ABSTRACT

HIGH-SPEED, CONTINUOUS MONITORING OF LIQUID SPRAYS BY
MULTI-WAVELENGTH ABSORPTION SPECTROSCOPY

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A fiber-optic array was created by arranging four Corning lensed fibers in a parallel, horizontal plane. It has been shown that through the use of multi-wavelength spectroscopy, this fiber array is capable of probing a spray in four discrete locations.

Two wavelengths of laser-sourced light were selected based on the optical properties of water, the fluid under investigation. Water was used as the working fluid only to evaluate the measurement techniques described here; the intent is to apply the techniques, once developed, to fuel sprays. One wavelength that is absorbed by water (1450nm) and one that is not (1310nm) were used for the spectroscopic analysis. A super-continuum (1300nm-2000nm) and diode lasers were independently used as the source of light for this experiment. In the case of
the super-continuum source, the absorbing and non-absorbing wavelengths were selected using fiber Bragg gratings or a custom filter based on a profile gauge.

By generating two pulses of different wavelengths and temporally separating them by various delay fibers, it was possible to make each wavelength distinct when received by a photodiode (detector). The dual-wavelength signal was split four ways to service each branch of the lensed-fiber array. Additional delay fibers were placed after the splitter and before the lensed fibers with the purpose of making each branch’s signal distinct. By keeping each delay described to the minimum detectable amount of time, it was possible to “freeze” the spray in time. In this situation, the dynamics of the spray are much slower than the dynamics of the optical system, a key requirement facilitating quantitative measurements even though the amount of scattering in the spray varies dramatically.

After the light has been transmitted through the spray, the light was collected by a detector. By comparing the transmitted strength of the absorbing and non-absorbing wavelengths, one may begin to make quantitative statements about the spray. Using the quantifiable measurements of droplet size, spray-plume geometry and fluid properties, complete measurements of the quantity of liquid can be made. Through the use of the multi-point measurements described in this work, one can produce a map of liquid and vapor throughout the spray plume at a given distance from the nozzle tip.
The results of trials using the various sources of light are consistent, as the diode lasers were tuned to produce similar characteristics to the super-continuum source. Further development of the processes described here depend on light sourced from super-continua, as this method provides greater flexibility and expandability.

Single-point measurements were also conducted using careful spatial filtering of the transmitted light. Through this method, it was possible to determine whether the light has contacted liquid only, vapor only, or both phases. The method of collecting light based on its direction of incidence at the detector is discussed in the body of this work. Future iterations of the multi-point technique may incorporate advanced spatial filtering techniques.
I dedicate this to my parents, for it is their support of my education which made this possible.
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1 INTRODUCTION

1.1 Goals

The research objective was to develop advanced optical diagnostics to be applied during liquid spray events. Given recent discoveries in combustion and spray dynamics, it has been shown that there is potential to control spray development, air entrainment, and atomization through the use of unique injector designs incorporating micro-nozzles. The aim of this research was to specifically examine the effect of injection pressure and nozzle configuration for cold and hot spray conditions. The use of water sprays described in this investigation is intended as a basis for continued investigation of hot and cold liquid hydrocarbon fuel sprays.

One technique with great potential is an enhanced version of absorption spectroscopy based on combined wavelength and spatial scanning of a laser beam [1]. In this technique, a laser that rapidly scans in wavelength is used to measure high-resolution absorption spectra along a line-of-sight; the laser beam is also scanned through space by a vibrating mirror so that data are recorded along many lines-of-sight. Tomographic reconstruction can be employed to obtain spatially resolved information (such as a 2-D image of fuel vapor concentration in a planar slice through the spray). A simplified version of tomography was used in the multi-point spray analysis used as the basis for this work.
Few measurements exist that have demonstrated the ability to describe quantitative fuel properties in practical, combusting sprays. A primary goal of this project has been to develop sensors for simultaneous liquid and vapor concentration as well as provide the groundwork for measurements of other quantities, including local temperature, oxygen concentration and liquid volume fraction. Multi-color laser sensors are critical to obtaining such quantitative information in sprays, and Prof. Sanders' group has developed into a unique expertise in this area.

Due to the absorption characteristics of hydrocarbon fuels, this technique was first conducted using a water spray. Liquid and vapor water have vastly different wavelength absorption characteristics, and through previous testing of water sprays, information has been collected and processed for evaporating water sprays. The previous method was not conducted in such a way as to be applicable to fuel sprays. The technique described here can be applied to fuel sprays. By first testing the technique with water, it was possible to compare characteristics to previous water spray tests.

1.2 Why Water?

One of the keys to effective diagnosis of sprays is the ability to distinguish liquid and vapor phases of the working fluid, so that effects of atomization and evaporation can be understood. In small molecules, such as H₂O, liquid and
vapor can be easily distinguished because of their unique absorption spectra as shown in Figure 1.1.

![Absorption Spectra](image)

**Figure 1.1:** Water absorption spectra showing easily distinguishable features of liquid and vapor.

This fortuitous situation allows simultaneous, independent measurements of liquid and vapor. In a previous experiment, measurements of H$_2$O liquid and vapor were performed in non-evaporating and evaporating water sprays, with the results shown in Figure 1.2. The liquid and vapor were distinguished on the basis of their spectra. This experiment was conducted using single line-of-sight measurement through the axis of the spray.

As can be seen from the water absorption spectra, liquid water results in the attenuation of a wide span of wavelengths. Water vapor causes attenuation to
narrow bands of wavelengths. These characteristics are quite distinct, and it was possible to create a LabView program to simultaneously analyze the attenuation from both phases. This was the first step in the spray research described here, and techniques more applicable to fuel sprays have since been developed based on these initial tests.

Figure 1.2: Simultaneous Liquid and Vapor Measurements

Unfortunately, in the larger molecules of interest in fuel injection research, distinguishing liquid and vapor by unique spectra is impossible. In larger molecules such as hydrocarbon fuels, the vapor spectra look nearly identical to the liquid spectra. It becomes impossible to detect one spectrum in the presence of another. In the case of an evaporating liquid spray, both phases would be present simultaneously.
As an example, the spectrum for liquid heptane is shown in Figure 1.3. Note that it is essentially indistinguishable from the heptane vapor spectrum shown in Figure 1.4. Thus, an alternative approach is required for distinguishing liquid and vapor in hydrocarbon fuel sprays. The work presented here serves as the starting point for research that will allow simultaneous analysis of liquid and vapor phases of fuels.

Figure 1.3: Hydrocarbon Fuel Spectra
Figure 1.4: Heptane Vapor Spectrum
2 BACKGROUND & LITERATURE REVIEW

2.1 Impetus for Investigation of Sprays

Diesel engines are capable of much higher fuel economy than comparably sized gasoline engines. Correspondingly, the diesel engine produces far less carbon dioxide emissions. These benefits have led to immense popularity of the diesel engine throughout the European market. Due to more stringent diesel engine emissions in the United States, this engine has remained a very small player in this market. Further impeding acceptance among U.S. customers is the historically high level of noise and vibration in passenger-car diesel powertrains.

Air-fuel mixing is a key component to achieve efficient combustion with minimal emissions. It is widely accepted in the engine community that the fuel injection process plays a significant role in the performance, economy, emissions and refinement of a modern Diesel engine [2-8].

2.1.1 Cavitation

It has been shown that cavitation within the injector contributes to the break-up of fuel jets and fuel atomization. Researchers at DaimlerChrysler Research and Technology have developed optical diagnostics and simulation tools to investigate this technique [4]. Their optical analysis utilizes a high-speed CCD camera and a transparent nozzle. Results of this analysis have shown that
hydrodynamic cavitation is the most significant effect. Pressure changes inside the nozzle cause bubbles to form inside the nozzle and subsequently collapse once the spray leaves the nozzle tip and the external conditions change.

2.1.2 HCCI

New manufacturing techniques are becoming available that will enable precise control of injector tip characteristics with holes sized significantly smaller than what is available today. Additionally, manufacturing techniques have shown the ability to produced grouped holes and alter hole geometry, including radiusing and conicity. The engine research community is finding new ways to take advantage of this technology.

One method being investigated to combat the high particulate matter (PM) and NO\textsubscript{x} engine-out emissions from the Diesel cycle is Homogeneous Charge Compression Ignition (HCCI) technology. In this form of combustion, the engine designer attempts to achieve a roughly homogeneous mixture in the combustion chamber, the same manner used in most gasoline engines. However, combustion essentially occurs as a random act of uncontrolled, compression-ignited combustion.

This regime results in low temperature, lean combustion and produces low NO\textsubscript{x} and PM emissions. Unfortunately, it is also incapable of high specific output at
its current state of development. As a result, high power requirements must be met through larger engine displacement or use of a dual mode cycle. Although HCCI combustion is largely uncontrolled, one way to influence the in-cylinder dynamics and combustion is through the use of advanced fuel injector strategy. This includes injector tip geometry and injection pressure.

2.1.3 NADI

A product of these new manufacturing techniques is aiding in the development of dual-mode combustion technology. Narrow Angle Direct Injection (NADI) is an active dual mode combustion strategy being developed at Institut Francais du Petrole (IFP) [2]. This technology uses injectors that produce a narrow included angle spray cone. These injectors produce an included angle between 50-100°, versus typical Diesel injectors which spray at an included angle of 145-155°.

Under low and medium load, the system utilizes early injection. This causes the fuel to swirl in the specially-shaped piston bowls and become highly premixed. At high loads, the system performs as a normal Diesel cycle and is capable of high specific output. The result at low and medium loads is approximately 100 times less PM and NOx emissions than Diesel engines, and significantly less unburned hydrocarbon (HC) and carbon monoxide emissions than HCCI. Currently, this method is being investigated in test engines. Neither IFP publications nor the IFP website describe optical analysis of this injection technique.
2.1.4 Grouped Holes

Another product of emerging injector manufacturing technology is that of grouped holes [3]. This strategy provides a passive means of operating a dual mode engine. Using newly-developed drilling techniques, it is possible to drill smaller holes in groups of two or three. These holes can be convergent, cylindrical or divergent, and they can be drilled at different lateral angles from each other. The result is greater surface area to volume ratio of the spray at low load. This promotes vaporization and mixing. As load and cylinder pressure increases, the sprays from each grouping of holes begin to merge, until they become a single large spray at peak load pressures. This single larger spray lends itself to traditional diesel combustion at high loads and increases peak engine power and torque.

This method promises many of the same benefits as the NADI system, and holds the potential to be a simpler system. As with the NADI system, the injector hole geometry and pressure is key to development of spray distribution and atomization. The researchers of this technique are currently investigating the spray invasively by measuring the momentum at different distances from the injector tip. They are also measuring the mass flow rate at ambient conditions as well as performing computational fluid dynamics simulations of spray development. While some of these measures are quantitative, they are also invasive techniques which alter the behavior of the spray.
None of the promising techniques described above utilize a means of analysis that is both quantitative and non-invasive. Clearly, such a technique would be valuable in comparing CFD simulation to actual spray patterns and atomization. The lack of such a technique served as a primary motivator to develop multi-wavelength absorption spectroscopic analysis.

2.2 Alternative Techniques

There are many methods of investigating sprays, depending on the type of information one wishes to gather. Diagnostics for spray length and angle exist in the form of CCD cameras, emission spectroscopy is useful in the analysis of combusting sprays, and droplet sizing can be accomplished by commercially available equipment to quantify sprays.

2.2.1 CCD Cameras

One popular method of qualitatively analyzing sprays is the use of high-speed charge-coupled device (CCD) cameras. CCD cameras are tools that are used in conjunction with specific optical methods of optical analysis, including emission spectroscopy and qualitative imaging. As with any method of analysis, CCD cameras have advantages and disadvantages. One of their primary advantages is their ability to produce spatially-resolved images of a spray. They are also
capable of providing qualitative information of a spray, such as its penetration length and cone angle.

Unfortunately, CCD cameras are limited by several types of noise. Of concern when researching low light intensity is dark noise. Dark noise is generated within a potential well at a rate proportional to the amount of time the well is occupied. In low light conditions, it is necessary to record over a long period of time. This generates an unacceptable amount of noise. Additionally, given the dynamics of a spray, it is not possible to make a measurement of a single point in time if the shutter must remain open for an extended period. Finally, CCD camera images have limited ability to produce quantitative results.

At DaimlerChrysler Research and Technology, an image intensified digital 2-channel CCD camera is used in conjunction with a long distance microscope (LDM) [4]. Using a transparent acrylic nozzle to minimize refraction of light, they are able to resolve cavitation bubbles within the nozzle. The light is able to transmit efficiently through the fuel and acrylic media, but vapor bubbles result in dark patches within the image. This particular method is claimed to be effective to a minimum exposure time of 20ns. This technology is appropriately applied in this case, as the research involves the qualitative investigation of an observed event.
2.2.2 Emission Spectroscopy

A general method that is used in the investigation of combusting sprays is that of emission spectroscopy. This is not a single method but several methods that may be used individually or in conjunction with each other or other methods to evaluate combustion.

The method of OH chemiluminescence takes advantage of the luminosity of the product gas OH. This gas is formed in the rich combustion zone of a traditional Diesel spray. OH chemiluminescence is valuable in the detection of the lift-off length, the most distant location of high-temperature combustion [9].

Laser-induced fluorescence (LIF) and laser-induced incandescence (LII) are used to monitor the formation and amount of soot in a combusting spray [10]. In each of these methods, incident laser light is used to excite light emission from soot precursors or soot, respectively. In doing so, light of a particular wavelength is absorbed by a molecule under investigation. By absorbing a photon of light at a specific wavelength, the molecule is excited to an unstable energy level. Due to instability at this excited state, the molecule emits a photon of light at a different wavelength and drops to a stable (but different) energy level. The amount of light emission from the molecules of interest is proportional to the quantity of that molecule present.
2.2.3 X-Ray Absorption

One very accurate method of analyzing sprays is through the use of x-ray absorption. Researchers at the Argonne National Laboratory have taken measurements very near the tip of a high pressure nozzle using synchrotron x-rays from their Advanced Photon Source [11]. This light source is not subject to the scattering experienced by other sources, and thus is able to overcome the large attenuation that other optical methods face when probing very near the nozzle tip. These researchers have been able to record time-resolved, quantitative measurements of fuel sprays.

Unfortunately, this method is time consuming and very expensive. This method of investigation requires mapping of the spray. For each spray condition, measurements were taken at approximately 1500 combinations of axial and radial locations, with each location representing a single pixel in the final spray image. Furthermore, in order to overcome a low signal to noise ratio, each measurement had to be repeated 50 times. Although expensive and time-consuming, the results are complete and accurate. The method produces a spatially-resolved map of fuel volume fraction, and the rate of injection can be derived based on this data as well.
2.2.4 Malvern Sizing

The final competing technique used to evaluate the content of a spray is through the use of a Malvern droplet sizing instrument. Malvern Instruments Limited produces a commercially available line of droplet sizing devices that operate on the Low Angle Light Scattering principle (LALS) [12]. Malvern uses Mie Theory and a transmitted wavelength of 630nm to calculate particle size distribution based on volume. Its capabilities span the range of particles from 0.02 – 2000um.

This technique is capable of producing quantitative results, however the Malvern is limited by several factors. It typically has a refresh rate on the order of 2500Hz. Considering that this rate is on the same order as the speed of an internal combustion engine, it is capable of taking only one sample per spray. Additionally, while this technique can monitor liquid and solid phases, it is incapable of detecting vapor. Rather, due to the internal simulations employed by the Malvern equipment, the system is unable to cope with beam steering produced by the presence of vapor. As a result, it is not useful during vaporizing or combusting sprays. Thus, the Malvern technique is ineffective for the type of sprays that we wish to analyze.
2.3 Simulation

Prior to the development of our optical spray sensor, simulations were conducted in LabView. The purpose of these simulations was to evaluate the effects of droplet size distribution on the transmission of the wavelengths selected. Different size droplets have different extinction efficiencies at various wavelengths. For example, a given droplet may transmit less light than its geometric size would indicate at one wavelength, while allowing more light to pass at another wavelength.

A LabView simulation was developed to show these effects using the optical properties of water, the wavelength range used by this research, and representative droplet sizes as inputs. Figure 2.1 shows the extinction efficiency as a function of wavelength for a 5um droplet over the range of 1300nm to 1460nm. Figure 2.2 shows the same effect for a droplet of 7um diameter. Clearly, these two droplet, although similarly sized, yield vastly different extinction efficiencies over the range of wavelengths used in this experiment. The spray under consideration contains a wide range of droplet sizes. Given the large differences in behavior of different sized droplets, it is a reasonable assumption that this diverse spray will have consistent extinction efficiency throughout the range of wavelengths considered.
Figure 2.1 5um droplet extinction efficiency vs. wavelength

Figure 2.2 7um Droplet extinction efficiency vs. wavelength
2.4 Mie Scattering

Mie Scattering occurs when a given wavelength of light is elastically scattered by a particle much larger than the wavelength of the incident light. Unlike Rayleigh, a special case of Mie scattering, which is scattered by molecular scale objects, Mie scattering is the result of solid dust or liquid droplets present in the path of light. Mie scattering theory is required for certain particle sizing and other experimental techniques. More information is available regarding the physics of Mie Scattering [13].

2.5 Absorption Spectroscopy

2.5.1 Background

Absorption spectroscopy is an optical technique which measures changes in quantum states for the substance under investigation. Absorption of light occurs when a molecule or atom is excited from a lower quantum state to a higher one, absorbing a photon of a specific wavelength of light in the process [14]. Typically, the substances being examined are excited by a laser light source, and transmission data is recorded by a photodiode (detector). As a result of the absorption of light by the substance under investigation, the detector will report a decrease in transmitted power.
Absorption is predictable, because a given substance will always absorb the same wavelength for a given species at a given set of external conditions. Absorption is calculated using Beer’s Law:

\[
Absorption = -\ln \left( \frac{I}{I_o} \right)
\]

As shown by the equation above, absorption is the negative of the natural log of transmitted intensity, I, divided by the initial intensity, I_o. Thus, one requirement of absorption spectroscopy is knowledge of the strength of the laser source prior to its transmission through the absorbing medium. A reference detector is used to monitor the output power of the light source for this reason.

**2.5.2 Benefits**

Absorption spectroscopy has several benefits compared to physical instrumentation. As an optical method, it does not interfere with the process being analyzed. Often in combustion or fluid events, the presence of a thermocouple or pressure transducer will disturb the system. When this is the case, the results produced by the analysis do not necessarily reflect the dynamics that the system would typically exhibit in the absence of the measurement tool.

Absorption spectroscopy also has a very fast time response. Because the probe itself is an electromagnetic wave (light), it is clearly not a limiting factor in the
response time of an instrument. It is the detection method that will limit the rate at which data can be recorded, and modern detectors and digital oscilloscopes allow material property data to be acquired on the order of $10^6$ times per second. The more frequently a sample of data can be recorded, the more continuous the data will become. Because physical instrumentation is based on the physics of weight and thermal capacity, they are unlikely to exhibit the fast response time exhibited by optical techniques.

Fast response times also have the benefit of being able to take more data in less time. Comparing two optical systems of different response time, a system with a refresh rate on the order of $10^6$ samples per second can take one thousand times more data than a system taking $10^3$ samples per second. Since signal to noise ratio is often dependent on the number of averages taken, the faster equipment will produce better results in less time.

2.6 Two-Wavelength Spectroscopy

It has been shown in the preceding sections that there was no single technique with the ability to quantify an evaporating or combusting spray. As a result, a multi-wavelength spectroscopy technique was developed. The concept of multi-wavelength spectroscopy is not a new one. As many as 25 years ago, a variation of this technique was being developed at the General Motors Research Laboratories [15].
In his research, Chraplyvy accounted for scattering through calculation. This method utilized a Malvern droplet sizing instrument to provide the distribution of droplet sizes. Mie theory was used to estimate the extinction coefficient of the spray under consideration. Using this estimation, it was possible to determine what amount of light intensity attenuation was due to scattering and what was due to vapor absorption.

This technique, although not fully developed at the time, bears a strong resemblance to the method that has been used in this work. The principle of the technique is to compare the transmission of two wavelengths along the same path through a spray. The wavelengths are ideally chosen such that they are close together but where one wavelength is not absorbed by the working fluid and the other is heavily absorbed. The difference in the absorption of the two wavelengths should be as pronounced as possible, within the constraint that the wavelengths should also be as similar as possible so that they behave similarly with respect to scattering in the spray. Large differences in wavelength could lead to significantly different diffraction behavior of the two wavelengths and could alter the results.

There are constraints to the selection of the two wavelengths. As seen below in Figure 2.3: Liquid water absorption spectrum highlighting the choice of an absorbing (1450 nm) and a non-absorbing (1310 nm) wavelength, 1310nm was
chosen as the non-absorbing wavelength, and 1450nm for the absorbing. Ideally, 1925nm would have produced a more pronounced difference in absorption. Unfortunately, the diffraction difference between 1925nm and 1310nm would negatively affect performance. In addition, the fiber Bragg gratings used to select the two wavelengths are not commercially available above 1700nm.

In performing two-wavelength spectroscopy, the power of each wavelength must be known prior to its entry into the spray. For the purposes of this investigation, a reference detector serves this function. By splitting the initial signal, it was possible to transmit 90% of the light intensity through the spray, while measuring

Figure 2.3: Liquid water absorption spectrum highlighting the choice of an absorbing (1450 nm) and a non-absorbing (1310 nm) wavelength
the remaining 10% before the spray. Post spray, the intensity of the light was measured by a detector of the same type used for reference measurement. To compensate for variations in the emitted power of the laser, the transmitted light intensity was normalized by the initial intensity of the same color. Following normalization, Beer’s law was applied:

\[ \frac{I}{I_o} = e^{-k_\lambda L} \]

Where: 
- \( I \) = Normalized transmitted intensity
- \( I_o \) = Normalized initial intensity
- \( K_\lambda \) = Absorption coefficient
- \( L \) = Transmitted path length

Dividing the normalized transmitted intensity by the normalized initial intensity produces the transmission efficiency. The absorption coefficient is a property of the working fluid and is wavelength dependent. Because this value was known, it was then possible to calculate the total distance through which the light was passing through the spray.

The key to making two-wavelength spectroscopy a valuable technique is the ability to take many measurements throughout a single spray event. With a laser repetition rate of 200 kHz, it was possible to take on the order of one thousand
measurements in a single spray. By accumulating this data, it was possible to make a quantitative statement about the amount of liquid in the spray.
3 Multi-Wavelength Laser Sources

Unique properties of laser as light sources, such as power, coherence and spectral purity, enable the use of and promote the discovery of advanced optical techniques [16]. Dr. Sanders’ research group is in a unique position as one of the premier proponents of wavelength-agile technologies. It is this technology that enables the spray analysis described within this work to be carried out.

3.1 Laser Super-continua

The laser super-continuum is perhaps the most valuable tool available to researchers working with Dr. Sanders. A super-continuum is a specific type of broadband light source, featuring high intensity throughout a very broad spectrum. A standard light bulb is a common type of broadband source. It produces a continuous, wide span of wavelength emissions, however, it lacks the uniform intensity required to be regarded as a super-continuum. Examples of super-continua are shown below in Figure 3.1 and Figure 3.2. These are super-continua generated in Dr. Sanders’ lab spanning the visible and infrared regions.
Figure 3.1: Super-continuum in space

Figure 3.2: Super-continuum in fiber
The above figures clearly illustrate the wide bandwidth of super-continuum light. The light shown in Figure 3.1 is being generated at 1064nm, while the light in Figure 3.2 is generated at 1550nm. Green light can be seen in each super-continuum, representing a wavelength of roughly 500nm. Because super-continua are roughly symmetric, this results in a super-continuum of 500nm to 2600nm in the case of Figure 3.2. Such a wide super-continuum is restricted by two opposing factors. In order to make this source useful, the wavelengths would have to be dispersed in time. However, the long fiber necessary to create such dispersion would also limit the transmission efficiency.

3.2 Generating Super-continua

Super-continuum generation is the spectral broadening of a short, intense pulse of a single pumped wavelength transmitted through a non-linear medium. Until very recently, super-continuum have been generated using highly-nonlinear (HNL) and photonic crystal fibers (PCF) [17]. These media have very small cross sectional area, which are able to support high irradiance at moderate power levels. Typically, this pulse will experience equal red and blue shifts, forming a super-continuum centered around the pump wavelength. This generation relies on the high irradiance supported by the HNL or PCF as well as its non-linear transmission behavior. This method of generation is proven successful, and a photonic crystal fiber was used for the super-continuum generation used for the single point measurement presented in this work.
Unfortunately, this method of super-continuum generation has drawbacks. The very small cross section makes coupling efficiency poor, and it precludes connectorization of the fiber. Thus, alignment of the system is critical and tedious. Additionally, as an essentially novel technology, they are relatively expensive and not always readily available.

In an effort to find relief from the drawbacks of the PCF and HNL generation methods, it has been shown that super-continua can be generated using ordinary telecommunication optical fibers [17]. These fibers are low-cost and readily available. They are also able to accept higher power levels due to their larger cross sectional area. Although a longer length of interaction is required with standard fiber, the results are largely the same. For the purposes of the multi-point measurements, a super-continuum generated in Corning MetroCor fiber was used.
Figure 3.3 Super-continua output dependence on pump laser power
In Figure 3.3 above, multiple super-continua are shown with respect to laser input power. These super-continua were generated consecutively using an IMRA uJewel pump laser operating at 1557nm in conjunction with a 20cm length of Corning MetroCor fiber. This data was recorded using an Ando optical spectrum analyzer; the data sheet for which is located in the Appendix.

From the graph, it is possible to see the progression of broader bandwidth super-continua generated by increasing input laser intensity. It is also apparent from this graph that super-continua intensity increases to a discrete plateau. Further increases in pump laser power only increase the width of the super-continuum, it will not increase the intensity. The generally symmetric nature of the super-
continuum can also be observed from this plot. This is due to the negative dispersive characteristic of the MetroCor fiber.

There are many sources available to the reader interested in the physics behind super-continuum generation [18, 19].

### 3.3 Challenges of Super-continuum Generation

As will be described in following sections, there are drawbacks to working with super-continua. These challenges involve the generation of stable super-continua and the ability to maintain an optical setup that utilizes very high concentrations of light intensity.

#### 3.3.1 Laser Stability

The power output of the pump laser greatly influences the intensity and bandwidth of a super-continuum. As a result, the stability of the pump source is a crucial aspect of many super-continuum generation systems. Particularly in investigations where fast time response is important, and where little or no averaging is to be used, the amplitude and bandwidth of the super-continuum must remain stable. When this is the case, a mode locked source is desirable, as it ensures consistency between each pulse generated by the pump source.
3.3.2 Fiber Damage

The bandwidth of a super-continuum is a function of the energy intensity in a pulse of light and the elapsed time over which that light is emitted. Therefore, it is advantageous to select a laser that emits very high intensity over the shortest possible span of time. Unfortunately, these intense pulses frequently have the potential to damage other optical equipment in the super-continuum generation system.

Most often, the generation fiber is the weak link in a given system. This is due to an extremely high amount of energy being focused on a very small area, or as a result of a non-optimized coupling. The result is that materials on the fiber surface, or adhesives used in the assembly of a fiber connector become burned. When the damage threshold of a fiber is exceeded, the result is an inefficient, non-circular pattern of light emission. This pattern is not optimized for transmission to other optical equipment, and the fiber must be replaced.

3.4 Fiber Bragg Gratings

Once a super-continuum has been generated using the methods described above, it is often desirable to filter or select certain wavelengths from the broadband source. Fiber Bragg gratings (FBGs) act as a filter that reflect one particular wavelength and allow all other wavelengths to pass through
unimpeded. One experimental setup used in conducting the research described in this work is shown below in Figure 3.4.

**Figure 3.4 Fiber Bragg grating setup**

Here, a super-continuum was generated by the IMRA µJewel pump laser and a 20cm Corning MetroCor fiber. The super-continuum produced by this arrangement spans from 1300nm through 1800nm. For the analysis of water sprays, it was desired to select light at 1310nm and 1450nm for use in two-wavelength absorption spectroscopy. Data sheets for the IMRA µJewel laser can be found in the Appendix.

After the super-continuum is produced in the generation fiber, it passes through a dispersion fiber. The dispersion fiber is used to spread out the broadband spectrum in time, thus preventing damage to downstream optical equipment. The super-continuum is then coupled into a two-way, equal intensity splitter. The
light is emitted through the two opposite leads of the two-way splitter. One lead is unnecessary and is terminated to a beam dump. This results in a 50 percent loss of super-continuum power and is an unfortunate side effect of this method.

The other output of the splitter is coupled into the 1310nm FBG. Here, only a narrow band of wavelengths surrounding 1310nm is reflected back to the splitter. The remaining super-continuum is transmitted with negligible losses and is sent through a 10m delay fiber. Following the delay fiber, the light is coupled into the 1450nm FBG. Only a narrow band of light surrounding 1450nm is reflected. This light travels back through the 10m delay fiber and then passes through the 1310nm FBG unimpeded, and arrives back at the splitter. Due to the delay fiber through which the 1450nm light must pass twice, it arrives at the splitter about 100ns after the 1310nm pulse. As described previously, this brief delay makes it possible to distinguish between the two wavelengths when processing the data collected from the experiment. The remaining broadband light is terminated to a beam dump.

At the two-way splitter, the two pulses of light (1310nm and 1450nm) exit through the two fibers at the right side of the splitter. One of these fibers is the delay fiber through which the super-continuum is generated. The light transmitted back through this fiber is lost, resulting in another 50 percent loss. The remaining light exits through the other fiber and is transmitted to the experiment.
As in any experiment, the use of fiber Bragg gratings has benefits and drawbacks. As mentioned above, there are two locations where the intensity of light is attenuated by 50 percent. This results in an overall loss of 75 percent of initial intensity of transmitted light. In experiments where high levels of attenuation occur within the experiment, this can be a significant drawback.

However, the use of FBG filters is a very simple method to execute and it can be very precise. Fiber Bragg gratings are available commercially (from wavelength of ~ 900 nm through 1700nm) and can be obtained with very narrow reflection bands (< 1nm) and with very high (95%) transmission of unfiltered light. They do not require alignment, as they are fiber coupled, and they do not require purging to prevent interference from airborne species. FBG filters can be added together to select as many or as few wavelengths as desirable for a particular experiment.

Refer to Appendix A for specifications of the fiber Bragg gratings used in this experiment.

### 3.5 Selectable Pin Filters

Another method of wavelength filtering is available that provides a different range of capabilities than the fiber Bragg grating system discussed in section 3.4. Through the use of a diffraction grating, the super-continuum can be spread out in space. As wavelengths will be predictably diffracted in a two-dimensional pattern in space, it is possible to prevent the transmission of certain wavelengths.
by placing a physical block in the path of the light. A schematic of this technique is provided below in Figure 3.5.

**Figure 3.5 Selectable pin filtering**

Here, a device is applied where a series of narrow pins are aligned in the path of the diffracted super-continuum. Lowering a pin prevents the transmission of light at that position. It was desired to transmit only 1310nm and 1450nm. Since the super-continuum in use spans from 1300nm to 1800nm, nearly all pins were in the lowered position. Only the two pins corresponding to the physical location of 1310nm and 1450nm light are raised, thus allowing light to be transmitted.

After passing through the pin filter, the pulses contact a concave mirror and are directed back through the filter and towards the grating. At the grating, the two wavelengths are reflected along the same path and collimated into a dispersion
fiber. In this case, the dispersion fiber causes the two wavelengths to spread in time by the requisite ~ 100 ns, allowing them to be detected separately by the detector.

One benefit of this method is its high level of adaptability. The method of raising or lowering pins to select wavelengths means that there is a wide range of systems to which this method may be applied. This system can be adapted to act as a low-pass, high-pass, band-pass or band-rejection filter. When used in trials in this experiment, it was used as a dual band-pass filter.

One drawback to the system is that it is a free-space system. Unlike fiber-coupled systems, it is susceptible to physical creep, airborne particles and contaminants. Alignment can be difficult, and the resolution is dependent on the number of pins in the filter. It is a discrete system that was shown to be capable of resolution on the 5nm scale in this experiment. Additionally, as a free-space system, it may require purging if it were used to investigate phenomena involving water vapor.

3.6 Diode Lasers

The use of a super-continuum and wavelength filters proved challenging in this experiment. The nature of this experiment requires high stability and fast time response, with no averaging. Because 1310nm is very near the edge of the super-continuum described in this chapter, it is subject to the greatest level of
variability in intensity. Any fluctuation in laser output intensity had a marked effect on the intensity of 1310nm light in particular. This produced an undesirable effect in the results of the experiment. In addition, a significant drawback associated with short-duration pulses was revealed in our application. The short-duration (1ps) pulses apparently saturate typical InGaAs photodiodes, even when low voltages are detected from the amplified output. This effect was evidenced by a highly non-linear response shown by the photodiodes. The result was that for very short pulses, large increases in intensity would yield small increases in photodiode output voltage. In preliminary testing, this effect produced what looked like absorption even when no absorbing wavelengths were used. This effect was the primary cause for switching to diode lasers, as diode lasers use a much longer (20ns) pulse.

In order to complete this experiment in the time provided, it was not possible to further refine the super-continuum source and detection equipment to circumnavigate the drawbacks. Another method was therefore developed using established technology. Diode lasers were selected as a source of stable, monochromatic light. Two diode lasers were available at 1300nm and 1444nm. These wavelengths have very similar behavior to the 1310nm and 1450nm light used in the FBG and selectable pin trials.

The use of two diode lasers, shown schematically in Figure 3.6, allows the system to be fully fiber-coupled. As mentioned earlier, a fiber coupled system
provides ease of use and is physically more robust than a free-space system. Here, an ultra-high speed pulse generator (AV-tech model AVM-2-C) was used to pulse the diode lasers at 200kHz. This repetition rate was selected because previous trials conducted using super-continua were generated using the IMRA uJewel laser, with the same repetition rate. Due to different input power versus output intensity behavior, each diode had to be supplied a separate offset current (bias) from an ILX precision current source. This allowed the two diodes to provide the same intensity of light. Data sheets for the AV-tech pulse generator, ILX current source, and both diode lasers can be found in the Appendix.

**Figure 3.6 Diode Lasers**

Once again, the absorbing wavelength (1444nm) was transmitted through a delay fiber to achieve an approximately 100ns delay. The two pulses of light are combined in a two-way splitter, where one output branch terminates to a beam
dump. The other branch, transmitting 50 percent of the generated power, is fed into the experiment.

This method proved to be simple and effective. This method was used as the source of light for the multi-point measurements described in Chapter 5. The diode sources were very stable, and also provided a lower level of noise than previous strategies. The system relied purely on commercially available equipment, and was entirely fiber-coupled. As a result, it was a robust system that was not highly susceptible to alignment or contaminants.

Unfortunately, this method may not be as expandable as the super-continuum-based approaches. Although adding more wavelengths is theoretically possible, use of many more wavelengths becomes an increasing experimental challenge. To add more wavelengths would require an additional diode and current source for each wavelength. It would also necessitate the addition of splitters, which frequently degrade the intensity of output of the system.

Furthermore, this system is capable of producing only discrete wavelengths. Broadband sources can be scaled down to filter single wavelengths, but this method cannot be scaled up to produce a wavelength scan. Because of this characteristic, the detection of complete spectra or the measurement of multiple species becomes difficult or impossible.
It should be clear from the preceding discussion that the use of laser diodes is not the only option available for the experiment described. The system of laser diodes used here was successful due to their combination of good signal to noise ratio and simplicity of implementation. The spray investigation could be made more adaptable through the use of a super-continuum source. However, recent developments have shown promise for increased flexibility of diode lasers as well. Future development of this spray research will depend on the refinement of the laser source.
4 SINGLE-POINT MEASUREMENTS

4.1 Ballistics

The approach chosen to distinguish liquid and vapors in sprays is to take advantage of the ballistics of the transmitted light. Figure 4.1 represents a simplified schematic of the possible transmission modes for a laser beam incident on a spray. Transmitted light that never contacts liquid droplets will emerge as an “undisturbed” collimated beam, and the remaining transmitted light is “scattered” by low angle light scattering (LALS) in a new direction by the liquid.

Figure 4.1: Light Transmission through a Spray
4.1.1 Collection Schemes

For the remainder of this work, a color code is used to aid in the interpretation of data. Please be aware that orange borders and data points represent the “scattered” setup, green represents the “undisturbed” setup, and magenta represents the “combination” setup.

4.1.2 Scattered Light

The “scattered” collection system receives only light that is scattered by the spray. More accurately, it receives only the light scattered by the spray at an angle < 26 degrees from the original path, the remainder of the light scatters at larger angles – including backscatter – and is not collected at all.

Collimated light, such as that transmitted “undisturbed,” is focused by the collection lens at its focal point. The scattered light that is incident on the lens is focused at a point located at twice the focal length of the lens. In order to collect only the scattered light, a pin is placed at the focal length of the collecting lens. This prevents the “undisturbed” light from reaching the detector. The detector is placed at twice the focal length so that it is able to collect the scattered light.
4.1.3 Undisturbed Light

The "undisturbed" collection system receives only light that never contacts liquid in the spray. This is collimated light, which is focused by the collecting lens at its focal point. By placing the detector at the focal point of the lens, it is possible to collect only the "undisturbed" light while minimizing the collection of "scattered" light. This collection technique is illustrated in Figure 4.3.

The detector being used in this experiment has a detection area 1mm by 1mm. It is likely that a very small amount of scattered light is being detected at this point.
In the results section, it will be shown that this does not produce noticeable effects. Nevertheless, in the next step of this experiment, the multi-point measurement, an iris was placed in front of the detector to reduce the amount of “scattered” light reaching the detector.

4.1.4 Combination Light

The “combination” collection system collects the sum of the “undisturbed” and “scattered” light. In principle, from measurements of any two of the three setups
described above, data for the third could be inferred without direct measurement. This will prove to be valuable for future experiments.

4.2 Experimental Setup

From the transmission data presented above, only the presence of a spray may be determined, not the quantity of the spray. To infer quantitative information, data must be recorded at multiple wavelengths using at least one absorbing wavelength in addition to at least one non-absorbing wavelength. Transmission of each wavelength must be conducted in a time that is short relative to any

Figure 4.4: “Combination” collection setup
physical timescales of the spray. To obtain such high-speed, multicolor data, the system shown in Figure 4.5 is used.

![Laser Schematic](image)

**Figure 4.5: Laser Schematic**

An amplified ultra-fast fiber laser generates super-continuum pulses in a photonic crystal fiber. These broadband pulses are split 50/50 using an ordinary single mode fiber coupler. The bottom leg of the splitter is dumped. The top leg is sent to a reflection-delay system based on fiber Bragg gratings (FBGs). The first fiber Bragg grating is chosen to reflect a non-absorbing wavelength (e.g., 1310 +/- 5 nm). The majority of the super-continuum falls outside this wavelength range and is simply transmitted through the FBG. The super-continuum travels through 10 m fiber (in ~ 50 ns time) and reaches another FBG. This FBG is chosen to reflect an absorbing wavelength (e.g., 1450 +/- 5 nm). The remainder of the super-continuum is transmitted through the FBG and discarded.
Propagating backwards toward the splitter, then, is a pulse of non-absorbing light followed by a pulse of absorbing light ~ 120 ns later. These are collected in the bottom-left leg of the splitter and connected to another splitter. This second splitter is another 50/50 splitter that allows us to determine how much energy is contained in each pulse (non-absorbing and absorbing) sent to the spray using a reference detector. The other output leg of the splitter is sent to the spray for the experiment.

4.3 Results

A sample pulse pair transmitted through the spray experiment is shown in Figure 4.6. This data was recorded using the “combination” setup. Each of the four total peaks represents the average of all 1310nm pre-spray data, 1310nm during-spray data, 1450 pre-spray and 1450 during-spray. Note that by measuring the amplitude of each pulse, we are able to record transmission at two wavelengths (non-absorbing and absorbing) within ~ 100 ns. This is a small time scale relative to the motion of the spray, and effectively “freezes” the spray in time. A pulse pair recorded prior to the start of injection is shown as a heavy line in Figure 4.6, and a pulse pair recorded during the spray is shown as a thin line. As expected, the overall pre-spray transmission is greater than the overall during-spray transmission.
Since the light transmitted at 1310nm is not absorbed in the spray, it is known that the light transmitted at 1310nm represents full transmission. If the during-spray data of Figure 4.6 is scaled by a factor of 3.44, the amplitudes of the non-absorbing peaks match, as shown in Figure 4.7. However, the amplitudes of the absorbing peaks do not match, because of absorption of the 1450nm light in the water spray. From this analysis, it is possible to infer the amount of the absorber present in the beam path. In this case, because the absorption was measured in the “combination” collection scheme, the absorption can be used to determine the total amount of absorber (liquid + vapor) present in the spray.
One pulse pair consisting of 1310nm and 1450nm light is passed through the spray every 5μs. Compiling this data over the period of one spray produces the sample raw data traces shown below. Figure 4.8 represents the “undisturbed” case, Figure 4.9 represents the “scattered” case, and Figure 4.10 represents the “combination” case. These traces are consistent with the results expected from each collection scheme.
For the undisturbed collection scheme, there is little transmission during the spray, so the amount of useful data is sparse. However, the available data indicate that the transmission does not deviate significantly from unity. This is as expected for the non-evaporating spray tested in this case. If vapor had been present, a significant deviation from 100% transmission would be observed.
For the “scattered” collection scheme, no data is available prior to the spray, because there is no scattered light at that time. After entrance of the spray, the data show a relative transmission less than unity, consistent with the presence of absorbing liquid.
Figure 4.10: Raw Transmission Data for “Combination”

The “combination” collection scheme shows a relative transmission of unity prior to the spray and, during the spray, a transmission similar to that obtained in the “scattered” case. As expected, the combination case effectively produces the same result as overlaying the other two cases.

The raw data presented above represents all light transmitted through the spray, such that there are thousands of data points alternately representing 1310nm and 1450nm data. The plots produced at this point are qualitative data, from which one could determine the relative density of the spray, the spray duration, and the amount of light scattered versus the amount transmitted undisturbed. Each plot represents a single spray event, as it was not possible to record data on multiple setups using a single spray event.
In order to form a quantitative analysis, the 1310nm intensities must be separated from the 1450nm intensities. The transmitted strength of each color at each point in time are first normalized by the initial intensity at the same point in time. Then, the 1450nm (absorbing) data are divided by the 1310nm (non-absorbing) data at the same point in time. The results are shown below in Figure 4.11, Figure 4.12, and Figure 4.13.

Figure 4.11: Relative Transmission Data for “Undisturbed”

Figure 4.11 shows the transmission efficiency for the “undisturbed” case. In this case, only light which transmits directly through the spray is collected. Therefore, none of the collected light has come into contact with water. Furthermore, the sprays were each carried out at room temperature and pressure. Because of
this, we would expect the sprays to be non-evaporating sprays, consisting of liquid water only. The results show this to be the case. Although there are few data points, owing to the fact that the transmitted light was heavily attenuated, those that were collected show that there was no relative absorption of the 1450nm light. The trend in this case is for the ratio of transmitted light at 1310nm and 1450nm to remain equal at a ratio of approximately 1.0.

![Figure 4.12: Relative Transmission Data for “Scattered”](image)

Figure 4.12 shows the processed data representing the “scattered” collection setup. First notice that there is no data prior to the start of injection. This is because prior to injection, all light is contained in a single collimated beam that is being prevented from reaching the detector. After the start of injection, light is scattered. This scattered light is collected by the lens and transmitted to the
detector. It is also shown that there is significantly more data collected by this setup. Very close to the nozzle tip (10mm) the spray is very dense. This causes heavy scattering and provides a large amount of scattered light to be collected at the lens. It is also possible to see from this plot that the ratio of transmitted intensity $1310\text{nm} / 1450\text{nm}$ is generally less than unity. This tells us that there is relative attenuation of the $1450\text{nm}$ light.

![Figure 4.13: Relative Transmission Data for “Combination”](image)

In Figure 4.13 results of the “combination” case are presented. Here, the results show that prior to the start of injection, there is full transmission of both wavelengths. As in the “undisturbed” case, this produces a transmission ratio of unity. After the start of injection, the data looks very similar to that from the
“scattered” case. This is because there is so little intensity transmitted without contacting water droplets that this effect is negligible in the “combination” case after the start of injection.

Figure 4.14, below, presents a direct comparison of the data shown in Figure 4.12 and Figure 4.13. These results show that our current spray experiment is repeatable in the sense that different sprays contain similar quantities of liquid at similar times. These results also confirm that there is negligible evaporation in this tested spray, as expected during our room-temperature testing. Had there been significant evaporation, excess absorption would have been expected in the combination case, consistent with absorption due to vapor as well as liquid.

![Figure 4.14: Comparison of Scattered and Combination Data](image)

Figure 4.14: Comparison of Scattered and Combination Data
The data shown in Figure can be converted into a quantitative liquid length fraction, as shown in Figure using the transmission equation:

\[ T = e^{-K_L L} \]

Where

- \( T \) = Transmission [%]
- \( K_\lambda \) = Absorption coefficient [cm\(^{-1}\)]
- \( L \) = Path length through absorber [cm]

From this experiment, the absorption coefficient of water is known. It has also been shown how to calculate the transmission through the spray. It is therefore possible to determine the physical distance that the light is transmitted through the water.

In this case, with the probe beam ~ 1.0 cm from the injector tip, the liquid length fraction is approximately 1%, as shown. This indicates that 1% of the path length intercepted by the laser is occupied by water. Obtaining a droplet size distribution from a droplet sizing instrument would allow us to determine the actual amount of water in the spray (volume fraction).

Data such as this are invaluable for determining the performance of new spray nozzle designs. This result highlights the unique capability of multicolor absorption techniques, because they are able to provide quantitative data even
under harsh measurement conditions. Data of similar or better quality is expected in hot and combusting environments.

![Figure 4.15: Quantitative Liquid Length Fraction](image)

In summary, we have demonstrated a novel laser diagnostic that is capable of both liquid and vapor measurements in practical fuel sprays. Our intention is to apply this diagnostic for tomographic measurements of practical vaporizing and combusting sprays contained in a constant volume combustion chamber.

### 4.4 Discussion

The spray diagnostic approach described here is one step in the path to the complete analysis of a practical evaporating spray. There are several steps that
will be taken to make this a more useful analysis. For example, quantitative analysis of our current data results in a liquid length fraction and thus the total amount of liquid and vapor being analyzed.

The single line-of-sight analysis presented up to this point represents a proof of concept for what is to come. As described here, this analysis is of limited use. In order to produce a more valuable description of the spray under investigation, it will be advantageous to take measurements over at least two dimensions simultaneously. To that end, the next step is a multi-point analysis of the same sprays. Taking multiple point measurements, and particularly taking tomographic measurements, allows one to integrate the total amount of fuel being injected by the nozzle over the length of the spray event.

Another means of improvement is to analyze an evaporating spray. This has been done previously by Dr. Sanders’ research group, but it has not been tested using the ballistics approach.
5 MULTI-POINT MEASUREMENTS

5.1 Experimental Setup

The final step in this spray analysis was the implementation of a multiple point analysis tool. Used in conjunction with tomographic data processing, this method is capable of providing a two-dimensional map of the spray. For the purposes of this analysis, the spray was assumed to be axissymmetric. This should be a reasonable assumption in certain sprays at certain locations, but may be a particularly poor assumption near nozzles. Figure 5.1 below shows a plume at full penetration length in a constant volume combustion chamber. Here, it could be reasonably stated that the spray plume appears symmetric. However, research at Honda Motor Co. has recently shown that very near the tip of a diesel fuel injector the spray does not exhibit symmetry.

![Figure 5.1 Axissymmetric Spray Image](image)
In order to take measurements of the spray at multiple points, an array of Corning lensed fibers was assembled into a horizontal plane of four fibers. More information regarding lensed fibers may be found in the Appendix. Each lensed fiber is approximately 0.5mm wide, so the array intercepts a 1.5mm wide section of the spray. Figure 5.2 below is a photograph of the fiber array and its position relative to the injector. The data sheet for the Corning lensed fibers is available in the Appendix.

![Figure 5.2 Four Fiber Array](image)

It was determined that the spray produced by the standard Bosch port-fuel injection-style injector produced a 22 degree cone. This was determined by visual assessment of the spray pattern when impinged upon a piece of dark
paper. Again, this test was conducted using water as the working fluid. Based on geometry, placing the fiber array 10mm above the nozzle exit would result in the beam from the inner fiber bisecting the spray, and the outer beam being just on the edge of the spray.

The fiber optic setup for the multi-point analysis is illustrated schematically in Figure 5.3 below, and in photographic form in Figure 5.4. In this arrangement, light from the diode laser source is coupled into a two-way 90/10 percent splitter. The 10 percent branch serves the reference detector. This allows any instability in the laser output to be monitored and those effects can be nullified in post processing. The remainder of the light is split evenly in a four-way splitter.
Figure 5.3 Multi-Point Optical Setup

Figure 5.4 Photo of Optical Setup
Following the splitter, delay fibers of different lengths are used to separate the pulse from each lensed fiber in time. The outer lensed fiber has no delay fiber and receives light first. Each subsequent branch has an additional 40m of delay fiber. This results in another 100ns delay between pulses from each branch. This delay is roughly the minimum spacing necessary for reliable post-processing analysis; closer spacing would raise the risk of information being too close to detect.

The lensed fibers are located less than 10mm from edge of the spray cone. This is due to the very short focal length of the lensed fibers. Significantly greater spacing would cause the beams to overlap somewhat before even entering the spray. Closer spacing would risk getting the lensed fibers wet from the spray. Because they are very fragile, it would be difficult to clean or dry the lensed fibers.

After each pulse is emitted from the lensed fibers, the light travels through the spray. Through experience with single-point measurements, it is known that most of the light is scattered. In this experiment, only the combination method is used, whereby the detector is placed at twice the focal length of the collection lens. This allows effective collection of both scattered and undisturbed light.
The light is converted to an electrical signal at the detector, where voltage is proportional to intensity of incident light. The response of the detector with respect to wavelength is provided in the Appendix.

5.2 Data Processing

A Tektronix 7154 digital phosphor oscilloscope was used to collect the signal from the detector. This oscilloscope is used in FastFrames mode, where the reference detector provides a trigger signal on one channel out of the four available. This mode allows one frame to be detected per pulse from the laser diodes. Breaking the data into frames simplifies the data reduction in LabView. The data sheet for the Tektronix scope is available in the Appendix.

The spray data is split to service two additional channels on the scope. In doing so, one channel is optimized for typical laser intensity, and another is set one order of magnitude lower. This second channel is optimized for instances of very weak transmission through the spray. Here, although the signal is still weak, the signal to noise ratio is improved. This allows more reliable data to be recorded throughout all conditions experienced during the spray.

A typical frame is shown below in Figure 5.5 Strong Transmission Data. Here, each of the three monitored channels is apparent. The reference/trigger signal is visible in red at the beginning of the frame. This represents the intensity of light emitted from the diodes at 1300nm and 1444nm, respectively. It also represents
the signal that is split four ways to service each branch of the fiber array. The eight blue, equally spaced peaks represent each 1300nm and 1444nm pulse emitted from each of the four branches. Finally, the eight green, saturated peaks are the high sensitivity spray data. In this frame, transmission is good and the standard spray data is acceptable.

![Figure 5.5 Strong Transmission Data](image)

Below in Figure 5.6, the spray is very dense and the high sensitivity data will be selected to analyze this frame. In this figure, it is apparent that the output of the laser diodes has not changed significantly. The transmitted data, however, has decreased substantially. The first and fifth blue peaks below are strong enough
to provide acceptable data, and the LabView data processing virtual instrument has selected these peaks for processing. Selected peaks are marked by an “X.”

In Figure 5.7, the reference data has been removed and the scale has been adjusted to better illustrate the standard spray data and the high sensitivity channel. Again, a black “X” represents a peak chosen by LabView to be used for processing. The first peak is shown to be strong, with LabView choosing the standard transmission data. Peaks two, three and four are weak, and LabView has chosen the high sensitivity data. This data is preferable in periods of weak transmission because of its superior signal to noise ratio. This effect is more pronounced in Figure 5.8, where only the high sensitivity data is shown. The presence of black “X”s shows the peaks chosen for processing.
Figure 5.7 Magnified Weak Transmission Data

Figure 5.8 Magnified High Sensitivity Weak Transmission Data
A LabView Virtual Instrument was produced for the purpose of converting the data recorded by the oscilloscope into useful information. The process is roughly described below:

1. From the oscilloscope, one file is saved per trial for each of reference data, transmitted data and high sensitivity transmitted data. This data is recorded frame by frame, analogous to single snapshots taken successively to form a movie.

2. In LabView, one trial is observed per execution. Each execution opens the reference, transmitted, and high sensitivity transmitted data from a single trial.

3. From each frame, a peak finder is used to detect the highest points per frame.
   a. For reference data, there are two peaks per frame.
   b. For spray data, there are a total of eight points per frame. These can be comprised of a mix of standard transmitted data and high sensitivity data. Standard transmission data is preferred, but it is tested against a threshold value. When standard data is rejected below a threshold value, High sensitivity data points are chosen and standard data is rejected and rejected.

4. The order of transmitted data points is known a priori based on the design of the optical setup. Within transmitted data, the first peak is the 1300nm
light transmitted at the outer line of sight. The second peak is the 1444nm light at the outer line of sight. The third peak is 1300nm light at the second line of sight, moving towards the center of the spray. This pattern continues to the center of the spray. Using this knowledge, the peaks are first normalized by the reference data. All 1300nm peaks are divided by the amplitude of the reference 1300nm peak. All 1444nm peaks are divided by the amplitude of the 1444nm reference peak.

5. Transmission is calculated after normalization. For each of the four positions, the normalized 1444nm amplitude is divided by the 1300nm amplitude. If no water is present, no absorption occurs and the resulting value is unity.

6. Step 5 is repeated for each frame, of which approximately 1000 are recorded per spray. The resulting data spans a time of approximately 5ms.

7. The data is subsequently processed in a variety of ways. For the purposes of later discussion, transmission and tomographic results are of the greatest importance.

Tomographic analysis was conducted using the three point Abel method. More information regarding this method is available [20].
5.3 Results

Initial results processed using the LabView code provided a qualitative illustration of the spray. Simply, the initial analysis shows the start of injection and the overall loss of transmission due to the presence of the spray. Figure 5.9 below shows qualitative data.

![Figure 5.9 Qualitative Spray Data](image)

This qualitative data is comprised of the transmitted data, and the graph above shows all data collected over the course of the spray. Breaking this data down
into frames of eight peaks each provides the snapshots of spray that effectively freeze the spray dynamics at each moment in time.

After breaking the data down the qualitative data by frames and calculating the transmission, the behavior of the spray at each of the four probed points can be plotted. Figure 5.10 provides an illustration of the transmission of the absorbing wavelength (1444nm) divided by the non-absorbing wavelength (1300nm) versus an arbitrary time scale. In this figure, the red line is the outermost line of sight, with green, blue and orange representing lines of sight approaching the axis of the spray.

From this graph, it is clear when the spray begins. It is also apparent from this graph that the outer line of sight, which is at the edge of the spray, encounters significantly less liquid water than the other three lines of sight. It requires tomography to make a greater distinction between the other three points.
The tomographic reconstruction of the spray takes into account the distance over which attenuation is observed. Each lines of sight intercepts a different length of the spray, as seen in Figure 5.11. The amount of attenuation encountered in each imaginary donut of the spray, combined with the distance that the beam travels through each of the four rings will affect the final tomographic result.
The results of many trials were processed using tomography. Six examples of the results are shown below, in Figure 5.12 through Figure 5.17. These represent the most complete single illustration of the events during the spray. The vertical axis contains the liquid volume fraction. This number states the distance through which light is in contact with water divided by the total distance through which the light is traveling through the spray. Simply, this unit of measure represents what portion of the idealized spray cone is occupied by liquid water.

The radial location axis represents the distance from the axis of the spray. The lensed fiber array is approximately 1.5mm wide. In the interest of providing a
complete illustration, a fictitious fifth line of sight was added to the array in data processing. This point would lie entirely outside of the spray, where absolutely no water was present. The use of this extra line of sight ensures that the edge of the surface returns to zero at a point outside of the spray.

The time axis simply represents the time from the start of data recording. The result of this tomographic surface is to quantitatively illustrate the behavior of the spray at each distance from the axis over the entire duration of the spray.
Figure 5.13 Tomographic Results (209)

Figure 5.14 Tomographic Results (211)
Figure 5.15 Tomographic Results (214)

Figure 5.16 Tomographic Results (217)
5.4 Discussion

The tomographic results presented above are the most complete measure of spray behavior produced from this experiment. It is a quantitative measure of the spray, and it represents all data accumulated at all points throughout the spray.

From the tomographic results, it is apparent that the spray is generally comprised of about 15 percent water. This amount of water is predominantly located within the centermost portion of the spray. The amount of liquid water present tapers quickly as distance away from the axis is increased. At the edge of the spray, along the fourth line of sight, there is a consistent increase in the quantity of liquid water. This is indicative of a hollow spray cone, where there is a ring of concentrated liquid water around the perimeter of the spray.
The data presented here represents very complete data for the behavior of a liquid pray. However, there are significant limitations as well. The primary limitation with respect to any type of spray to be analyzed with this method is the use of only four lines of sight. This results in a very coarse resolution image of the spray under investigation. Increasing the number of lines of sight requires two modifications to this system. First, the Corning lensed fibers cannot be made smaller without seeing a penalty in focal length. The current 0.454mm wide lensed fibers already have a focal length that is less than ideal. Making these smaller would allow more lines of sight to be taken through the spray. In order to achieve the same optical efficiency, the focal length of the lensed fibers would have to be retained. However, the laser beam emitted from the 0.454mm diameter lens is only 62µm. Therefore, there is plenty of excess material that could be trimmed off of the lens to facilitate closer spacing of the lensed fibers.

The other limiting factor to increasing the resolution is the need to increase the intensity of the light used to probe the spray. The power requirements scale linearly with the number of lines of sight. If one were to use eight lines of sight instead of four, twice as much light intensity would be required. This was already a limiting factor in the use of a super-continuum.
Presently, this system would be difficult to implement on a spray other than water. Using a super-continuum would make this system more adaptable to fluids with different absorption characteristics. Future iterations of the spray research established with this work will utilize a wavelength agile approach. This will not only ease the adaptability between sprays of different fluids, but will also allow the monitoring of multiple species, multiple phases, and possibly other physical conditions such as temperature and pressure.
6 Future Work

6.1 Super-continuum

As stated previously, the use of super-continuum-sourced light would greatly increase the adaptability and expandability of this research. A powerful and stable super-continuum is the key to this improvement. Once such a super-continuum is produced and includes the colors required for spray experiments of interest, a filtering method such as fiber Bragg gratings could be used to select the appropriate wavelengths for the species under investigation. If multiple species were to be investigated, it is very easy to incorporate more fiber Bragg gratings to add more wavelengths. If other physical conditions were to be investigated, a pin filter could be used. This would allow a combination of specific wavelengths and broad bands of wavelengths to be used simultaneously.

6.2 Hydrocarbon Fuel Sprays

The chief interest of the Engine Research Center in spray research is in the development of advanced fuel systems. To this end, sprays using realistic spray media must be considered. Particularly in the case of diesel sprays, it is highly desirable to use actual diesel fuel using a proper diesel injector. The research described in this thesis is intended to lay the groundwork for the investigation of realistic fuel sprays. Again, this improvement is dependent upon the generation of reliable super-continua or the acquisition of 1650nm and 1720nm diode lasers.
6.3 Combusting Sprays

The ultimate use of this spray research would be to investigate the behavior of a combusting fuel spray during in-cylinder conditions. In order to implement this improvement, the optical setup would have to be adapted to fit into or around a constant volume combustion chamber. Currently, the optical setup is too large to fit into the vessel, but the focal lengths of the optics are too short to work effectively if placed outside of the vessel.

Corning is working on advanced versions of the lensed fiber that was used in this research. One iteration under development at Corning is an array of lensed fibers implanted in a clear acrylic block. This would make the delicate lensed fibers much more robust and may allow them to be placed inside of the combustion vessel. If this were the case, the collection lens could also be replaced. One option would be to place a large diameter fiber very close to the spray opposite the fiber array. This would retain the optical efficiency of the present arrangement while allowing the optics to be placed within the vessel.

Corning, the manufacturer of the lensed fibers used in the current experiment, is developing a more robust system. This Collimator Array system uses multiple lensed fibers embedded in a single body of clear material. This adds strength and makes the system easier to align. One version of the array is shown in Figure 6.1 below. The data sheet for the Corning Collimator Array can be found in the Appendix.
Figure 6.1 Corning Collimator Array

Most of the improvements listed above is viable using current technology. They were not used in this research due to the constraint of time. The Corning Collimator Array is still in the developmental stage.
BIBLIOGRAPHY


# APPENDIX

## IMRA \( \mu \)Jewel Laser

### Specifications

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<tr>
<th>Optical (From Laser Head Main Laser Aperture)</th>
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<tr>
<td>Pulse width</td>
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<tr>
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JDS UniPhase 34-AIT637 1444nm Diode Laser

**LASER MODULE TEST DATA**

**Model Number:** 3400-0250-CW0-325  
**Serial Number:** 34-AJW759

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<td>$V_{Pmin}$ (V)</td>
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**Kink (mA):** 1620.30  
**Tracking Ratio:** 1.099  
**$P_{TOP}$ Tracking Rate (mW):** 142.34  
**TEC V @ 70 Test Results**  
| LaserCurrent (mA)         | 1373.65|
| TEC Current (A)           | 2.15   |
| TEC Volts (V)             | 2.85   |
| Imax/loa:                 | 1.30   |

**Date Tested:** 9/20/02  
**Time:** 20124 PM
### Absolute Maximum Ratings

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<td>Bend radius</td>
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1. Typical; may exceed some value under worst-case condition except as indicated otherwise.
2. Human body mode.
3. Applied is planar rib etched, $T_{f}$ min 67°C.

### Fiber Pigtail

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<td>122 µm</td>
<td>125 µm</td>
<td>128 µm</td>
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<tr>
<td>UV coating/buffer diameter</td>
<td>300 µm</td>
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1. Laser pigtail shall consist of a best 1.5 m of SMF10 fiber bared pigtail maintaining fiber BD1 step-index to insertion is a pigtail maintaining fiber with cut-off 1500 nm and buffer diameter of 160 µm, using incident QF 200.
Lucent 741287 1300nm Diode Laser

PACKAGE 741287  
LUCENT, ANALOG LASER 2000 L/I/V DATA SHEET

Fiber Power (mw)

\[
\begin{array}{c|c}
\text{Current (mA)} & 0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
\hline
\text{Lfd} & 0 & 500 \mu A & 1000 \mu A & 1500 \mu A & 2000 \mu A & 2500 \mu A & 3000 \mu A & 3500 \mu A & 4000 \mu A & 4500 \mu A & 5000 \mu A \\
\text{cl/dl} & 0 & 500 \mu A & 1000 \mu A & 1500 \mu A & 2000 \mu A & 2500 \mu A & 3000 \mu A & 3500 \mu A & 4000 \mu A & 4500 \mu A & 5000 \mu A \\
\text{Vf} & 0 & 500 \mu A & 1000 \mu A & 1500 \mu A & 2000 \mu A & 2500 \mu A & 3000 \mu A & 3500 \mu A & 4000 \mu A & 4500 \mu A & 5000 \mu A \\
\text{Ibd} & 0 & 500 \mu A & 1000 \mu A & 1500 \mu A & 2000 \mu A & 2500 \mu A & 3000 \mu A & 3500 \mu A & 4000 \mu A & 4500 \mu A & 5000 \mu A \\
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TEST DATE = 10/08/1996
TEST TIME = 5:24-45 PM
Wavelength = 1302.74
TEST TEMP = 24.8 deg C.
lth = 0.93 mA
DE = 0.33 mw/ma

See Analog Test Result sheet for Operating Bias Conditions
OE Land Fiber Bragg Grating 1310nm

O/E Land Inc.
4321, Garand, Montreal, Quebec, Canada
(514)334-4588 www.o-erland.com

Acceptance Test Report

Model: OEFBG-100
Name: Fiber Bragg Grating
S/N: 645-1-1/1

Test Date: 2/16/05
Ambience temperature: 23

Performance:

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<td>connector</td>
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<td>FC/APC both ends</td>
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Remark:

Product Accepted: John
OE Land Fiber Bragg Grating 1450nm

O/E Land Inc.
4321, Garand, Montreal, Quebec, Canada
(514)434-4588 www.o-eland.com

Acceptance Test Report

Model: OEFBG-100
Name: Fiber Brng Grating
S/N: 645-3-1/1

Test Date: 2/24/05
Ambiance tempeature: 23

Performance:

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Remark:

Center Wavelength(\lambda) 1450.012nm 2005.2.24 Resolution 0.05nm
Loss(\lambda1-\lambda2) 12.79dB 71 1450.012, -12.79 \lambda2
Bandwidth(\lambda2-\lambda1) 0.229nm 1449.912nm 1450.136nm

Product Accepted: John

file://\Server\Database\viewtest.htm 3/2/2005
ThorLabs PDA255 Photo Diode

Figure 1 - PDA255 Spectral Responsivity Curve

Fiber Adapters and Other Accessories
Thorlabs sells a number of accessories that are compatible with the 1" thread on the PDA housing including FC, SMA, and ST fiber adapters, stackable lens tubes for mounting optics, and cage assemblies that allow the PDA to be incorporated into elaborate 3-D optical assemblies.

Caution: The PDA255 was designed to allow maximum accessibility to the photocell by having the front surface of the diode extend outside of the PDA housing. When using fiber adapters, make sure that the fiber ferrule does not crash into the detector. Failure to do so may cause damage to the diode and / or the fiber. An easy way to accomplish this is to install a SM1RR retaining ring (included with the PDA255) inside the 1" threaded coupler before installing the fiber adapter.

Also available in the PDA series are Silicon, switchable gain InGaAs and switchable gain silicon models.

Maintaining the PDA255
There are no serviceable parts in the PDA255 optical head or power supply. The housing may be cleaned by wiping with a soft damp cloth. The window of the detector should only be cleaned using optical grade wipes. If you suspect a problem with your PDA255 please call Thorlabs and an engineer will be happy to assist you.
ILX LightWave LDX3525 Precision Current Source

### Specifications

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<td>100 VDC to 240 VAC</td>
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<td>0 to 100 mA</td>
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<td>±0.1% FS</td>
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<tr>
<td>Voltage Range</td>
<td>0 to 100 V</td>
<td>0 to 100 V</td>
<td>0 to 100 V</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01 µV</td>
<td>0.01 µV</td>
<td>0.01 µV</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±0.1% FS</td>
<td>±0.1% FS</td>
<td>±0.1% FS</td>
</tr>
<tr>
<td>Notes</td>
<td>1) All values measured at room temperature.</td>
<td>1) All values measured at room temperature.</td>
<td>1) All values measured at room temperature.</td>
</tr>
<tr>
<td></td>
<td>2) One day for warm-up period, 10 minute warm-up period.</td>
<td>2) One day for warm-up period, 10 minute warm-up period.</td>
<td>2) One day for warm-up period, 10 minute warm-up period.</td>
</tr>
<tr>
<td></td>
<td>3) Over a 4-hour period, measurement made at 5°C interval.</td>
<td>3) Over a 4-hour period, measurement made at 5°C interval.</td>
<td>3) Over a 4-hour period, measurement made at 5°C interval.</td>
</tr>
<tr>
<td></td>
<td>4) Frequency response measured at 500 MHz for sine wave.</td>
<td>4) Frequency response measured at 500 MHz for sine wave.</td>
<td>4) Frequency response measured at 500 MHz for sine wave.</td>
</tr>
<tr>
<td></td>
<td>5) Maximum input current 100 mA at 0 to 10 V.</td>
<td>5) Maximum input current 100 mA at 0 to 10 V.</td>
<td>5) Maximum input current 100 mA at 0 to 10 V.</td>
</tr>
<tr>
<td></td>
<td>6) Maximum output power 1000 mW at 0 to 10 V.</td>
<td>6) Maximum output power 1000 mW at 0 to 10 V.</td>
<td>6) Maximum output power 1000 mW at 0 to 10 V.</td>
</tr>
<tr>
<td></td>
<td>7) Maximum output power 1000 mW at 0 to 10 V.</td>
<td>7) Maximum output power 1000 mW at 0 to 10 V.</td>
<td>7) Maximum output power 1000 mW at 0 to 10 V.</td>
</tr>
<tr>
<td></td>
<td>8) Measured at 5°C.</td>
<td>8) Measured at 5°C.</td>
<td>8) Measured at 5°C.</td>
</tr>
</tbody>
</table>

For information call 1-800-456-8459

www.ilxlightwave.com

P.O. Box 620, Bozeman, MT 59771 • FAX 406-586-9029

*For commercial purposes, contact ILX Lightwave for further information.*
AV-tech AVM-2-C Ultra-High Speed Pulse Generator

The models in the AVM family provide very fast rise times (100 or 150 ps), with high repetition rates (25 MHz), variable pulse widths, and amplitudes as high as 15 Volts.

Model AVM-1-C provides amplitudes up to 5V, with pulse widths variable from 0.2 to 6 ns. The rise time is less than 100 ps, and the fall time is less than 150 ps.

Model AVM-2-C provides amplitudes up to 15V, with pulse widths variable from 0.2 to 2 ns. The rise time is less than 100 ps, and the fall time is less than 135 ps.

Model AVM-3-C operates over a wider pulse width range of 2 to 15 ns, with amplitudes up to 15V. The rise time is less than 150 ps, and the fall time is less than 600 ps.

The pulse repetition frequency is variable from 3 kHz to 25 MHz on all -C models using the internal clock oscillator, which is controlled by a switch-position front panel switch and a one-turn fine control. A delay control and a sync output are provided for sampling scope triggering purposes. The units can also be triggered externally using a TTL level pulse. The propagation delay in the externally triggered mode is typically 30 ns, and an optional variable relative delay (0 to 8 ns) is available. Either output polarity or an optional dual output polarity can be provided. A DC offset or bias insertion (similar to Model AVX-T, see [source](http://www.avtechoutput.com/black bury1.html)) is included. The required DC offset or bias is applied directly to rear panel solder terminals.

An available option provides an internally-generated DC offset (0 to ±5V) controlled by a front panel one-turn dial. Polarity inversion in dual polarity units is accomplished by means of an inverting transformer module that connects to the pulse generator's output port. AVM units are available with a monitor option that provides an attenuated (20 dB or x10) coincidence replica of the main output pulse. Additional options include electronic control (0 to ±10V) of output amplitude, pulse width, propagation delay, and DC offset.

Units with these options also include the standard front panel one-turn controls. All -C units require 100-240V, 50-60 Hz prime power. All AVM units are also available in a DC-powered miniature module format. The AVM-1 and AVM-2 modules require ±24V DC, and the AVM-3 requires ±28V DC. These modules require a TTL input trigger signal and the output PRF equals the input trigger PRF. Pulse width and output amplitude are controlled by one-turn trimmer controls. An optional relative delay (0 to 5 ns) control is available.

The output amplitude and pulse width for the AVM series interact to the extent that for a given pulse width setting, decreasing the output amplitude increases the output pulse width. This interaction may be eliminated by using external variable attenuations to control the amplitude or by using the 300 ps rise time AVMM series. The AVM series is ideally suited for systems or laboratory applications such as logic testing, TDR, radar, optical and cable communications, SAW, nuclear, switching and propagation time studies and educational fields. In some cases, the specifications can be adapted to satisfy a particular requirement. Contact the factory ([source](http://www.avtechoutput.com/blackbury1.html)) with your special requirements.

---

1. `-C` suffix indicates stand-alone lab instrument with internal clock and line power only. No suffix indicates miniature module requiring DC power and external trigger. (See [source](http://www.avtechoutput.com/blackbury1.html) for additional details of the basic format.)
2. `-A` suffix indicates electronic control (0 to ±10V) of amplitude, pulse width, delay or offset. Model number with `-A` or `-AW` or `-ED` or `-EO` electronic control units also include the standard front panel one-turn controls.
3. For operation at amplitudes less than 20% of full-scale, best results will be obtained by setting the amplitude near full-scale and using external attenuations on the output.
# Specifications

<table>
<thead>
<tr>
<th>ando AQ-6315A Optical Spectrum Analyzer</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Applicable fiber</strong></th>
<th>Single-pass monochromator mode</th>
<th>Double-pass monochromator mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement wavelength range</td>
<td>350 to 1550nm</td>
<td>350 to 1550nm</td>
</tr>
<tr>
<td>Wavelength span</td>
<td>0 to 1000nm</td>
<td>0 to 1000nm</td>
</tr>
<tr>
<td>Wavelength accuracy</td>
<td>±0.06nm (min: 0.1% of scan length)</td>
<td>±0.06nm (min: 0.1% of scan length)</td>
</tr>
<tr>
<td>Wavelength linearity</td>
<td>±0.02% (1:30:1 deviation from the scan length)</td>
<td>±0.02% (1:30:1 deviation from the scan length)</td>
</tr>
<tr>
<td>Wavelength reproducibility</td>
<td>±0.005nm (1 minute)</td>
<td>±0.005nm (1 minute)</td>
</tr>
<tr>
<td>Measurement level accuracy</td>
<td>±0.05% of full scale</td>
<td>±0.05% of full scale</td>
</tr>
<tr>
<td>Level accuracy</td>
<td>±0.1% of full scale</td>
<td>±0.1% of full scale</td>
</tr>
<tr>
<td>Polarization dependence</td>
<td>±0.1dB (at 1310/1550nm)</td>
<td>±0.1dB (at 1310/1550nm)</td>
</tr>
<tr>
<td>Level scale</td>
<td>0.1 to 10dB steps</td>
<td>0.1 to 10dB steps</td>
</tr>
<tr>
<td>Dynamic range (gray level)</td>
<td>40dB (±1nf, 1310/1550nm)</td>
<td>40dB (±1nf, 1310/1550nm)</td>
</tr>
<tr>
<td>Sweep time</td>
<td>0.5 s or less (200nm or less)</td>
<td>0.5 s or less (200nm or less)</td>
</tr>
<tr>
<td>Display</td>
<td>10-bit display, analog output display</td>
<td>10-bit display, analog output display</td>
</tr>
<tr>
<td>Functions</td>
<td>Max/min, hold, data calculation (addition, subtraction, division), normalization, display memory, curve-fit display, power density display function, dBm/dBm, % level scale</td>
<td>Max/min, hold, data calculation (addition, subtraction, division), normalization, display memory, curve-fit display, power density display function, dBm/dBm, % level scale</td>
</tr>
<tr>
<td>Other</td>
<td>Program function (200 steps/20 programs), wavelength calibration function, calendar/date function, help function, user-defined function, label function</td>
<td>Program function (200 steps/20 programs), wavelength calibration function, calendar/date function, help function, user-defined function, label function</td>
</tr>
<tr>
<td>Optical output</td>
<td>Insertion loss: 200mV or less (1310/1550nm)</td>
<td>Insertion loss: 200mV or less (1310/1550nm)</td>
</tr>
<tr>
<td>Memory</td>
<td>500 Mbps/sec</td>
<td>500 Mbps/sec</td>
</tr>
<tr>
<td>Data Output</td>
<td>Printer</td>
<td>Printer</td>
</tr>
<tr>
<td>GP-IB</td>
<td>2 ports</td>
<td>2 ports</td>
</tr>
<tr>
<td>Interface</td>
<td>Other</td>
<td>Other</td>
</tr>
<tr>
<td>Display</td>
<td>6.4-inch color LCD, resolution: 480 x 640</td>
<td>6.4-inch color LCD, resolution: 480 x 640</td>
</tr>
<tr>
<td>Optical input connector</td>
<td>FC (standard SC, LC, ST, ST, ST, etc.)</td>
<td>FC (standard SC, LC, ST, ST, ST, etc.)</td>
</tr>
<tr>
<td>Power requirements</td>
<td>AC100V to 120V, 200V to 240V, 45 to 63Hz, approx. 200VA</td>
<td>AC100V to 120V, 200V to 240V, 45 to 63Hz, approx. 200VA</td>
</tr>
<tr>
<td>Environment</td>
<td>Operating temperatures: 0°C to 40°C</td>
<td>Operating temperatures: 0°C to 40°C</td>
</tr>
<tr>
<td>Dimensions and mass</td>
<td>Approx. W: 450 x 450 x 280 mm, approx. 38kg</td>
<td>Approx. W: 450 x 450 x 280 mm, approx. 38kg</td>
</tr>
</tbody>
</table>

Note: Device adapters, power cord, and power supply are optional. Please consult with your vendor separately.

*These specifications are for products delivered later than October 1997.

**Note**

1. After power-on and more than two hours of warm-up, within 24 hours from wavelength calibration with 1529nm
2. 1325 ± 0°C, resolution 0.5nm or more
3. 10125 SM fiber, 25 ± 0°C, input level -30dBm or more
4. 10125 SM fiber, 25 ± 0°C, resolution 0.5nm or more
5. 20 ± 0°C, sensitivity 35G
6. 10125 SM fiber, 25 ± 0°C, resolution 0.05nm, excluding high-order and low-order harmonics
7. Single-trace display, sampling point: 501, sensitivity NORMAL HOLD. Average time: 1, no changes of
   distortion order within sweep range except the full span
8. A501315A only

Specifications are subject to change without notice.
### Tektronix TDS 7154B Digital Phosphor Oscilloscope

#### Characteristics

**Vertical System**

<table>
<thead>
<tr>
<th></th>
<th>TDS7054</th>
<th>TDS7104</th>
<th>TDS7154/TDS7254</th>
<th>TDS7404</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Channels</strong></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Analog Bandwidth (≥3 dB)</strong></td>
<td>500 MHz</td>
<td>1 GHz</td>
<td>2.5 GHz (TDS7154)</td>
<td>4 GHz</td>
</tr>
<tr>
<td><strong>Calculated Rise Time 10 mV/div to 1 V/div</strong></td>
<td>800 ps</td>
<td>400 ps</td>
<td>160 ps (TDS7154)</td>
<td>100 ps</td>
</tr>
<tr>
<td><strong>Hardware Bandwidth Limits</strong></td>
<td>150 MHz or 20 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Input Coupling</strong></td>
<td>AC, DC, Gnd</td>
<td>DC, Gnd</td>
<td>DC, Gnd</td>
<td>DC, Gnd</td>
</tr>
<tr>
<td><strong>Input Impedance</strong></td>
<td>1 MΩ ±0.5% or 50 Ω ±1%</td>
<td>50 Ω ±3%</td>
<td>50 Ω ±3%</td>
<td>50 Ω ±3%</td>
</tr>
<tr>
<td><strong>Input Sensitivity, 1 MΩ</strong></td>
<td>1 mV/div to 10 V/div</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Input Sensitivity, 50 Ω</strong></td>
<td>1 mV/div to 1 V/div</td>
<td>2 mV/div to 1 V/div</td>
<td>2 mV/div to 1 V/div</td>
<td></td>
</tr>
<tr>
<td><strong>Vertical Resolution</strong></td>
<td>8-Bit (±11-Bit waveforming)</td>
<td>8-Bit (±11-Bit waveforming)</td>
<td>8-Bit (±11-Bit waveforming)</td>
<td></td>
</tr>
<tr>
<td><strong>Max Input Voltage, 1 MΩ</strong></td>
<td>±150 V CAT I on 15Ω at 20 dB/decade to 2.5 V Vac above 200 kHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Max Input Voltage, 50 Ω</strong></td>
<td>±5 V Vac, with probe less than ±30 Vdc</td>
<td>Determined by TekConnect™ Accessory</td>
<td>Determined by TekConnect™ Accessory</td>
<td></td>
</tr>
<tr>
<td><strong>DC Gain Accuracy</strong></td>
<td>1%</td>
<td>±0.2%</td>
<td>±0.2%</td>
<td>±0.2%</td>
</tr>
<tr>
<td><strong>Offset Range</strong></td>
<td>1 mV/div to 100 mV/div ±1 V</td>
<td>2 mV to 50 mV/div ±0.5 V</td>
<td>2 mV to 50 mV/div ±0.5 V</td>
<td>2 mV to 50 mV/div ±0.5 V</td>
</tr>
<tr>
<td><strong>Channel-to-channel Isolation</strong></td>
<td>≥1000:1 at 100 MHz and ≥50:1 at the rated bandwidth</td>
<td>≥1001:1 at ±3.5 GHz and ≥50:1 at 4 GHz</td>
<td>≥1001:1 at ±3.5 GHz and ≥50:1 at 4 GHz</td>
<td>≥100:1 at ±3.5 GHz and ≥50:1 at 4 GHz</td>
</tr>
<tr>
<td><strong>Timebase System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Timebase Range</strong></td>
<td>200 ps/div to 40 s/div</td>
<td>50 ps to 10 s/div</td>
<td>50 ps to 10 s/div</td>
<td>50 ps to 10 s/div</td>
</tr>
<tr>
<td><strong>Timebase Delay Time Range</strong></td>
<td>15 ns to 250 s</td>
<td>16 ns to 250 s</td>
<td>16 ns to 250 s</td>
<td>16 ns to 250 s</td>
</tr>
<tr>
<td><strong>Channel-to-channel Delay Time Range</strong></td>
<td>±25 ps</td>
<td>±25 ps</td>
<td>±25 ps</td>
<td>±25 ps</td>
</tr>
<tr>
<td><strong>Delay Time Measurement Accuracy</strong></td>
<td>±(0.05 sample interval) + (15 ps RMS)</td>
<td>±0.005 sample between RMS</td>
<td>±2.5 ppm between RMS</td>
<td>±2.5 ppm between RMS</td>
</tr>
<tr>
<td><strong>Trigger Jitter (RMS)</strong></td>
<td>8 ps RMS typical</td>
<td>6 ps RMS typical</td>
<td>6 ps RMS typical</td>
<td>6 ps RMS typical</td>
</tr>
<tr>
<td><strong>Long-Term Sample Rate and Delay Time Accuracy</strong></td>
<td>±10 ppm over ±1 ns interval</td>
<td>±10 ppm over ±1 ns interval</td>
<td>±10 ppm over ±1 ns interval</td>
<td>±10 ppm over ±1 ns interval</td>
</tr>
</tbody>
</table>
Digital Phosphor Oscilloscopes  
> TDS7000 Series

### Acquisition System

<table>
<thead>
<tr>
<th></th>
<th>TDS7054</th>
<th>TDS7104</th>
<th>TDS7154/TDS7254</th>
<th>TDS7404</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Real-Time Sample Rates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 channel (max)</td>
<td>5.05 Gs</td>
<td>10.0 Gs</td>
<td>20.0 Gs</td>
<td>26.0 Gs</td>
</tr>
<tr>
<td>2 channels (max)</td>
<td>5.05 Gs</td>
<td>5.05 Gs</td>
<td>10.0 Gs</td>
<td>10.0 Gs</td>
</tr>
<tr>
<td>4-8 channels (max)</td>
<td>1.5 Gs</td>
<td>2.6 Gs</td>
<td>5.0 Gs</td>
<td>5.0 Gs</td>
</tr>
<tr>
<td><strong>Equivalent Time Sample Rate (max)</strong></td>
<td>150 Gs</td>
<td>250 Gs</td>
<td>250 Gs</td>
<td>250 Gs</td>
</tr>
<tr>
<td><strong>Maximum record length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per channel with standard memory</td>
<td>400 k (1-CH), 200 k (2-CH), 100 k (4-CH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Memory Opt. 1M</td>
<td>2 M (1-CH), 1 M (2-CH), 500 k (4-CH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Memory Opt. 2M</td>
<td>8 M (1-CH), 4 M (2-CH), 1 M (4-CH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Memory Opt. 3M</td>
<td>16 M (1-CH), 8 M (2-CH), 4 M (4-CH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Memory Opt. 4M</td>
<td>12 M (1-CH), 6 M (2-CH), 2 M (4-CH)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Maximum Duration at Highest Real-time Resolution (1-CH)

<table>
<thead>
<tr>
<th></th>
<th>TDS7054</th>
<th>TDS7104</th>
<th>TDS7154/TDS7254</th>
<th>TDS7404</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Resolution Single-shot</strong></td>
<td>200 ps (5 ps/div)</td>
<td>100 ps (10 ps/div)</td>
<td>50 ps (20 ps/div)</td>
<td></td>
</tr>
<tr>
<td>Max Duration with Standard Memory</td>
<td>80 µs</td>
<td>40 µs</td>
<td>20 µs</td>
<td></td>
</tr>
<tr>
<td>Max Duration with Opt. 1M</td>
<td>400 µs</td>
<td>200 µs</td>
<td>100 µs</td>
<td></td>
</tr>
<tr>
<td>Max Duration with Opt. 2M</td>
<td>1.6 ms</td>
<td>800 µs</td>
<td>400 µs</td>
<td></td>
</tr>
<tr>
<td>Max Duration with Opt. 3M</td>
<td>3.2 ms</td>
<td>1.6 ms</td>
<td>800 µs</td>
<td></td>
</tr>
<tr>
<td>Max Duration with Opt. 4M</td>
<td>1.6 ms</td>
<td>1.6 ms</td>
<td>800 µs</td>
<td></td>
</tr>
</tbody>
</table>

### Acquisition Modes

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<tr>
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<th>TDS7154/TDS7254</th>
<th>TDS7404</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FastAcq Acquisition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Maximum FastAcq Waveform Capture Rate</strong></td>
<td>&gt; 200,000 wfm/s</td>
<td>&gt; 400,000 wfm/s</td>
<td>&gt; 400,000 wfm/s</td>
<td></td>
</tr>
<tr>
<td>Waveform Database (requires Option 5M)</td>
<td>Accumulate Waveform Database providing three-dimensional array of amplitude, time and counts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sample</strong></td>
<td>Acquire sampled values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak Detect</strong></td>
<td>Captures narrow glitches at all real-time sampling rates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Minimum/Peak Detect Pulse Width</strong></td>
<td>≤ 1 ms</td>
<td>400 ps</td>
<td>400 ps</td>
<td></td>
</tr>
<tr>
<td><strong>Averaging</strong></td>
<td>From 2 to 10,000 waveforms included in average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td>From 2 to 2x10⁶ waveforms included in min-max envelope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hi-Res</strong></td>
<td>Real-time borescan averaging reduces random noise and increases resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FastFrame™ Acquisition</strong></td>
<td>Acquisition memory divided into segments; maximum trigger rate &gt; 160,000 waveforms per second. Time of event recorded with each event</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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# Digital Phosphor Oscilloscopes

## TDS7000 Series

## Trigger System

<table>
<thead>
<tr>
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<th>TDS7054</th>
<th>TDS7104</th>
<th>TDS7154/TDS7254</th>
<th>TDS7404</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal DC Coupled</td>
<td>0.35 div DC to 50 MHz increasing to 1 div at 500 MHz</td>
<td>0.35 div DC to 50 MHz increasing to 1 div at 1 GHz</td>
<td>0.35 div DC to 50 MHz increasing to 1.5 div at 3 GHz</td>
<td>0.35 div DC to 50 MHz increasing to 1.5 div at 3 GHz</td>
</tr>
<tr>
<td>External (Auxiliary Input)</td>
<td>400 mV from DC to 50 MHz increasing to 750 mV at 100 MHz</td>
<td>250 mV from DC to 50 MHz increasing to 500 mV at 150 MHz</td>
<td>250 mV from DC to 50 MHz increasing to 350 mV at 500 MHz</td>
<td>250 mV from DC to 50 MHz increasing to 350 mV at 500 MHz</td>
</tr>
<tr>
<td><strong>Main Trigger Modes</strong></td>
<td>Auto, Normal and Single</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger Sequences</strong></td>
<td>Main, Delayed by Time, Delayed by Events. All sequences can include separate horizontal delay after the trigger event to position the acquisition window in time</td>
<td></td>
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<td></td>
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<tr>
<td><strong>Trigger Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Standard Trigger Types</strong></td>
<td>Edge, Glitch, Start, Width, Transition time, Timeout, Pattern, State, Setup/Hold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Communications-related Triggers (requires Option SM)</strong></td>
<td>Support for AM, HDB3, BaZS, CMI, Ml3, and NRZ encoded communications signals. Select between isolated positive or negative one, zero pulse form or eye patterns as applicable to standard</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Serial Pattern Trigger (requires Option ST)</strong></td>
<td>32-bit serial word recognizer; bits specified in binary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger Level Range</strong></td>
<td>±12 divisions from center of screen</td>
<td>±8 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td>fixed at 0 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger Coupling</strong></td>
<td>DC, AC (attenuates &lt;0 Hz), HF Rej (attenuates &gt;30 kHz), LF Rej attenuates &lt;80 kHz, Noise Reject (on/off sensitivity)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Trigger Holdoff Range</strong></td>
<td>250 ns minimum to 12 s maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Corning Lensed Fibers

<table>
<thead>
<tr>
<th>Optical Performance Characteristics for Standard Products</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Code</strong></td>
</tr>
<tr>
<td>Mode-field Diameter (MFD)</td>
</tr>
<tr>
<td>Thickness (T)</td>
</tr>
<tr>
<td>Radius of Curvature (Rc)</td>
</tr>
<tr>
<td>Distance to Beam Waist (f)</td>
</tr>
<tr>
<td>AR Coating</td>
</tr>
<tr>
<td>Fiber Type</td>
</tr>
<tr>
<td>Pigtail Length</td>
</tr>
<tr>
<td>Insertion Loss</td>
</tr>
<tr>
<td>Return Loss</td>
</tr>
<tr>
<td>Refractive Index</td>
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<td></td>
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</tr>
</tbody>
</table>

Customized Products
Lensed fiber can be tailored to collimate or focus light with a range of beam diameters and optimum working distances.

Figure 2. The thickness of the lens (T) and radius of curvature (Rc) defines the mode-field diameter (MFD) and the distance to beam waist (f). The ball size is equal to 2xRc.
Corning 2D Collimator Arrays
Developmental Product

Product Description
Corning Collimator Arrays are designed utilizing a combination of Corning's precision alignment and lensing technologies: Corning Polymer Gripper, SMILE™ Lens Array and OptiFocus™ Lensed Fibers.

Applications
- Switches, OADMs and OXCs
  - 2D MEMS
  - Liquid Crystal
- Arrayed Devices
  - VCSELs
  - VOAs
  - Isolators

Key Benefits
- Precise fiber-to-lens tolerances
- Passive alignment of lenses
- Low pointing angles
- Low insertion loss
- Design flexibility

Radial-8 Channel Collimator Array for potential rotary MEMS applications utilizing Corning Polymer Gripper and OptiFocus Lens Technology
Configurations

Option 1 for working distances < 4.2mm
- Linear
- Radial
- Custom

OptiFocus™ Collimating or Focusing Lensed Fiber

Option 2 for working distances > 1mm up to 300mm

SMILE™ Lens Array
This thesis has been approved:

Dr. Scott T. Sanders