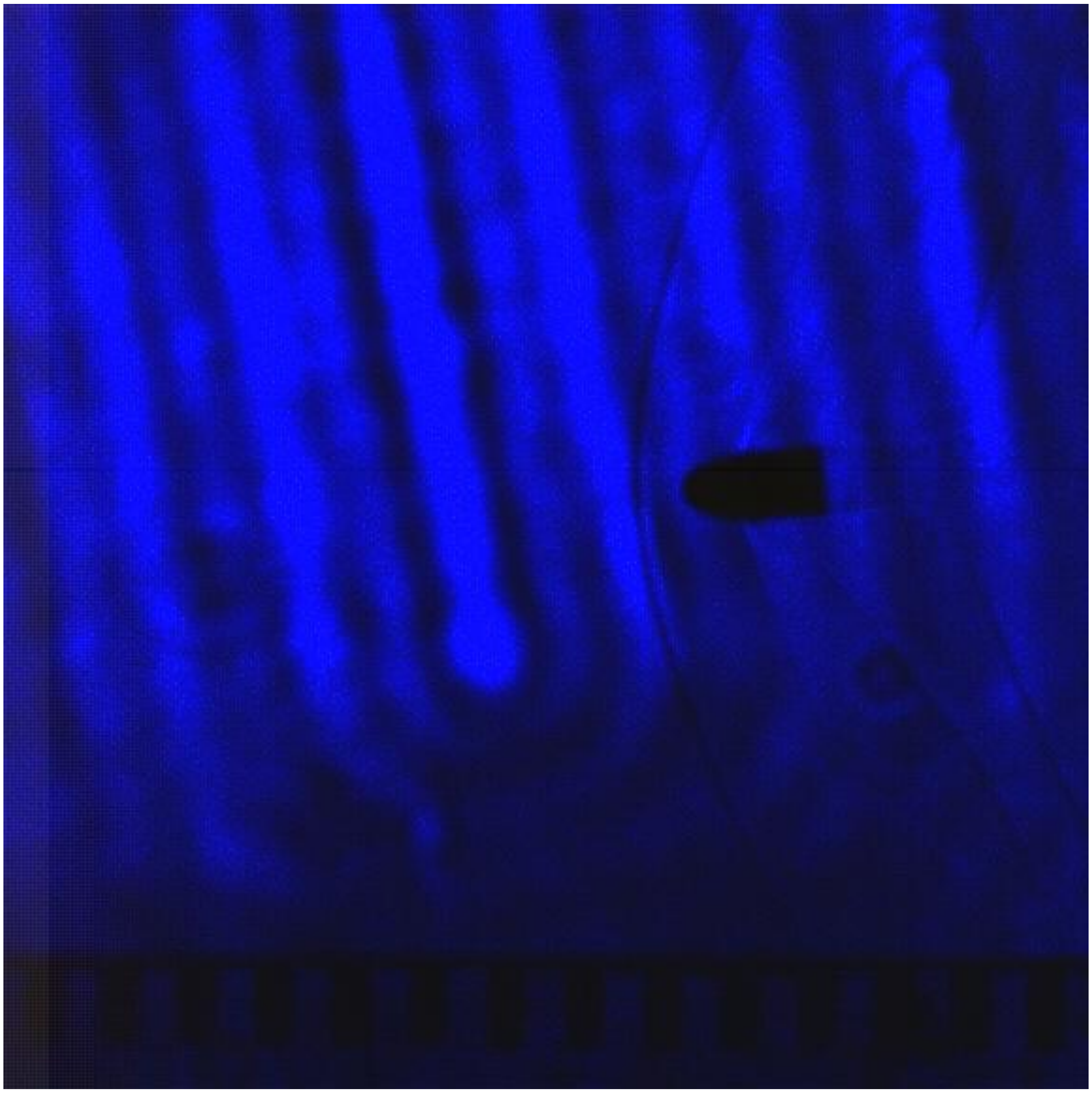


Figure 6.1. Shadowgraph captured with laser strobography which shows a compression wave in front of a bullet in flight.

Several technical issues had to be overcome to successfully create the images.

1. Aperture diameter of the lens.
2. Determining the imaging sensor vulnerability to laser energy source.
3. Using a laser of sufficient response time and energy to create an image.

4. Synchronizing the laser pulse to the high speed camera exposure.
5. Determining the proper pulse width of the laser.
6. Proper alignment of the laser to the laser divergence tool.
7. Proper focus of the shadowgraph.
8. Gunpowder residue affecting the shadowgraph.
9. Taking advantage of the properties of the laser to see through fire.

6.1 Aperture Diameter of the Lens

The camera lens used in the experiment was a fixed 50mm Nikon lens with an f 1.4 aperture. The aperture was usually left open as wide as possible to maintain the ability to see around the laser tool which was fabricated for this experiment. Due to the fact that the camera had to see around the tool, a lens with a larger diameter glass optic was used. Lenses with smaller diameter glass caused the tool to interfere with the image. Because the aperture of the lens was effectively fixed, the exposure of the photo was determined by the pulse duration of the laser.

6.2 Determining the Imaging Sensor Vulnerability to Laser Energy Source

Vision Research is the manufacturer of the Phantom V10 high speed camera. It is widely known that lasers are very likely to damage digital imaging sensors. Because this particular experiment involves such a high value camera, the manufacturer became involved to determine the risk associated with exposing the CMOS sensor in the V10 to

laser energy. The determination was made that as long as the beam was diffused sufficiently no threat to the sensor existed.

6.3 Using a Laser of Sufficient Response Time and Energy to Create an Image

The laser used in this experiment was a 445nm blue laser diode. Figure 6.2 shows the drive circuit used to fire the laser. The diode (D1) was capable of delivering 1800 mW of optical power. An input power of 12V DC was provided to V1. The MOSFET was activated by a TTL input pulse delivered at U in.

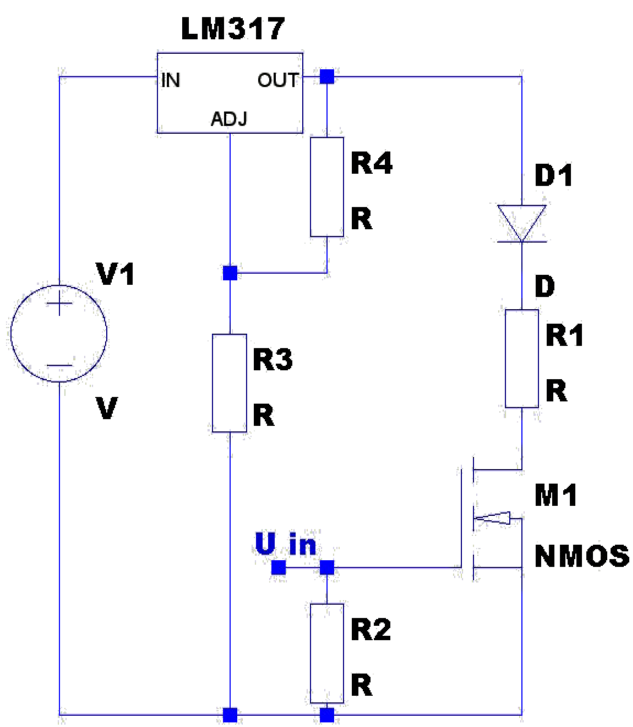


Figure 6.2. Drive circuit for 445nm laser diode (D1).

The camera was tested at several different pulse durations to determine what energy was required to obtain an image. Because almost all of the energy shined from the laser is captured by the camera, it was determined that even a 1 microsecond pulse duration was sufficient to create an image. A 2 microsecond pulse width will provides an image with ideal contrast. The energy needed to create this image is calculated using the equations 6.1 and 6.2 below.

$$Energy_{Optical}(J) = \frac{Power_{Laser}(W)}{Time_{Pulse}(\sec)} \tag{6.1}$$

$$3.6\mu J = \frac{1.8W}{2\mu \sec} \tag{6.2}$$

Because the laser energy is so efficiently applied to the CMOS sensor, the shadowgraph can be captured in a well lit room without significant degradation in image quality. The laser used is shown in Figure 6.3 and Figure 6.4.

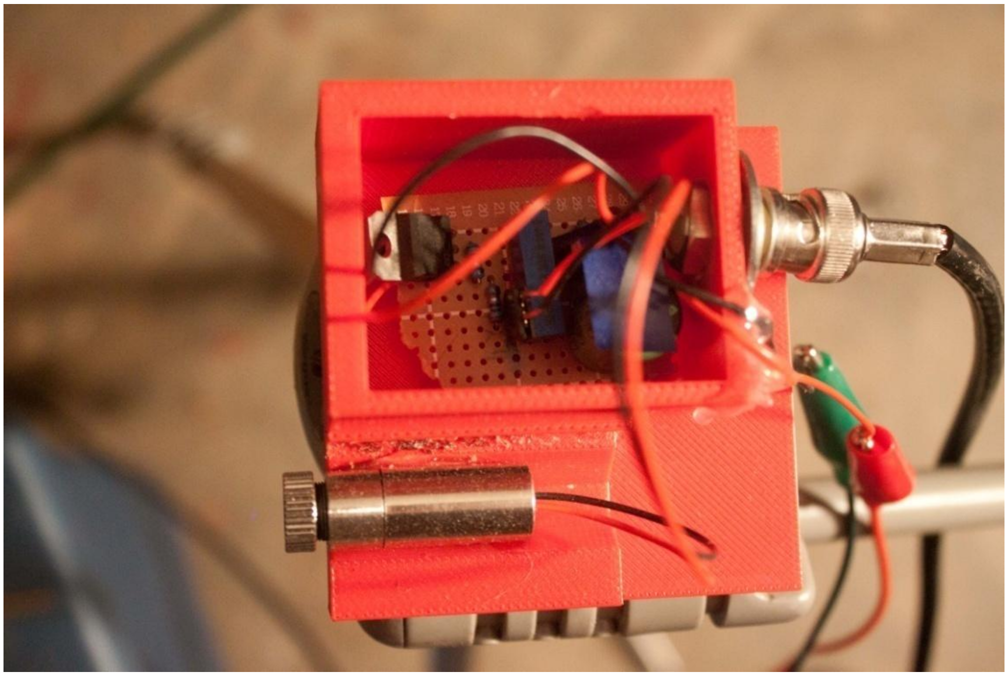


Figure 6.3. 445nm Blue laser diode and drive circuit. The TTL input signal is connected to the circuit on the right via the coaxial cable.

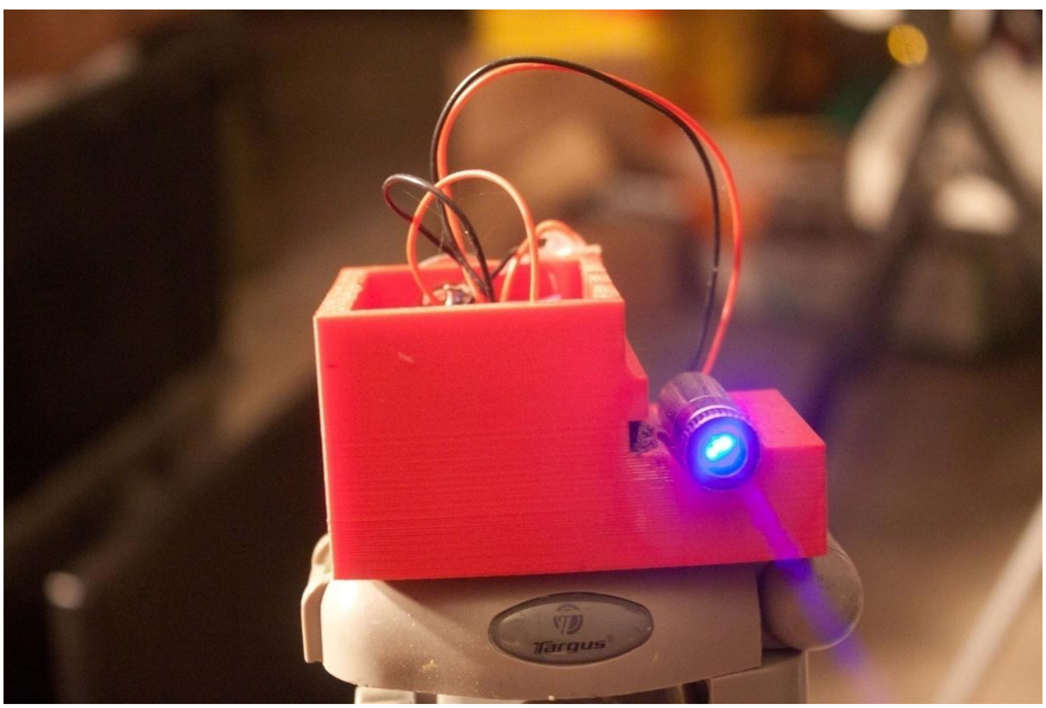


Figure 6.4. 445nm blue laser operating at a 10% duty cycle.

6.4 Synchronizing the Laser Pulse To The High Speed Camera Exposure

The blue pulsed laser's rise time is roughly 1 microsecond to 80% power and 2 microseconds to 90% power. The fall time is approximately .5 microseconds. The output was measured at 180mW at 10% duty cycle. Therefore, the peak power is approximated at 1.8W. A 5V input is used to power the laser. All laser pulses were controlled using a Quantum Composer 9524 Pulse Generator, shown in Figure 6.5.

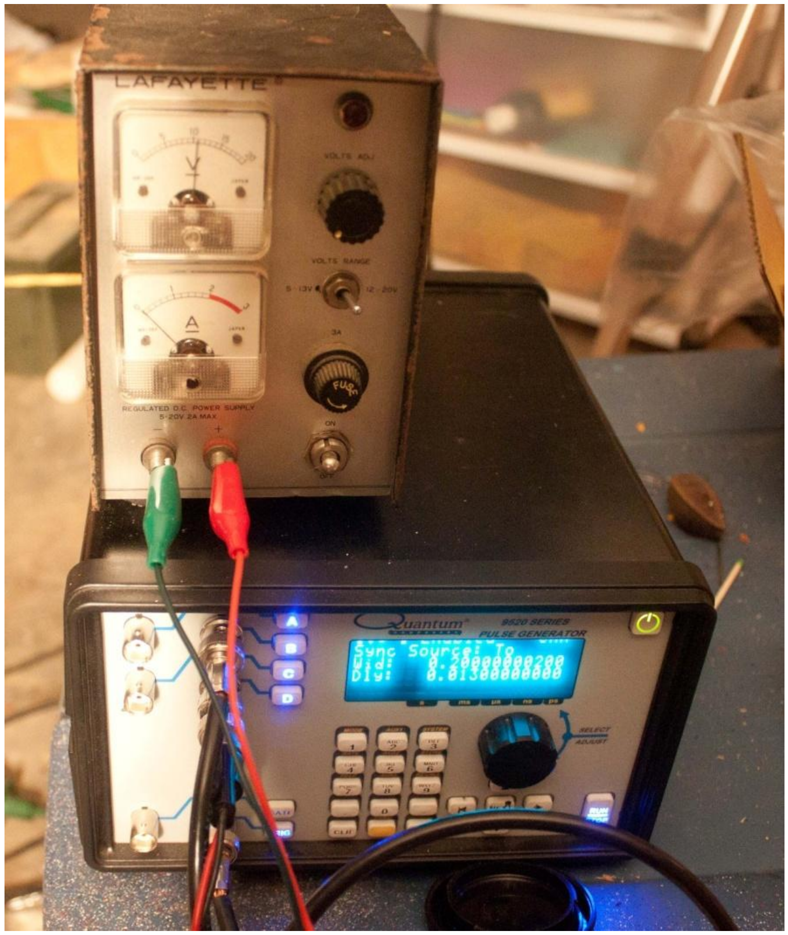


Figure 6.5. Pulse Generator used to switch the laser power supply, which is resting on top of it.

The laser was triggered using the 9524 Quantum Composer Pulse Generator. A piezoelectric buzzer (Radio Shack Part No. 273-073) was used as a microphone to trigger the Pulse Generator, which in turn generated a custom laser pulse sequence. The high speed camera was setup several different ways, depending on the data to be collected. Even though the V10 camera is capable of capturing exposures as short as 2 microseconds, the exposure time must encompass the laser pulse to ensure that an exposure occurs. The ideal timing configuration is shown in Figure 6.6. The tighter the

exposure time is able to bracket the laser exposure, the less noise or ambient lighting affects the images. One challenge in setting up the exposure times in this manner is the ability to synchronize the camera shuttering time with an external event.

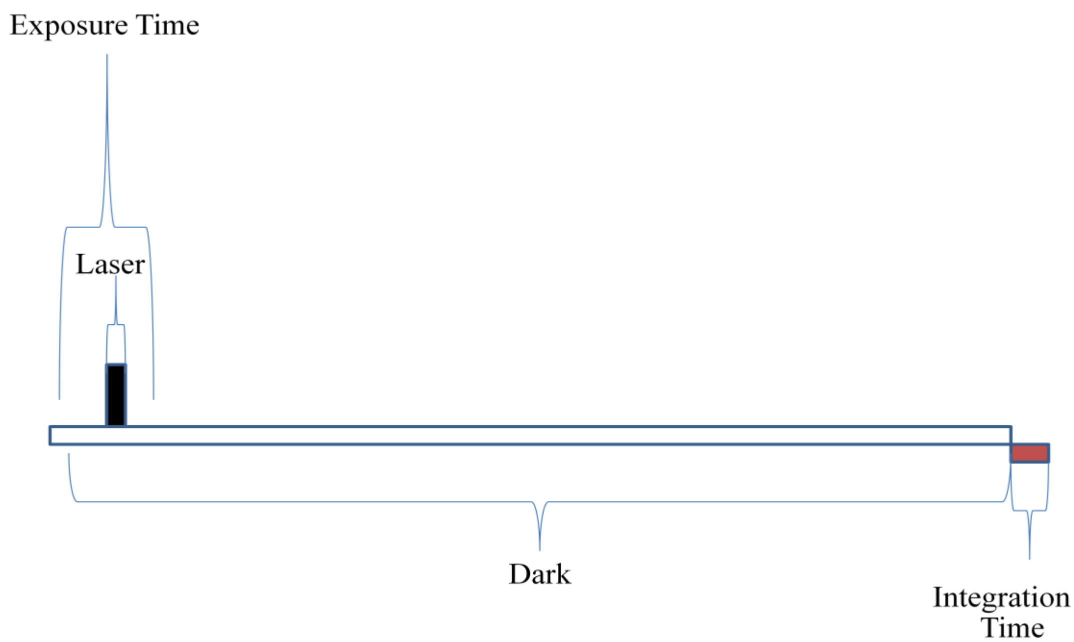


Figure 6.6. Timeline of laser image exposures.

To get around the shutter synchronization issue, a long camera exposure time is used (almost the entire duration of the frame interval) and the laser is pulsed to provide the exposure at the exact moment of interest. Figure 6.7 shows this timeline. Using this method, the laser can be triggered at any random time while the camera is operating. The risk of using this method is that it is possible to fire the laser during the integration time

instead of during the exposure time. The probability of this occurring is simply the ratio of the integration time to the sum of the exposure time and the integration time. For inexpensive events, this minimal risk is acceptable. If an event is extremely costly, this risk may not be acceptable.

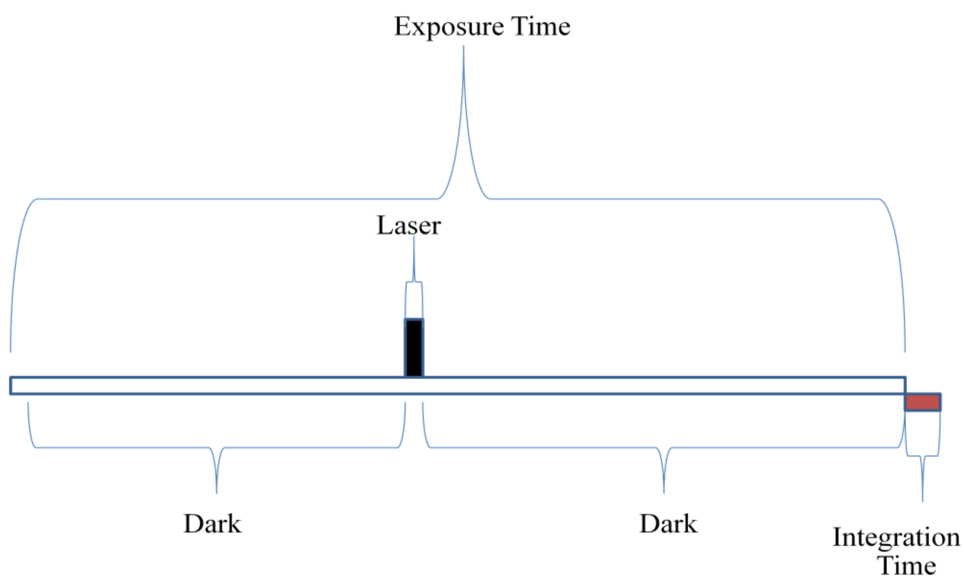


Figure 6.7. Timeline of camera exposures.

The laser pulse interval and the time between frames must be synchronized exactly. Figure 6.8 shows an image captured in which a single camera exposure was illuminated by two laser pusles. The match is used as a marker to determine whether or not the bullet has passed the position or not. The first time the bullet is exposed is approximately 3 cm away from the match. The second time the bullet is exposed is when the bullet is only just touching the match. No shock waves are visible in the photography because the darkness is “overwritten” by the subsequent laser flash.

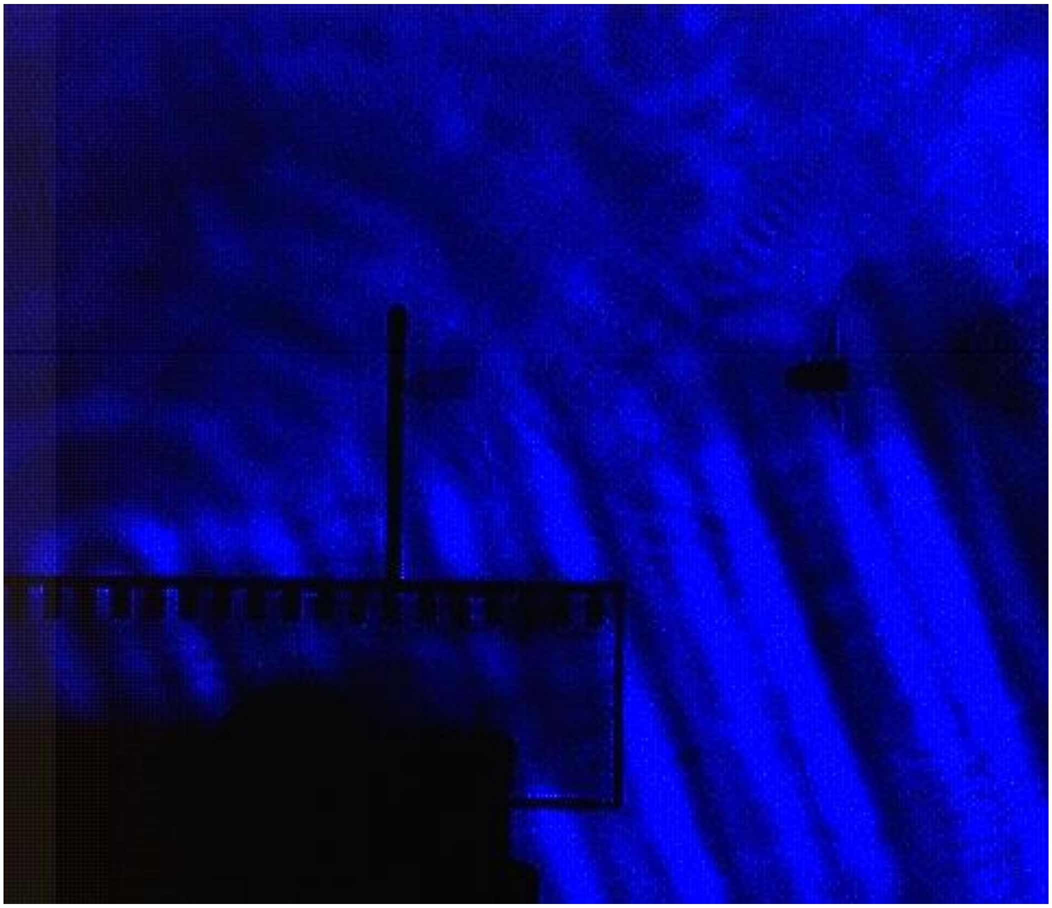


Figure 6.8. A double exposure caused by an improperly synchronized laser.

After the bullet passes the match marker it was then again imaged. The image is much darker because it only has the exposure energy of one 2 microsecond laser pulse instead of 2 as can be seen in Figure 6.9. Although improper focus causes the compression waves to not be clearly identifiable in this particular image, they are present. While double exposures are indicative of a laser pulse rate being too high, black images in the video sequence are indicative of a laser pulse rate which is too low.

Figure 6.9. Single exposure laser strobograph.

Another example of a double exposure can be seen in Figure 6.10. The match head is flipping around in the air and is capture twice on the same exposure by the laser beam.

Figure 6.10. Double exposure of broken match head flipping in air.

Although an acoustic trigger was used in this demonstration, any TTL trigger method may be used. A more exact method would be to use a second laser as a break beam time of arrival sensor.

6.5 Determining the Proper Pulse Width of the Laser

The pulse width of the laser is determined by the sensitivity of the imager, as well as the aperture of the lens. Another factor to take into account is the velocity of the object. For the bullet fired, the ideal exposure time is calculated by Equation 6.3.

$$6\mu\sec \leq \frac{1.016_{BulletLength}(cm)}{10*16764_{BulletVelocity}\left(\frac{cm}{\sec}\right)} \tag{6.3}$$

Since the imager used is able to capture enough light at a 2 microsecond exposure, this is over three times shorter than the ideal exposure time.

6.6 Proper Alignment of the Laser to the Laser Divergence Tool

In a production system, the laser illumination tool would have an integrated laser into the lens filter itself. For purposes of this demonstration, a reflector is used on the tool so mechanical packaging and powering of the laser is not necessary for demonstration purposes. The laser tool is attached to the camera with a threaded filter holder. The mirror does not have to be aligned at an exact 45 degree angle to the camera lens face. The laser is positioned on a tripod and aimed at the mirror located within the laser divergence tool. The laser is then diverged and shined onto the retroreflective screen. Figure 6.11 shows a model of a laser interacting with the laser divergence tool.

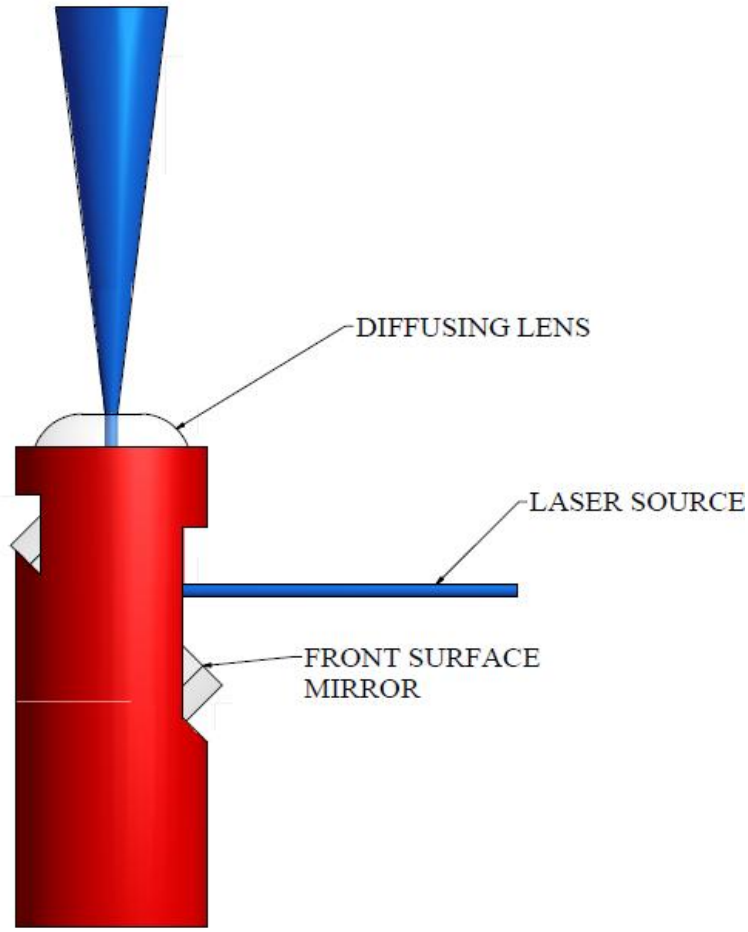


Figure 6.11. Laser divergence tool invented for this application.

Because the laser diode typically has fringes and artifacts within it, it may be important to align the fringes so they do not interfere with the shock wave imaging. It may be desirable to diffuse as well as diverge the laser energy to breakup the fringe patterns created by the imperfections of the laser diode. Figure 6.12 shows the laser divergence tool installed on the camera.

Figure 6.12. Laser divergence tool mounted to a high speed camera shown with an active laser.

Since the tool is affixed to the camera lens, it may be used on any device which is able to accept the mount. Figure 6.13 shows it being used on a Digital Single-Lens Reflex (DSLR) camera.

Figure 6.13. Nikon D40 with installed divergence tool and active laser.

6.7 Proper Focus of the Shadowgraph

The plane that the camera is focused on is important for the correct observation of the shadowgraph. Instead of focusing on the bullet, the camera must be focused on the retroreflective screen itself. Per Dr. Gary Settles, “You must focus on the screen, because that is where the shadow is produced”. This may be counterintuitive to the operator. Figure 6.14 shows an ideal shadowgraph of a hand held Walther P22 pistol. The diffused laser is aimed slightly to the left center to catch a bullet upon muzzle exit.

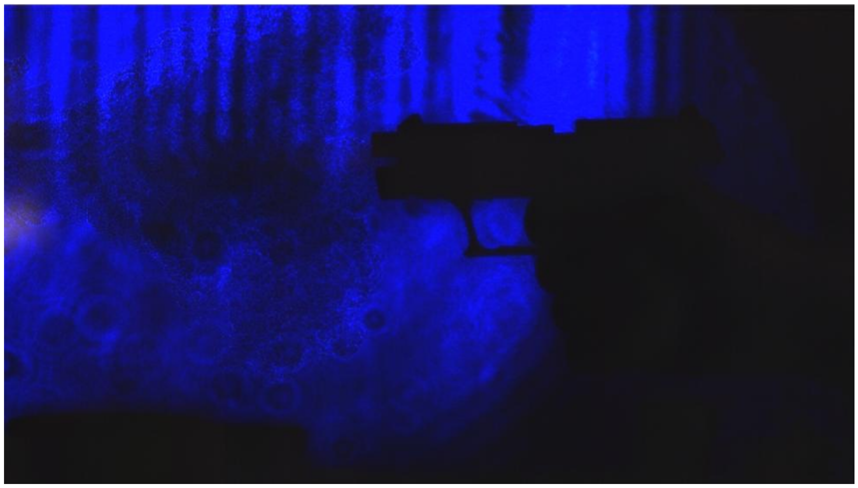


Figure 6.14. Shadowgraph of hand held pistol.

Although the shadowgraph appears to be sharply focused in Figure 6.14, the camera is actually out of focus with respect to the pistol. To demonstrate this, a Canon 580 EXII flash was fired less than 1 millisecond after the shadowgraph was taken to enable the visualization of the pistol. The image shown in Figure 6.15 uses the exact same camera settings as that of Figure 6.14.

Figure 6.15. Hand held pistol visualized by camera flash.

Figure 6.16 shows an example of an image captured with improper focus. Even though the bullet and match are easy to see, the disturbance wave in the air is difficult to see because the focus is too shallow.

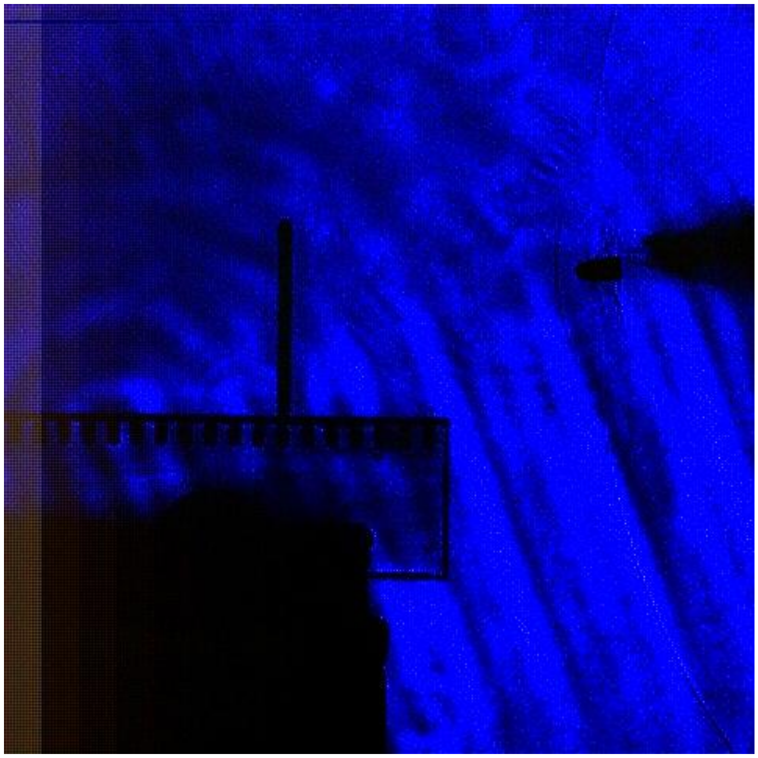


Figure 6.16. Improperly focused shadowgraph.

Another advantage of this method once a proper focus is achieved is the fact that the low diffraction of the laser light maintains edge sharpness of the shadowgraph. Figure 6.17. Demonstration of shadowgraph edge sharpness at varying distances. Figure 6.17 shows two images which were captured using different distances from the camera lens. The distance from the camera to the screen, focus and zoom of the camera lens were all maintained between the photographs. The edge clarity between the two images is maintained, even though the position of the object is drastically changed.

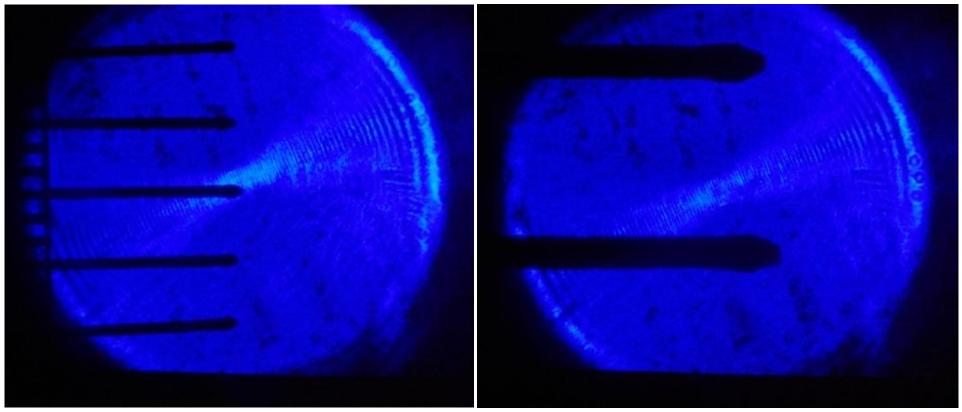


Figure 6.17. Demonstration of shadowgraph edge sharpness at varying distances.

6.8 Using the Technique to Measure Impact Fracture Mechanics

Because this technique is well suited to capturing images at extremely short time intervals, it is ideal for high speed events such as bullet impacts. Figure 6.18 shows a series of four images which were captured with a DSLR camera. The laser pulses used were 300 nanoseconds in duration. This image sequence was captured by firing four separate bullets at and capturing four different images using different time delays. The delays were approximately 10 microseconds between.

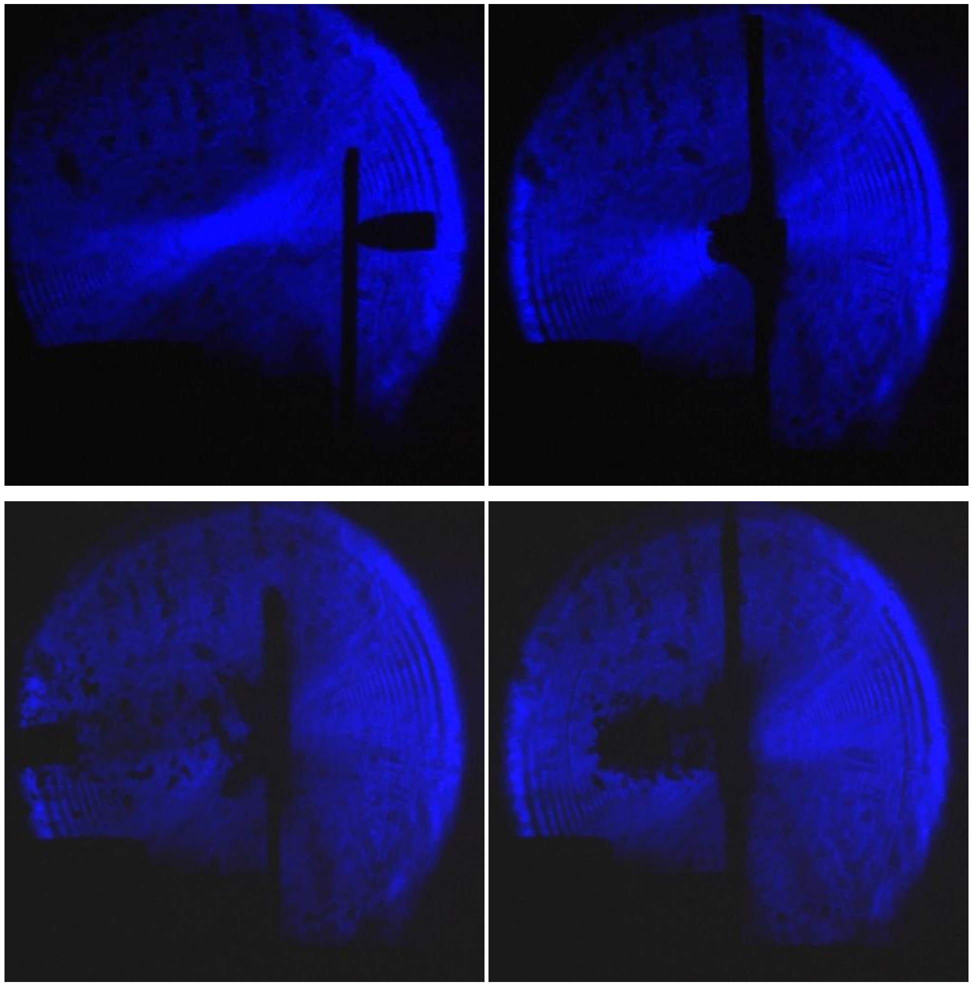


Figure 6.18. Bullets impacting plexiglass sheeting.

A closer look at these images reveals some very interesting and useful data. Figure 6.19 shows a close up image of the exact moment a bullet rips through a piece of flat plexiglass. Using the invented method several new pieces of data are able to be captured. Arrow 1 shows the direction of bullet travel. The back of the bullet is visible as it enters the plexiglass from the right. Arrow 2 shows the reflection of the bullet's initial shock wave off of the plexiglass surface. Arrow 3 shows the shock wave created by the impact on the face of the plexiglass. Arrow 4 points out the discontinuity in this

reflected shock wave created by the bullet travel itself. Arrow 5 shows the shock wave created on the exit side of the plate.

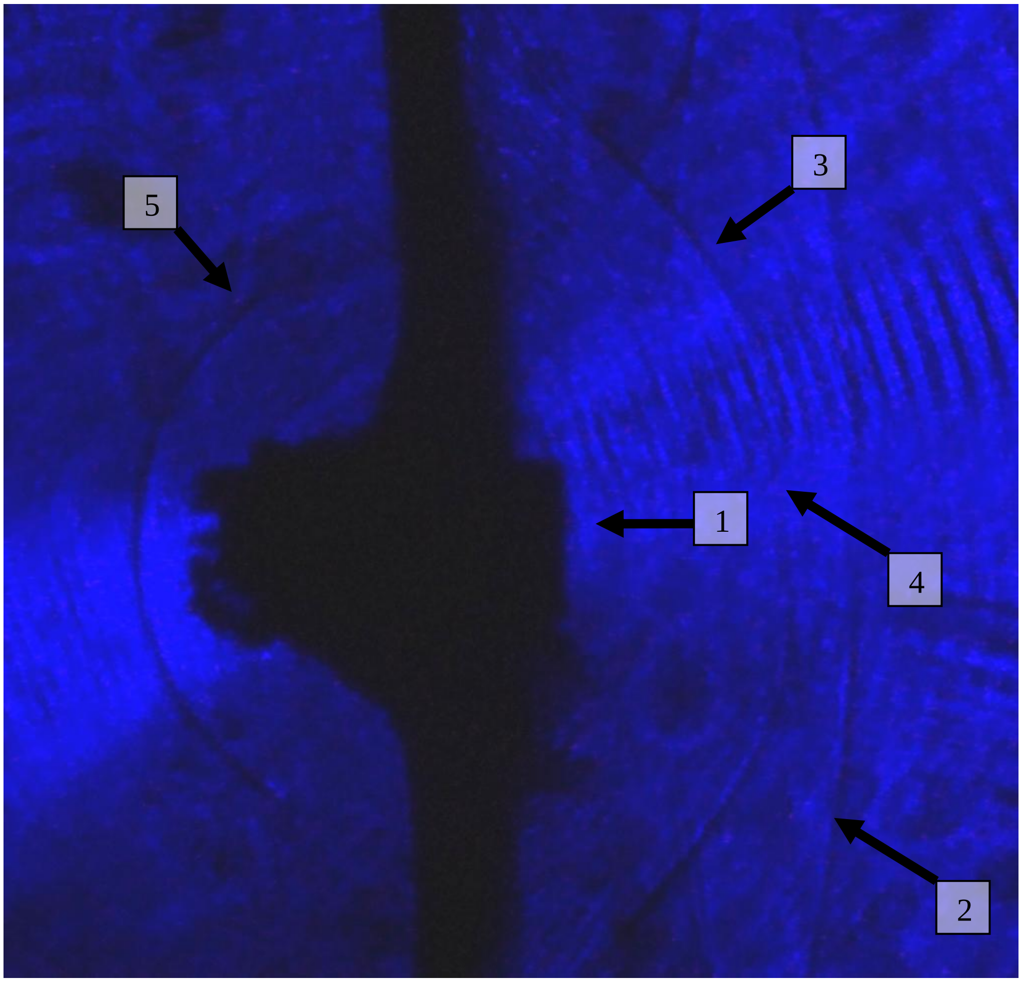


Figure 6.19. Detailed shadowgraph of bullet impact created by direct retroreflective laser strobography.

6.9 Taking Advantage of the Properties of the Laser to See Through Fire

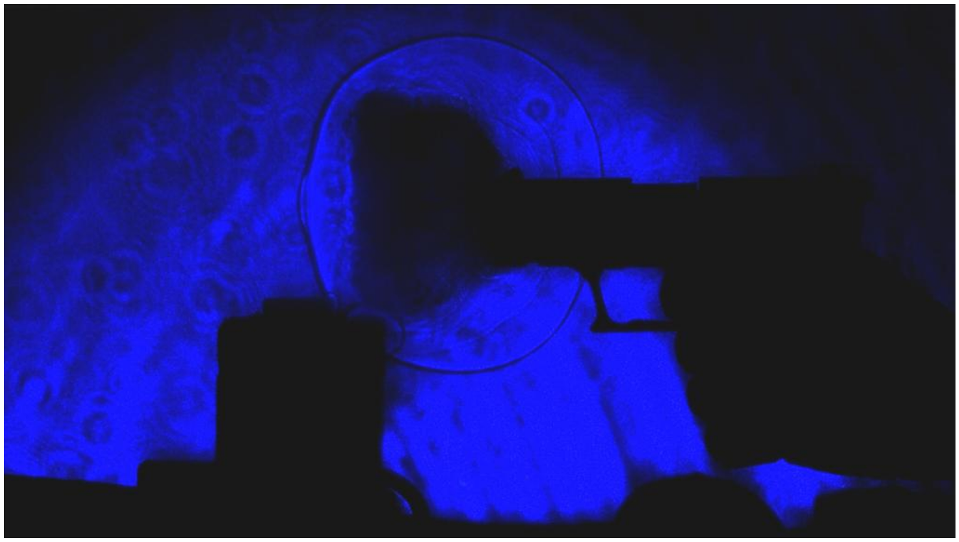
For scientists studying energetic events, one problem that often causes loss of data is “white out” due to fire. Usually the fire is a by-product of a propulsion method and inhibits the ability to gather important data from an energetic event. By taking advantage

of the coherent nature of the laser light, all unnecessary light can be filtered out. Figure 6.20 shows a 442 nm band pass filter (Edmund Optics Item No. 65200) which has a 10nm band width. Figure 6.21 shows the filter installed onto the camera using an empty filter mount (Edmund Optics Item No. 67690).

Figure 6.20. Band pass filter (442 nm) positioned beside laser divergence tool.

Figure 6.21. Laser divergence tool installed in front of beam pass filter.

This unique configuration allows for high speed digital imaging of object which cannot normally be seen due to flame. Figure 6.22 shows a pistol being fired with and without this filtering technique.



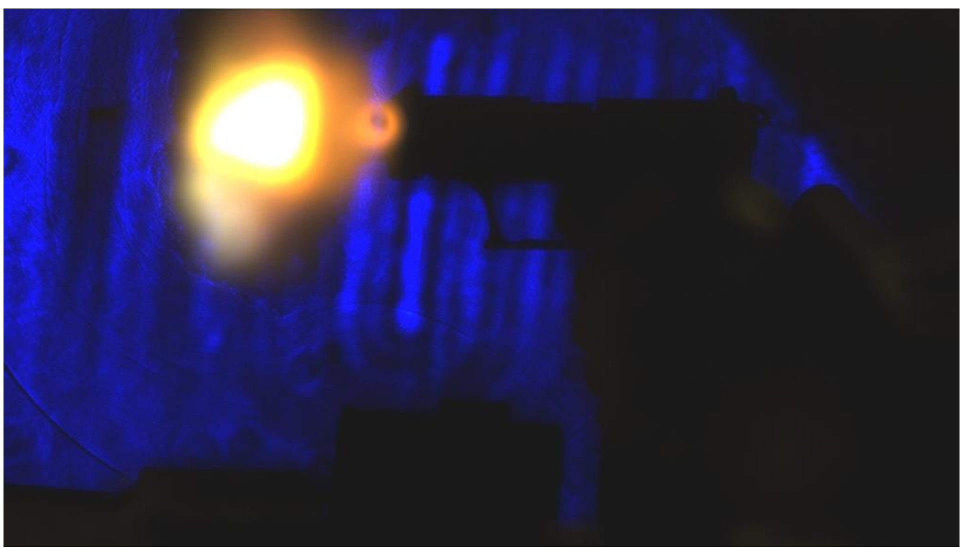


Figure 6.22. A .22 caliber pistol shadowgraph fired with and without filtering.

This filtering technique has also proven to be useful for more violent deflagration events. Figure 6.23 shows a row of matches with a .22 caliber rifle aimed such that it

will sever the matches in half when fired. A test was performed using a candle and ether as a flame obscurant *while* firing the rifle. The size and intensity of the flame can clearly be seen in the video image sequence.

Figure 6.23. A can of ether is sprayed over a candle to produce a huge flame obscurant over a row of matches.

This violent event was captured on high speed video both with and without the filtering method. Figure 6.24 shows a high speed image sequence of the event observed without any filtering.

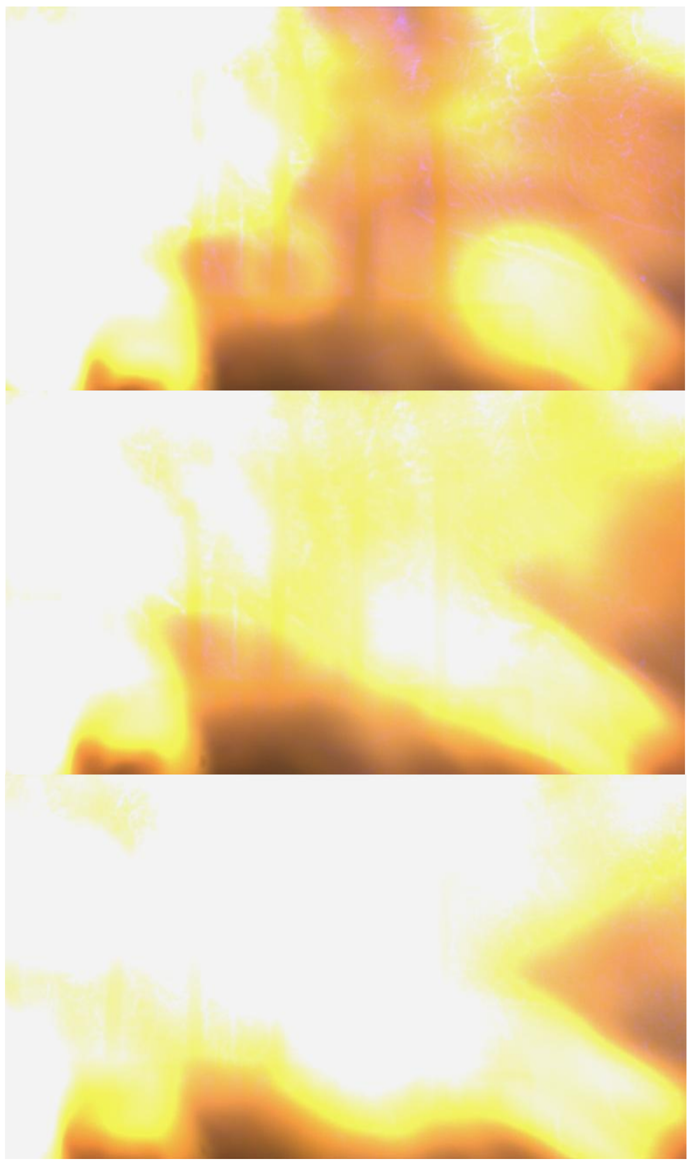


Figure 6.24. Image sequence of bullet breaking matches inside of large fireball.

The test was repeated with the laser filtering technique in play. Figure 6.25 and Figure 6.26 show two different image sequences of this event. The triggering method is exactly the same as used to create Figure 6.24. Notice no flame is seen on the first frame. The bullet is circled in red and is travelling from right to left.

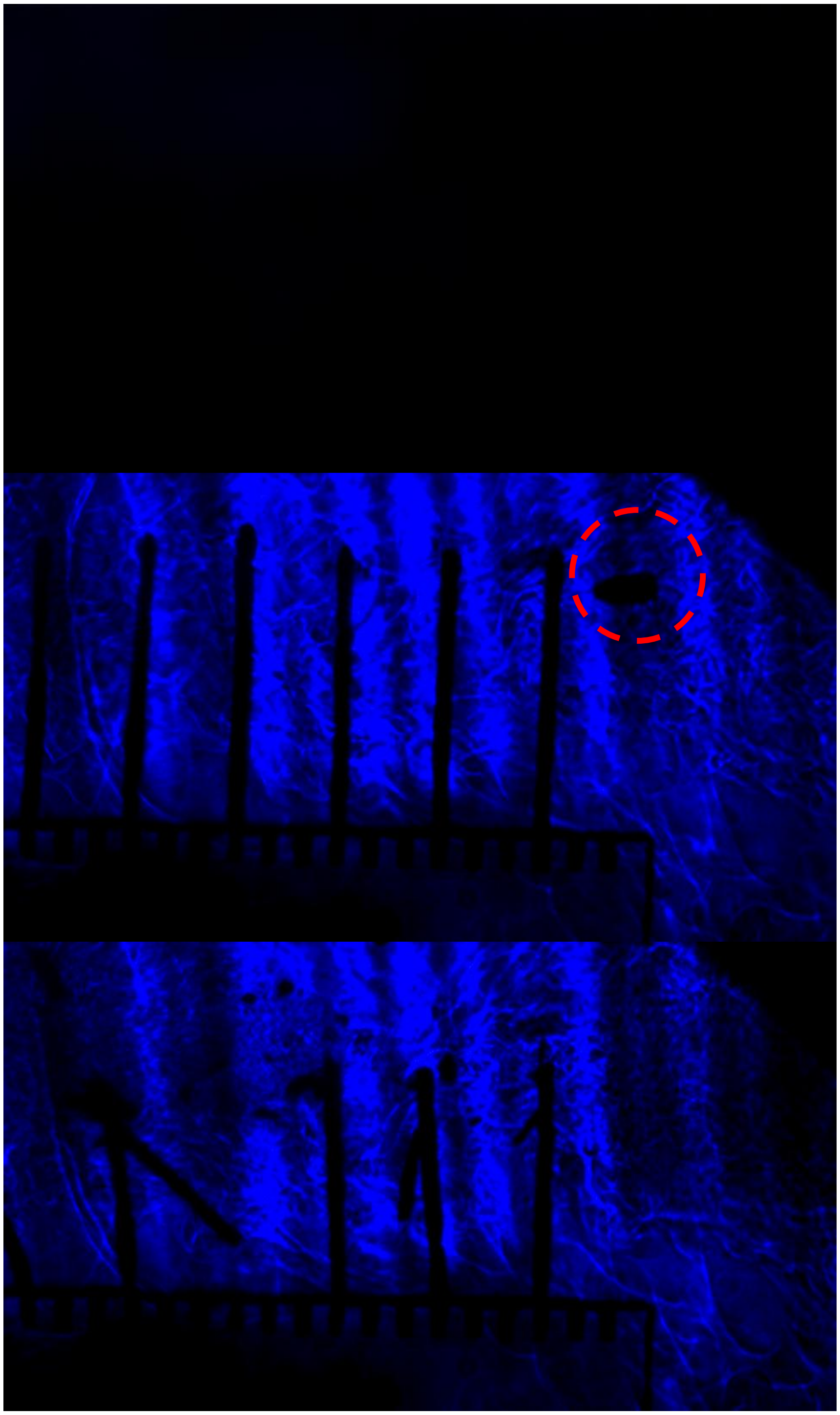


Figure 6.25. Image sequence of bullet cutting matches.

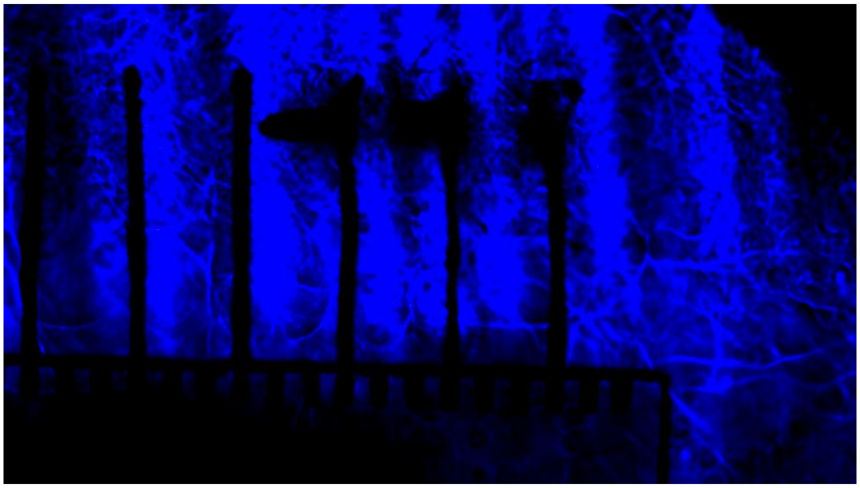


Figure 6.26. Image of bullet cutting matches (inside a flame).

6.10 Results

The new method successfully demonstrated the ability to both create shadowgraphs showing fluid disturbances and objects through fire. The method is simple, reliable, easy to use, and inexpensive. It has been demonstrated on both inexpensive DSLR cameras, and expensive high speed digital video cameras.

CHAPTER SEVEN

CONCLUSIONS/RECOMMENDATIONS

While this new method represents a great leap forward in high speed shadowgraphy technology, credit must be given to the pioneers who helped create the methods which it leans on. In particular Dr. Gary Settles's work was well written and presented in a way which allowed to author to arrive at the conclusion that this method was possible.

7.1 Capabilities

The method demonstrated is superior to the current state of the art in several ways. These ways include ruggedness, cost, reliability, ease of setup/operation, ability to see through fire, energy efficiency, and safety.

- The electronics used in a solid state laser diode are more rugged both mechanically and electrically.

- With the exception of when a high speed camera is being used, this new method is extremely cost effective. The author assembled all equipment necessary to perform the experiment by personally procuring or building the equipment. The Quantum Composers Pulse Generator can easily be replaced with a simple Pulse Width Modulation circuit triggered by a TTL signal. Instead of using a high speed digital camera a consumer grade DSLR camera may be used as demonstrated with a Nikon 40D.

- This technique is simple to setup and very reliable once operational. The previous method required an optical table and precise adjustment instruments. All tests described in this document were conducted with two inexpensive tripods constructed from aluminum and plastic.

- The small components make this technique ideal for in-the-field situations. All equipment (except for the retroreflective screen) can easily be carried in a small cardboard box.

- Energy required to create images is over one thousand less than arc flashes or x-ray methods. Fragments and objects can be clearly observed in the presence of a large fireball. Images may also be created in daylight.

- Typical shadowgraphy test setups involve precise alignment of a light source, the imager, and the item under test, which can be time consuming. The method described in this document simply involves repositioning the retroreflective screen and refocusing the camera in order to reframe a shot.

- Because the image being created is a shadow located on the retroreflective screen, the edge clarity of the image is always sharp regardless of where the object is located between the laser source and the screen. This is caused by the low diffraction of the laser energy being used.

7.2 Limitations

Although Direct Retroreflective Laser Strobographic Shadowgraphy increases capabilities in most areas, there are several limitations.

- Retroreflective screen could be damaged when observing fragmenting events.

- To see through fire, a specific band pass filter must be purchased that corresponds with the illumination laser. These filters are often rather expensive. The color of the illumination laser should be carefully selected by determining what type of light energy is created by the accelerant. band of the spectrum is not produced by the fire the observation is being made through.

- If a DSLR camera is uses, the shutter must be timed correctly to limit ambient light (even if filtered) from exposing the imaging sensor.

- Opaque particles absorb the laser energy, stopping the beam from completing its path to the camera lens. If a “dirty burn” condition exist, a cloud will be observed.

- Depending on the design and makeup of the laser diode, current limiting circuitry built in to the laser driver can cause long pulse durations to be realised. Current technology available to consumers allows for very fast pulse duration diodes to be

readily accessible in the blue and red colors. Green diodes may require a warmup time of several milliseconds, which is not ideal for illumination of ballistic events.

7.3 Recommendations

Several additional enhancements to this method are possible. The power of the laser could be increased and the pulse duration could be decreased. An interesting experiment would be to use an RGB laser to take white images on a color camera. The pulses of the different lasers could even be fired at different times to collect three different shadowgraphs on a single exposure. Using this method, the data rate of a high speed camera could easily be trippled. One concern is if the three laser diodes don't have similar "ramp up" times. For example, if one is photographing a bullet traveling at 350 meters per second (extremely fast) and can tolerate only .5mm of image blur. The required time is (.0005/350) 1.5 microseconds to get a image without any blur. This may prove to be very difficult to do with a common off the shelf laser diode, but it should at least be attempted. If three different colors of laser light are used then the rise time of each individual laser diode is important to ensure proper alignment of the “laser flashes.” If the lasers are able to accomplish these types of rise times, then a 2 microsecond difference in time between the green laser and the other two lasers may create a green "halo" effect on the bullet if they are all triggered at the same time. One way to get around this problem would be to drive each individual colored laser from of a different channel from the pulse generator. Any delays which may exist between different colored laser diodes can be negated by adjusting the trigger times on a different channel of the pulse generator, thereby making each R,G, and B color laser lighting independently

controllable via TTL. The laser diodes could also easily be integrated into the lens filter assembly, negating the need to perform an alignment each time a setup if moved.

APPENDIX

JENOPTIK DIFFUSER

The manufacturing method used to create the diffuser is simple injection molding. Table A.1 shows a listing of the different types of diffusers present on the diffuser sample provided by Jenoptik from Huntsville, Alabama.

Table A.1. Laser Diffuser Shapes

Part #	Shape	Full Angular Divergence (Horizontal)	Full Angular Divergence (Vertical)	Line Width
D001	Rectangle	5	3.3	-
D002	Rectangle	5	3.6	-
D003	Rectangle	5	3.9	-
D004	Scope	10	10	0.4
D005	Rectangle	5	4.3	-
D007	Scope	5	5	0.4
D009	Scope	2	2	0.3
D010	Scope	2	2	0.1
D011	Scope	1.1	1.1	0.2
D012	Rectangle	5	3.1	-
D013	Crosshair	10	10	0.9
D014	Crosshair	10	10	0.4
D016	Crosshair	5	5	0.9

Table A.1 Continued

D017	Crosshair	5.1	5.1	0.4
D019	Crosshair	1	1	0.4
D021	Rectangle	2	1	-
D022	Rectangle	5	2.5	-
D023	Rectangle	10	5	-
D028	Rectangle	5	3.8	-
D029	Rectangle	2	1.5	-
D032	Rectangle	13.1	8	-
D038	Square	2	-	-
D039	Square	1	-	-
D040	Square	0.5	-	-
D041	Ellipse	9.9	2	-
D042	Ellipse	9.9	5	-
D048	Round	2	-	-
D049	Round	1	-	-
D050	Round	0.5	-	-
D051	Lines(1)	10	-	1
D053	Lines(100)	14.4	14.4	0.1
D058	Lines(10)	6.7	6.7	0.4
D059	Lines(10)	5	5	0.2
D063	Grid (24x24 square)	14.1	14.1	0.2
D064	Grid (24x24 square)	10.6	10.6	0.2
D065	Grid (24x24 square)	6.5	6.5	0.1
D067	Grid (9x9 square)	5	5	0.2
D068	Grid (9x9 square)	2.7	2.7	0.1
D069	Rectangle	5	3.5	-
D070	Ring/Concentric (24)	21	-	0.2
D071	Ring/Concentric (10)	9.7	-	0.2
D072	Ring/Concentric (9)	9.9	-	0.2

Table A.1 Continued

D073	Ring (1)	11.4	-	0.7
D074	Ring (1)	10.3	-	0.2
D075	Ring (1)	5.4	-	0.2
D076	Rectangle	5	3.2	-
D077	Rectangle	5	4.2	-
D078	Rectangle	5	4.5	-
D079	Ring/Concentric (25)	11.3	-	0.1

Figure A.1 is a grid map which shows the correlations between the laser diffuser positions and the areas of the plastic laser diffuser. Each small grid represents a different laser diffusing method characterized by a geometric shape generated by the laser beam.

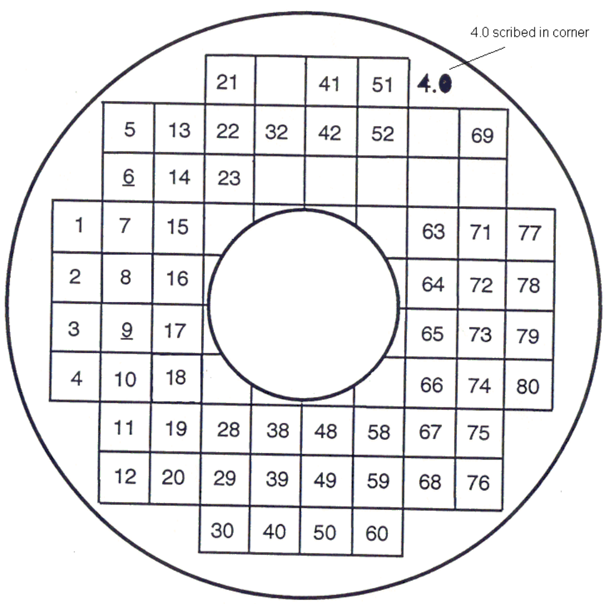


Figure A.1. Jenoptik Diffuser Sample Disc grid map.

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