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OH Planar Laser Induced Fluorescence (PLIF) Measurements for the Study of High Pressure Flames: An Evaluation of a New Laser and a New Camera System

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May 2012

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Abstract

Planar laser induced fluorescence (PLIF) is used by the Combustion Branch at the NASA Glenn Research Center (NASA Glenn) to assess the characteristics of the flowfield produced by aircraft fuel injectors. To improve and expand the capabilities of the PLIF system new equipment was installed. The new capabilities of the modified PLIF system are assessed by collecting OH PLIF in a methane/air flame produced by a flat flame burner. Specifically, the modifications characterized are the addition of an injection seeder to a Nd:YAG laser pumping an optical parametric oscillator (OPO) and the use of a new camera with an interline CCD. OH fluorescence results using the injection seeded OPO laser are compared to results using a Nd:YAG pumped dye laser with ultraviolet extender (UVX). Best settings of the new camera for maximum detection of PLIF signal are reported for the controller gain and microchannel plate (MCP) bracket pulsing. Results are also reported from tests of the Dual Image Feature (DIF) mode of the new camera which allows image pairs to be acquired in rapid succession. This allows acquisition of a PLIF image and a background signal almost simultaneously. Saturation effects in the new camera were also investigated and are reported.

Introduction

The NASA Glenn Research Center (NASA Glenn) Combustion Branch uses planar laser induced fluorescence (PLIF) to characterize the combustion process during testing of aircraft fuel injectors in the combustion facilities, CE–5 and CE–13 (Ref. 1). The CE–5 facility (Ref. 2) can simulate the conditions of aircraft combustors, up to 30 atm. The CE–13 combustor facility is used for fundamental fuel-air mixing studies and can operate up to 5 atm.

PLIF is a technique that targets minor combustion species, such as OH, CH, and NO by exciting electrons in those species to an excited energy level, then measuring the fluorescence emitted when the molecules relax back to a lower energy state. A wavelength-tunable laser system is needed to excite the desired energy level of any given species. A detector (in this case a camera) is used to collect as much of the fluorescence as possible. The fluorescence signal is proportional to the number of molecules within measurement volume.

New equipment was installed to expand and improve the capability to perform these PLIF measurements. This new equipment consists of an optical parametric oscillator (OPO) and a new camera with an interline CCD. Laboratory experiments were conducted to find settings for the equipment that will yield the best OH PLIF signal. Similar experiments using the original equipment were made in parallel to provide a baseline for comparison to the performance of the new equipment.

The OPO used in this experiment converts 355 nm light emitted by a frequency-tripled Nd:YAG laser to a tunable range of ultraviolet (UV) wavelengths. The UV light emitted from the OPO can be used to produce a fluorescence signal from molecules of interest when tuned to their excitation line wavelengths. The OPO was purchased to replace the traditional dye laser and ultraviolet extender (UVX) combination that converts 532 nm light to a tunable range of UV wavelengths. The advantage of this OPO over a dye/UVX system is its smaller footprint, useful for laboratories with limited space. The OPO also offers more straight forward tuning capability over a wider range of wavelengths than the dye/UVX system. For example, in order to access NO with the dye/UVX, a different laser dye must be used, and the UVX optics must be changed to allow the frequency-doubled dye laser output to be mixed with the fundamental Nd:YAG laser wavelength, 1024 nm. For the OPO, only minor optical changes are needed to access NO, OH, or CH. A disadvantage of this OPO is that it has a wider linewidth than the previously used dye/UVX laser and therefore there is less energy contributed to each fluorescence excitation line, thus creating a lower fluorescence response (Ref. 1). OPO systems exist that have narrower linewidths than the one purchased, but those systems are currently unaffordable for our organization at approximately $300,000.

The new OPO addition was previously characterized in Reference 1, where it was found that its linewidth was too wide to achieve enough signal for measurement in the combustor subcomponent test facility (bldg. 5, cell CE-5). Following the recommendation of Reference 1, an injection seeder was added to the Nd:YAG laser to narrow the line width output of the OPO. To characterize the new laser configuration, wavelength scans of the laser were taken. Also, fluorescence levels at selected excitation lines of OH were measured in a methane/air flame produced by a flat flame from a Hencken burner at atmospheric pressure. All measurements taken using the OPO were repeated with a dye/UVX laser for comparison of performance.

The other component change to the PLIF system is a new, higher frame rate, camera which uses an interline CCD array. The performance of the interline camera was assessed by comparing its OH PLIF detection to a camera which uses a standard CCD array. A Hencken burner flame was used to determine the best settings of the interline CCD for optimal collection of OH PLIF. In addition to having a faster frame rate (23 frames/s compared to approximately 1 frame/s for the standard CCD), the interline CCD provides the ability to take image pairs separated by an interval as short as 2 μs. This Dual Image Feature (DIF) may be useful to collect a more accurate background in conditions where a constantly changing luminous background is present, as in the combustion produced by aircraft fuel injectors. The Hencken burner flame is used to characterize this new camera feature although the flame produced has low intensity background luminosity and is relatively stable. To more fully determine the response of the chip in the new camera, saturation curves were obtained by exposing the camera to a uniform light source.

Experimental Setup

The experimental setup to compare the performance of two different laser configurations (the new injection seeded OPO and the dye, UVX combination) and old and new cameras is shown in Figure 1. The new laser setup characterized in this experiment is a 10 Hz, injection seeded, Q-switched, frequency-tripled Nd:YAG laser that emits 355 nm wavelength light. This light is passed into an OPO where the light is converted to UV wavelengths tunable from 206 to 425 nm. The energy emitted by the laser varies with the wavelength to which it is tuned. For this experiment the OPO was tuned to the OH fluorescence band near 280 nm at which it emits approximately 6 mJ/pulse.

The performance of this laser was compared to a Nd:YAG-pumped dye and UVX combination used previously to produce UV laser light for PLIF measurements. The Nd:YAG used in this combination is similar to the Nd:YAG used with the OPO except that it is not injection seeded. In this configuration the Nd:YAG frequency doubled light at 532 nm is used to pump a dye laser with Rhodamine 590 for a gain medium. This 550 to 600 nm tunable light is passed through the UVX which converts the light to a tunable range of 275 to 300 nm. This laser configuration is capable of emitting up to 30 mJ at the OH excitation wavelengths. To allow a one-to-one comparison of the PLIF signal, the doubling crystal in the Nd:YAG laser was detuned so that the output energy matched the energy emitted by the OPO. Three OH excitation lines considered as candidates for creating the most fluorescence response were, $R_1(1)$, $R_1(10)$, and $R_2(7)$ at 281.4005, 281.5368, and 281.5989 nm, respectively. Figure 2 shows a fluorescence scan comparing the resolution of the OPO and the UVX. These scans were produced by collecting the intensity of fluorescence of OH from a propane flame produced in a Bunsen burner with a photomultiplier tube. The OPO linewidth is broader than the UVX and distributes its energy over a wider range of wavelengths; therefore the OPO has less energy to excite specific OH fluorescence lines.

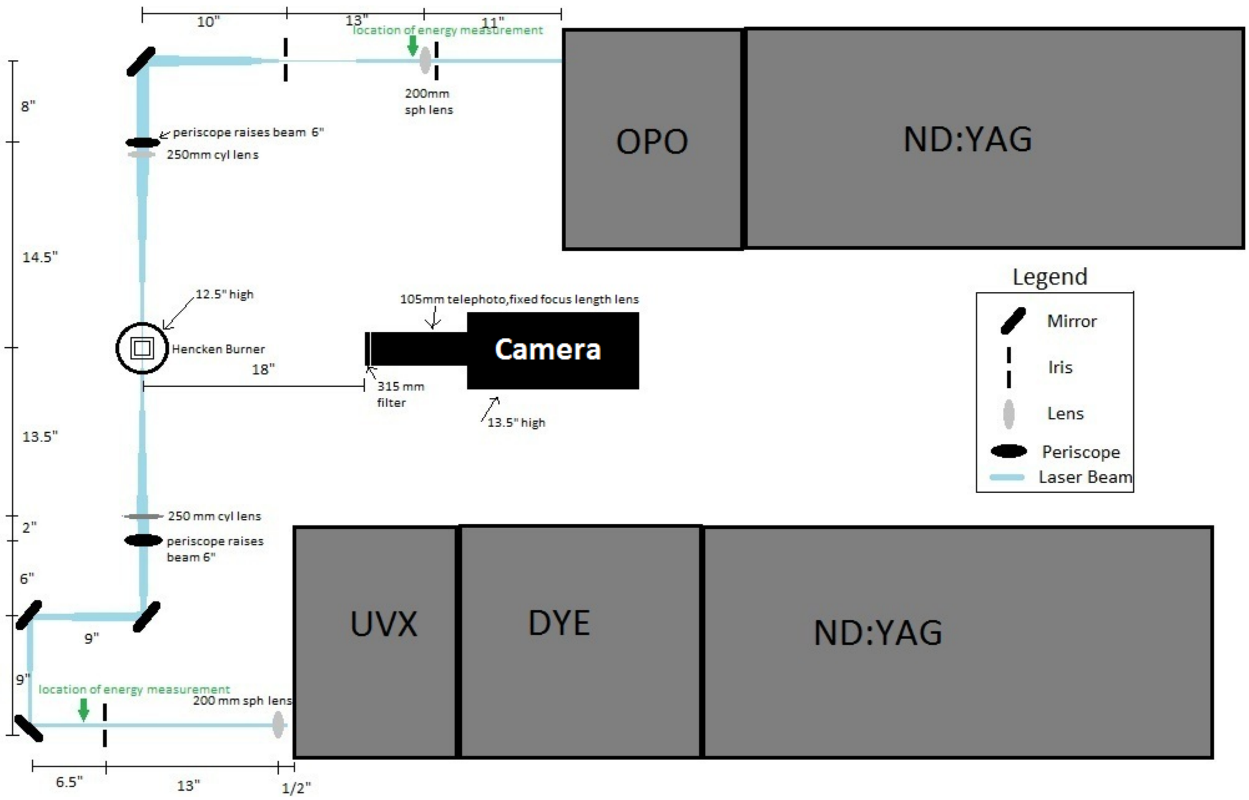

Figure 1.—Drawing of experimental setup.

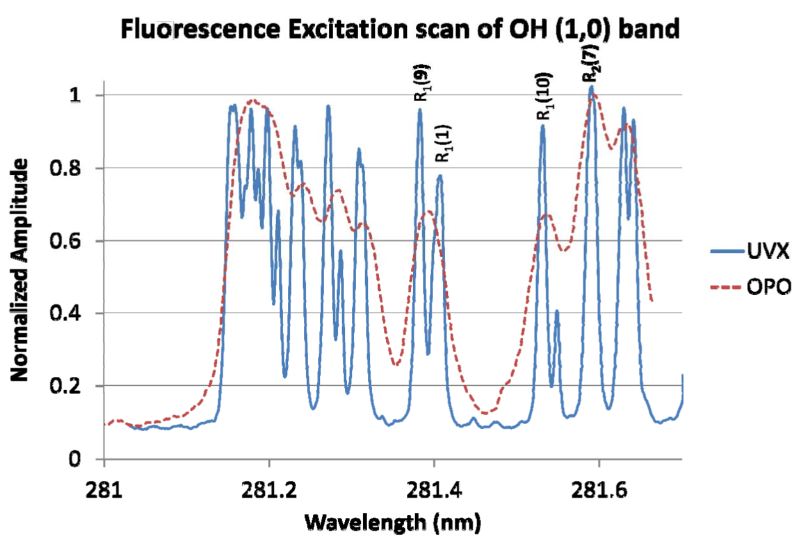

Figure 2.—Scan of UVX and OPO Lasers over the wavelengths of the OH (1,0) fluorescence band versus the intensity of the fluorescence normalized to maximum.

As seen in Figure 1, the OPO and UVX laser performances are compared in a Hencken burner flame. The laser paths drawn in Figure 1 show that both lasers are focused and then expanded by a 200 mm spherical lens. The lasers then are focused into a sheet at the center of the Hencken burner flame using a 250 mm cylindrical lens.

The laser sheets are matched at the measurement volume not only in energy but in shape, size of focus, location of focus at the center of the burner, and in the location of the path though a Hencken burner flame. Matching all the characteristics of the lasers and the measurement volume ensures a valid comparison. The height of the laser sheets was approximately 35 mm. The thickness of the laser sheets at the edges of the flame was 1 mm and at the center it was near 0.03 mm. The bottom of the laser sheets slightly overlapped the bottom of the burner to ensure excitation of fluorescence down to the surface of the burner. The laser sheets are oriented to excite a vertical slice of the flame at the geometric center of the Hencken burner.

The Hencken burner is a flat flame burner that evenly mixes the reactants. For this experiment methane was used as the fuel. Methane and air flow were regulated by digital flow controllers. Two flame parameters were set for this experiment: an equivalence ratio (ϕ) of 0.75 and ϕ of 2.0. The overall volumetric flow rate for both of these equivalence ratios was 6-SLM. Matching the flow rates removes flow rate as a variable that can affect the results. Figure 3 shows photos of the Hencken burner flame at ϕs of 0.75 and 2.0. The fuel flow rate for $\phi = 0.75$ is 0.44-SLM and the air flow rate is 5.56-SLM. The fuel rate for $\phi = 2.0$ is 4.96-SLM and the air flow rate is 1.04 SLM. These flow rates are the same as used in Reference 1.

The new interline CCD (Princeton Instrument's PIMAX3), and the standard CCD (PIMAX) cameras are set up perpendicular to the propagation of the laser sheets, as shown in Figure 1. The same 105 mm telephoto lens was used for both cameras. The interline CCD and the standard CCD are both intensified and both have a Super blue intensifier (see Ref. 3 for response curves). The magnification of the two cameras is matched as shown in Figure 4, where an image of a ruler on the burner is shown. The ruler in these images is placed in the plane where the laser sheet passes, showing that the focus of the cameras is matched at the plane of the laser sheet. Comparing the images, the positioning of the camera's field of view is close, but not perfectly matched. The burner in Figure 4 is shown to be slightly higher in the image taken with the standard CCD compared to the interline CCD. The height is still closely matched enough to allow for a valid intensity comparison in the flame measurements.

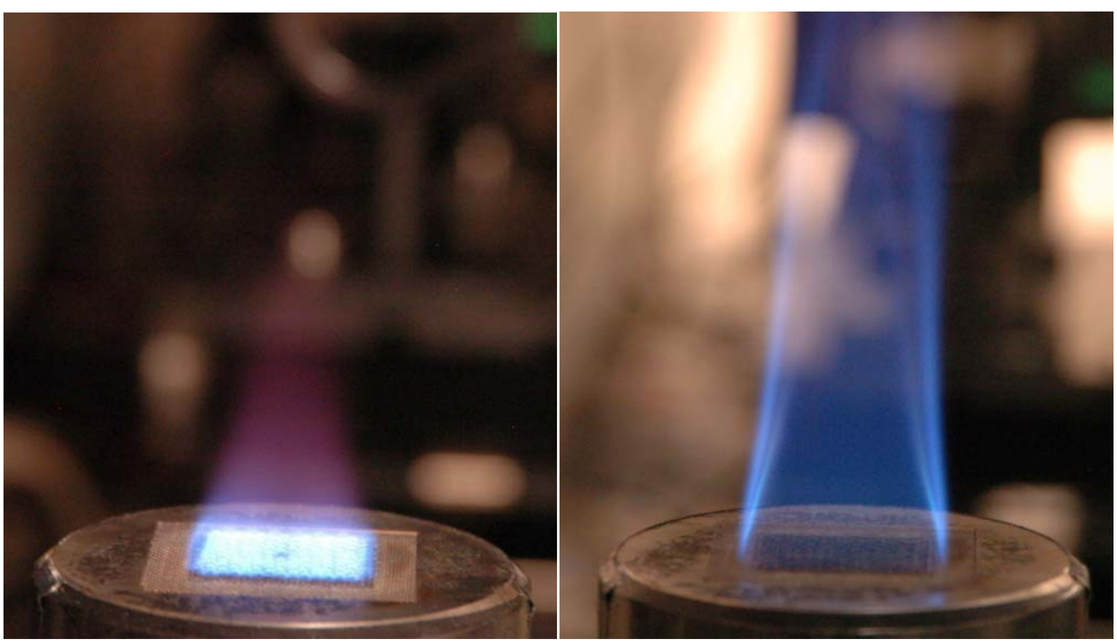

Figure 3.—Photos of the Hencken burner producing a methane flame of $\phi = 0.75$ on the left and $\phi = 2.0$ on the right.

Standard CCD Interline CCD

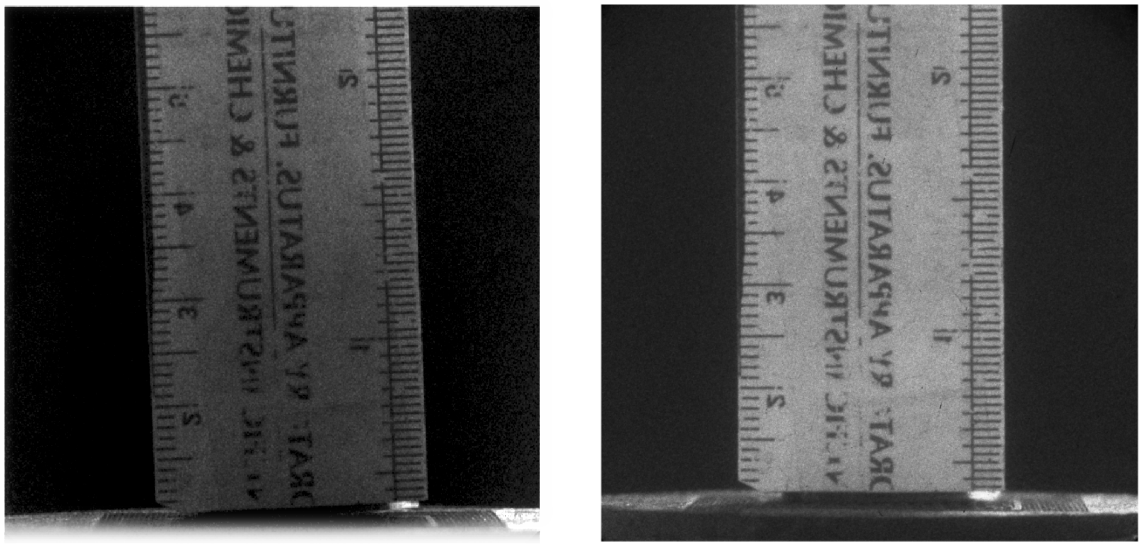

Figure 4.—Photo of rulers set at the location of the laser sheet on top of the Hencken burner to compare scaling of standard CCD (left) and interline CCD (right).

A filter is placed on the end of the 105 mm telephoto lens to filter light that is not in the wavelength range of the OH fluorescence. This filter is a 315 nm, wide bandpass filter (P024-01) chosen in Reference 1 over a narrow bandpass filter for its better transmission. This filter has a pass band width of 15.8 nm centered at 315 nm. In measurements of the saturation levels of the cameras, a deuterium uniform light source is used in place of the Hencken burner flame and the filter is removed.

The timing of image collection is determined by the “Q-switch sync” output of the Nd:YAG laser (see the Powerlite Precision 8000 manual, Ref. 4) and an internal delay set in the program that drives the camera. The cameras are operated in the gate mode (see the PIMAX or PIMAX3 manual, Ref. 3). A gate width of 200 ns and 50 nsec delay is used for both cameras. All images presented here are 60 on-chip accumulations, unless otherwise noted.

The interline CCD camera was also tested in Dual Image Feature (DIF) mode; in this mode two single shot images are collected 2 μs apart. The timing for this mode requires at least an 85 μs delay between the initial trigger and the first image collection. But the “Q-switch sync” output sends a trigger only nanoseconds before the laser pulse arrives at the measurement volume, therefore an earlier trigger is required. For images taken in the DIF mode the trigger is taken from the “flash lamp out” (see Ref. 4) signal from the Nd:YAG which is approximately 200 μs before the Q-switch releases light in the laser cavity. The camera trigger is delayed to match the arrival of the laser at the measurement volume using a pulse generator. The timing is set so that the first image contains the PLIF signal and the second image contains the luminous background of the flame.

The images presented in this work have all been averaged over 10 collections of 60 on chip accumulations, unless otherwise noted. The averaged images are corrected by subtracting an average of 10 collections of 60 on chip accumulations taken while the lasers are tuned off any of the OH excitation lines (a wavelength between $R_1(1)$ and $R_1(10)$). The images collected while the laser is tuned off any excitation line measure the response to the laser light not due to the OH fluorescence and include background light. After subtracting the off-line image, any negative pixels are set to zero. The pixel in the top left corner of each of the images is assigned a value, which is greater than the maximum value in any of the collection of images. This makes all the images have the same maximum and minimum for easier comparison.

For the line plots in the results section, the images are further processed. First, the pixels below 5 percent of the maximum intensity are eliminated. The rest of the pixels are then averaged for an "averaged signal". The error bars shown in the line plots represent plus or minus one standard deviation of 10 averaged accumulations. To find the signal-to-noise ratio the average signal (found as described above) is divided by an average of the pixels below 5 percent of the maximum (noise).

The DIF mode images are processed differently; from each fluorescence image is subtracted the next image collected 2 μs later. The second image includes the background luminosity but not the laser light response. The subtracted images are then averaged. Next, negative numbers in the processed image are set to zero.

Results and Discussion

The results presented in this section are measurements made with the injection seeded OPO laser and the interline CCD camera and measurements made with the UVX and the standard CCD camera for a baseline comparison. First presented are the measurements made to characterize the OPO system.

OPO Versus UVX Fluorescence Excitation

The fluorescent response of OH in a methane flame excited by the OPO laser compared to the UVX laser is shown in image form in Figure 5. These images are taken at a ϕ of 0.75. The images are scaled to a maximum of 16000 counts and the lasers are matched in energy at each wavelength. The highest fluorescent response for both the UVX and the OPO laser is the $R_2(7)$ line. The lowest signal response for the UVX is the $R_1(1)$ line, but for the OPO the $R_1(10)$ line has the lowest response.

Figure 6 shows the same selection of OH excitation lines for both lasers with the methane flame at ϕ of 2.0. The same trend of fluorescence intensity for the excitation lines is present in Figure 6 as in Figure 5. Notice the images in both Figures 5 and 6 have nonuniformities in the intensity. These nonuniformities appear as horizontal strips of changes in intensity. This nonuniformity is due to modes in the cross section of laser beams. Comparing Figures 5 and 6, the UVX appears to have more modes than the OPO. As this nonuniformity is a property of the laser intensity and not of the OH that is being measured, this nonuniformity is an incorrect representation of the location and quantity of the OH in the flame.

The same data shown in Figures 5 and 6 in image form is shown in a line plot in Figure 7. Figure 7 plots the average signal at both ϕs versus the wavelength of the laser at each of the OH excitation lines. The error bars in Figure 7 represent the standard deviation of the average of 10 collections. The graph shows the same trend for intensity versus the laser wavelength as seen in Figures 5 and 6. The graph includes the $R_1(9)$ excitation line, which is not included in the previous figures. The $R_1(9)$ line results in a higher intensity than the $R_1(1)$ line. This offers an explanation of why the response of the OPO $R_1(1)$ is larger than the response of the $R_1(10)$ line. The fluorescence excitation scans of the OPO and UVX as seen in Figure 2 show that the linewidth of the OPO laser causes the PLIF signal from $R_1(1)$ and $R_1(9)$ to be combined, therefore the PLIF signal from the OPO when tuned to $R_1(1)$ includes the excitation of the $R_1(9)$. Images of the UVX-excited $R_1(1)$ and $R_1(9)$ lines and the $R_1(1)$ line excited with the OPO can be seen in Figure 8. In summary, Figures 5 to 7 show that the PLIF signal is lower when excited by the OPO than when excited by the UVX. This is because the UVX's narrower linewidth puts more energy into the wavelengths corresponding to the excitation wavelengths of OH than does the OPO.

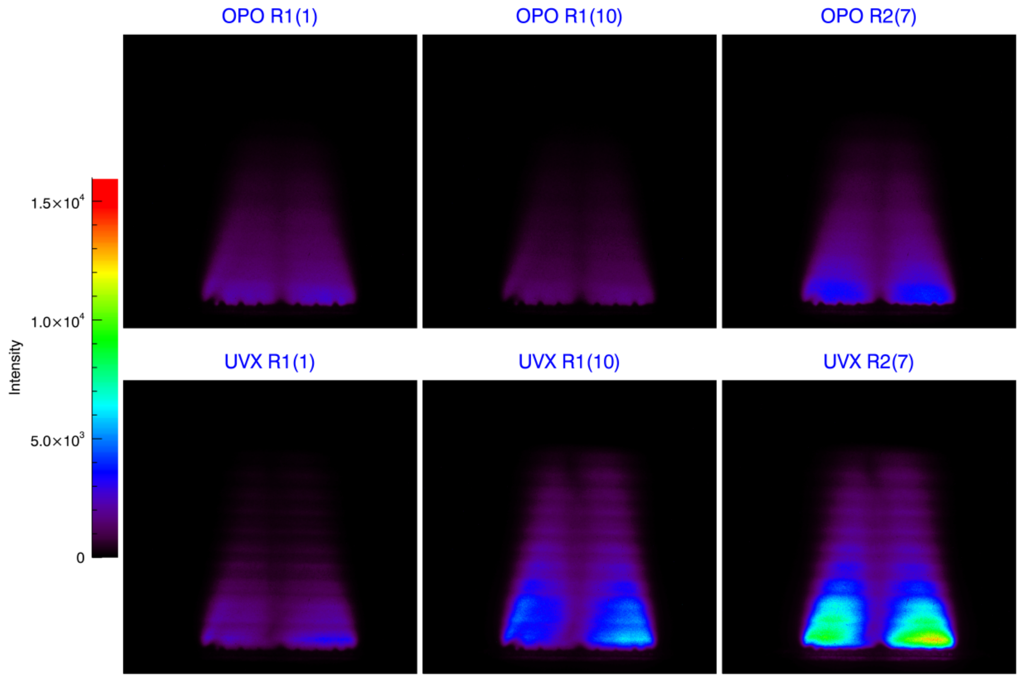

Figure 5.—The PLIF signal from a methane flame at an equivalence ratio of 0.75 produced by the Hencken burner at a range of OH excitation lines for the OPO and UVX lasers.

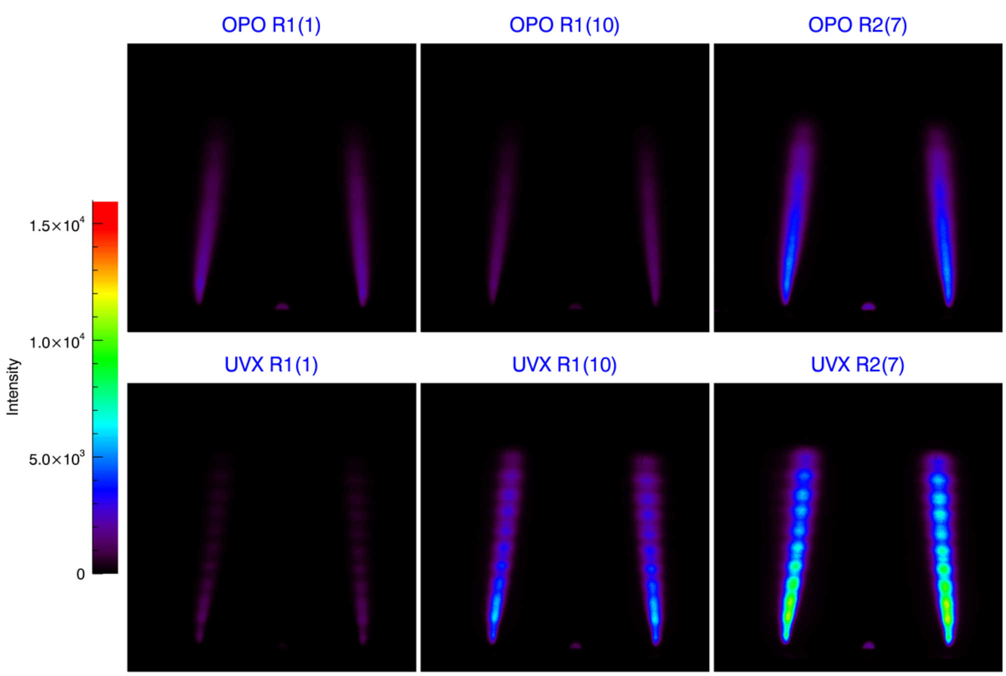

Figure 6.—The PLIF signal of methane flame at an equivalence ratio of 2.0 produced by the Hencken burner at a range of OH excitation lines for the OPO and UVX lasers.

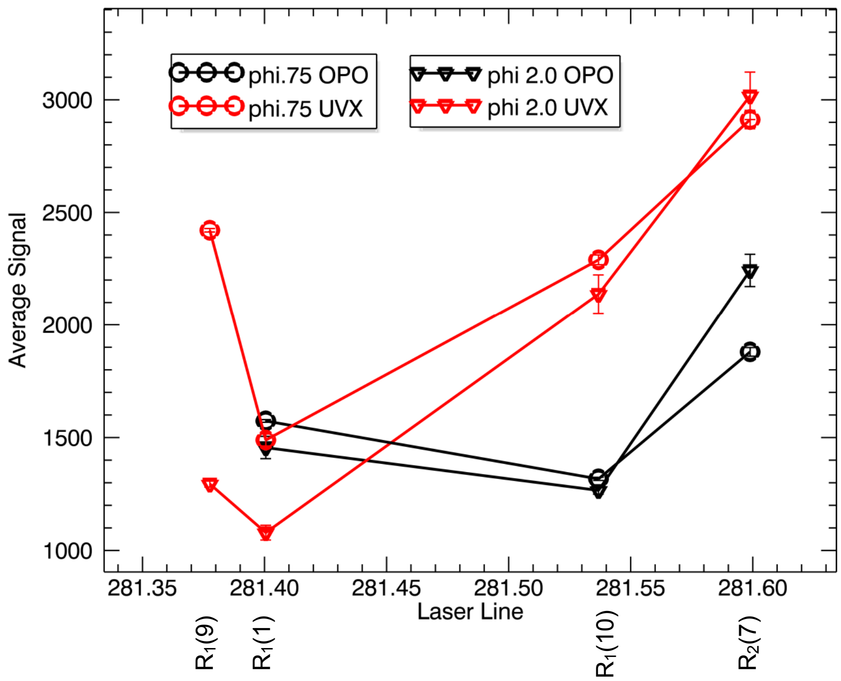

Figure 7.—Average PLIF signal verses the OH excitation line wavelengths for both lasers and both equivalence ratios. $R_1(9)$ = 281.3776 nm, $R_1(1)$ = 281.4005 nm, $R_1(10)$ = 281.5368 nm, and $R_2(7)$ = 281.5989 nm.

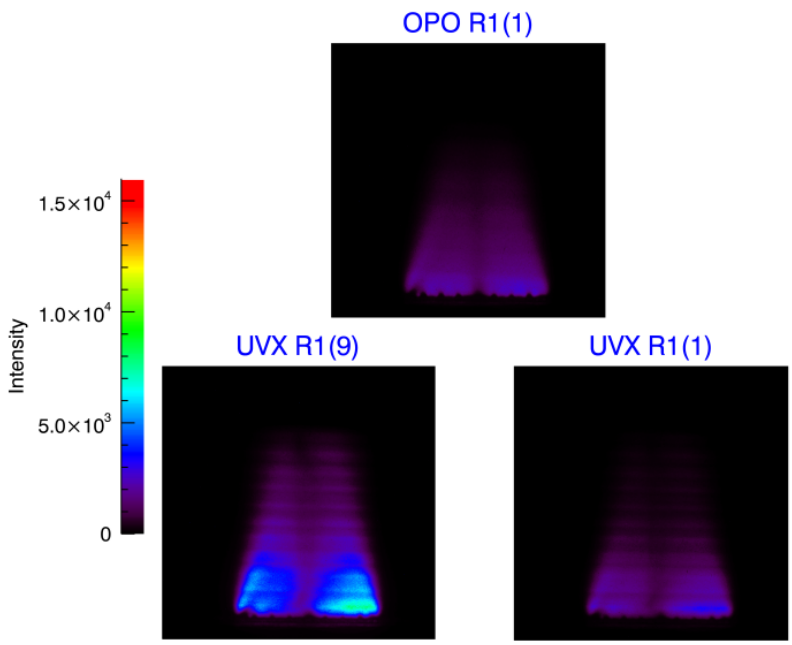

Figure 8.—OH PLIF images in methane flame at ϕ of 0.75 comparing the intensity of UVX $R_1(9)$ and $R_1(1)$ to OPO $R_1(1)$.

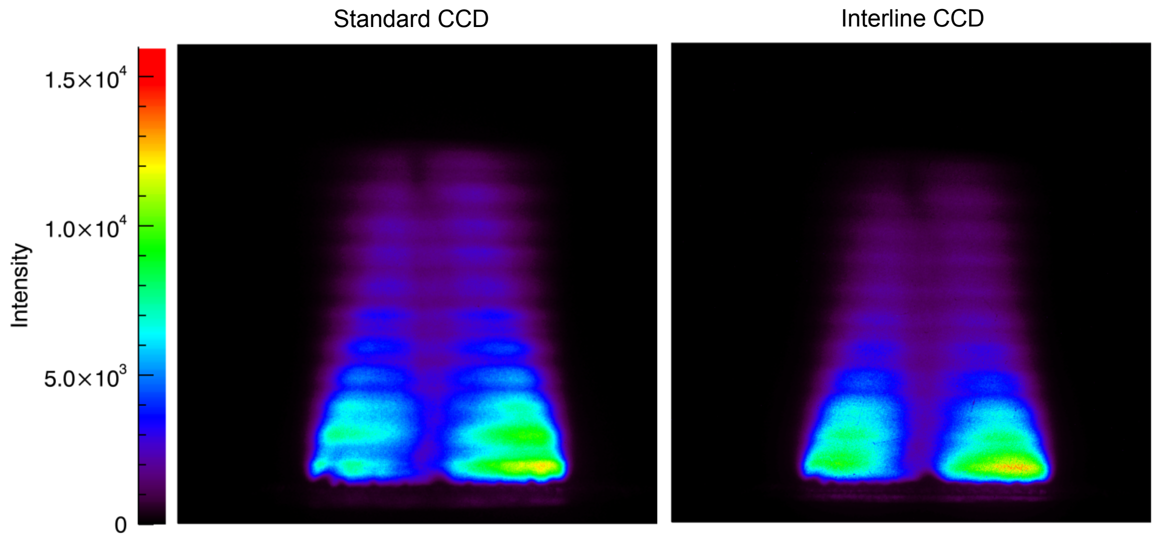

Figure 9.—A comparison of the standard CCD and interline CCD cameras response to the fluorescence signal of OH at $R_2(7)$ in the methane flame at a ϕ of O.75 with the UVX laser.

Interline CCD OH PLIF Collection

The interline CCD's response is compared to the standard CCD with a similar intensifier in Figure 9. The UVX laser is tuned to the OH PLIF line with the highest response, $R_2(7)$, at a ϕ of 0.75. The camera settings are matched (an average of 10, 60 on-chip accumulations). The images have the same scaling and show that the intensity response of the cameras is nearly identical.

Use of MCP Bracket Pulsing With the Interline CCD

The effect of MCP bracket pulsing for the interline CCD was studied; the results are shown in Figures 10 to 12. Bracket Pulsing (Princeton Instruments, Trenton, NJ) gates the voltage across the multichannel plate in addition to the main photocathode gate pulse by turning off the MCP voltage immediately before and immediately after the main photocathode gate pulse. MCP bracket pulsing is designed to decrease collection of background light. Further details can be found in Reference 3. Figure 10 shows the images with the MCP bracket pulsing on and off at ϕ of 2.0 for both the OPO and the UVX tuned to $R_2(7)$. The images indicate that the MCP bracket pulsing increases the signal. Figure 11 plots the average signal at $\phi = 2.0$ at all the excitation line wavelengths for all lasers. Comparing average signal intensity with the MCP bracket pulsing is turned on to those with MCP bracket pulsing turned off indicates that the MCP increases the signal. Figure 12 is a plot showing the average signal with the MCP bracket pulsing off versus the difference between the average signal with the bracketing on and the bracketing off. Figure 12 indicates that the MCP bracket pulsing increases the signal more when more signal is available. MCP increases the signal-to-noise ratio as shown in Figure 13. Figure 13 also shows that the signal-to-noise ratio increases with increasing signal whether the MCP bracket pulsing is on or off. The higher slope of the MCP bracket pulsing on trend line (red) than the MCP bracket pulsing off trend line (black) indicates that the signal-to-noise ratio increases with increasing signal.

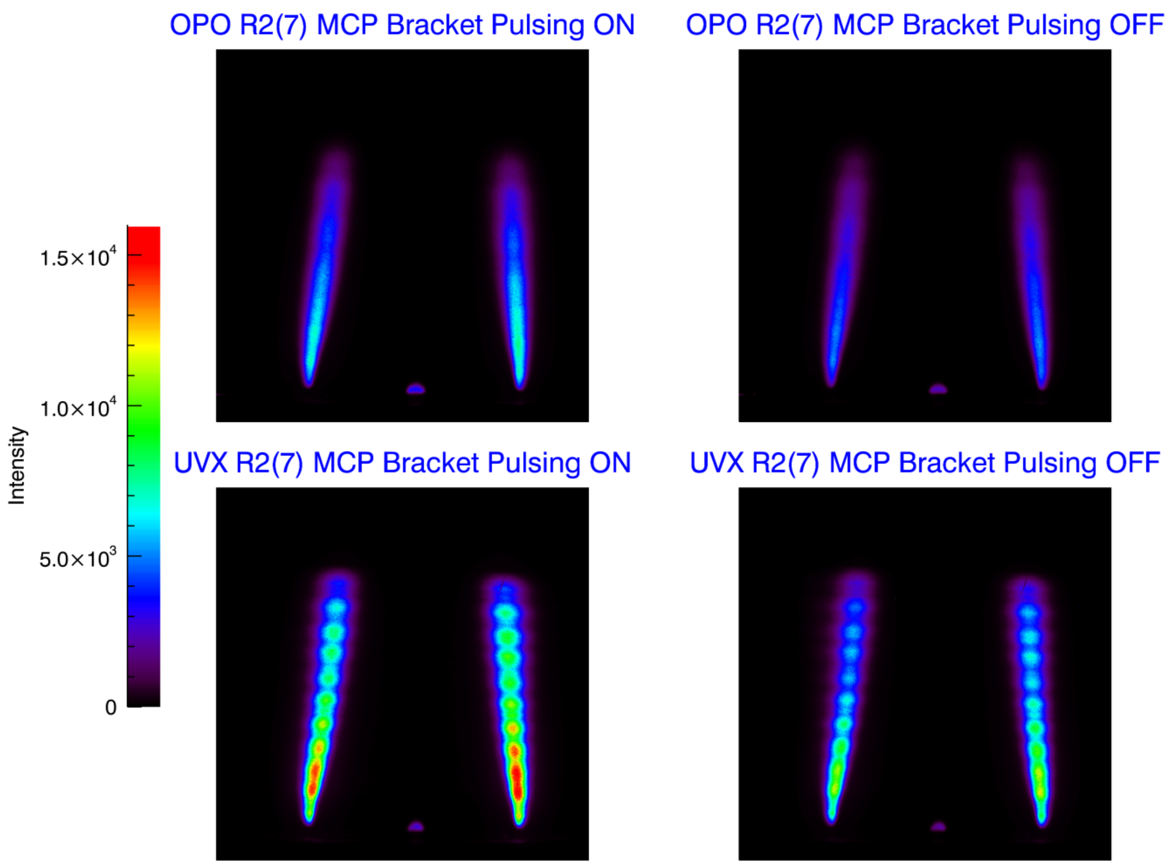

Figure 10.—Images of OH PLIF with MCP bracket pulsing on and off in methane flame at ϕ = 2.0.

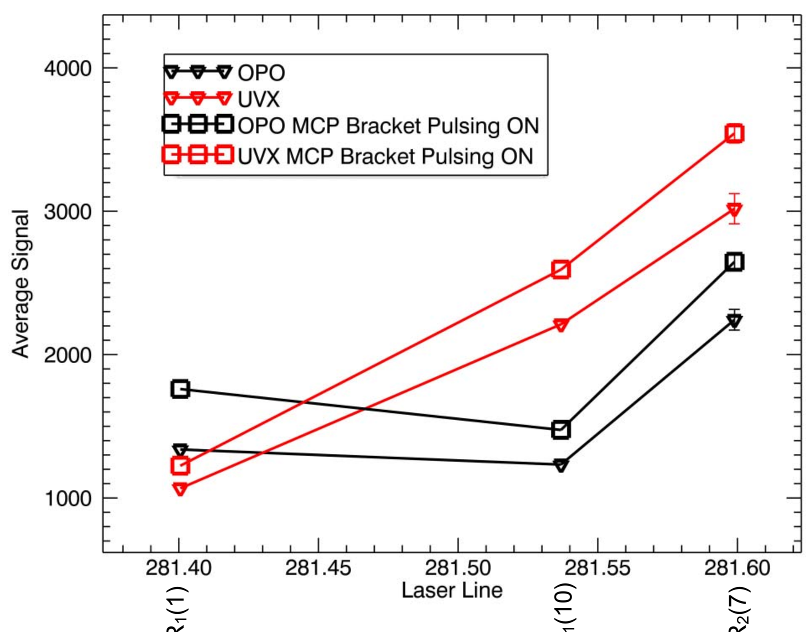

Figure 11.—Average signal versus OH excitation wavelength comparing MCP bracket pulsing on and off, ϕ = 2.0.

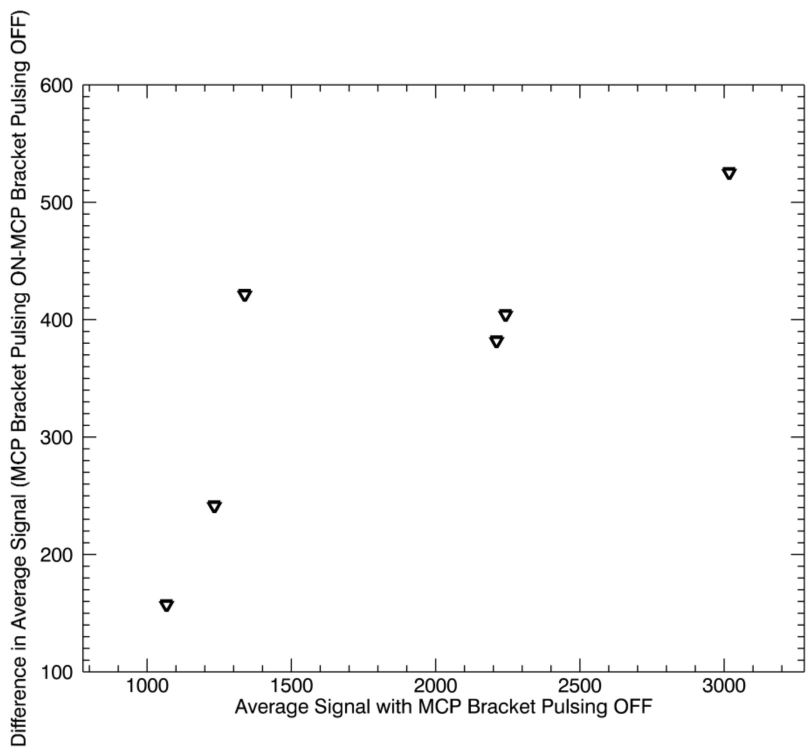

Figure 12.—Average signal with MCP bracket pulsing on minus MCP bracket pulsing off versus average signal with MCP bracket pulsing off, ϕ = 2.0.

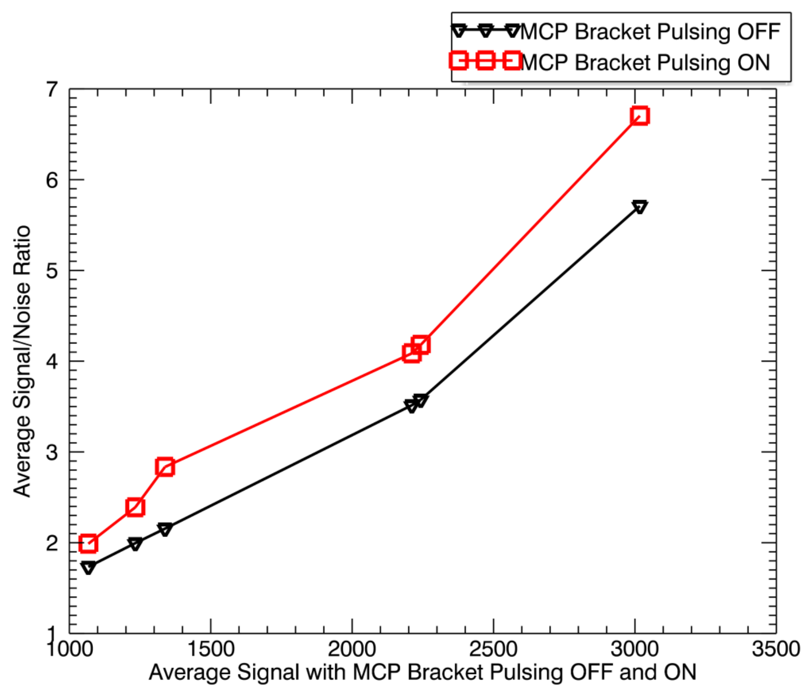

Figure 13.—Average signal/noise ratio versus average signal with the MCP bracket pulsing off and on.

Dual Image Feature of the Interline CCD

The DIF mode is a feature of the PIMAX3 camera, which has an interline array. This feature acquires image pairs, separated by a minimum of 2 µs. Using this feature, the background luminosity produced by a fluctuating flame can be collected more closely in time to the PLIF signal collection. Previously, with the standard CCD, the background was collected separately (minutes to hours later). The Hencken burner flame is steady and produces low background luminosity so the DIF mode probably has no advantage over on-chip averaging for this flame; however, the Hencken burner was used to test the DIF functionality with a $\phi = 0.75$ flame. To test the DIF mode the timing was set so that the first image collects the OPO-generated PLIF signal and the second image is the background light (no laser light). Figure 14 shows the unprocessed PLIF signal image, unprocessed background light, and then the difference of the two images. Figure 15 shows the result of averaging 50 OH images using the processing scheme just described. Note that for the image presented in Figure 15, light produced or reflected by molecules that are not OH has not been eliminated. Therefore, this laser light background is still present in the averaged image. To eliminate this light, one would also collect offline images and subtract the averaged background corrected offline signal from the averaged signal.

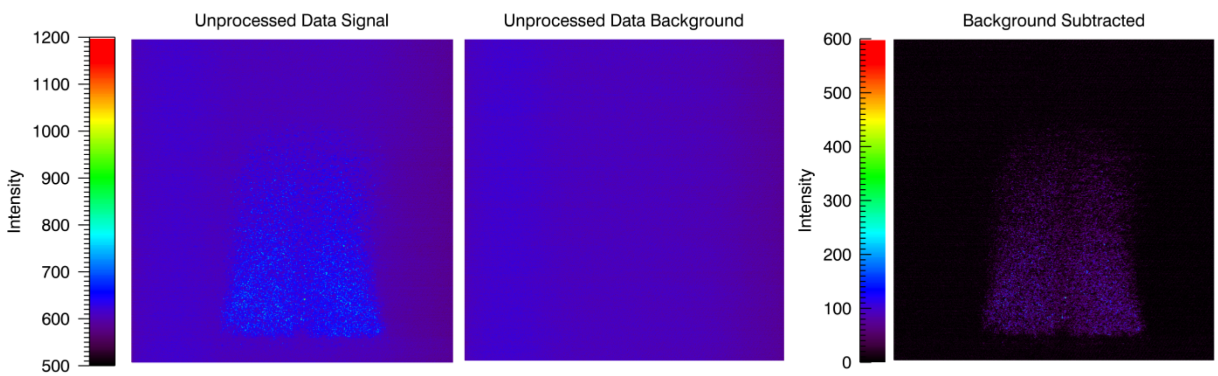

Figure 14.—Single shot images taken in DIF mode, from left to right: unprocessed data of signal and background scaled the same, and an image with the background subtracted from the signal, collected at $\phi = 0.75$ in methane flame, excited by the OPO.

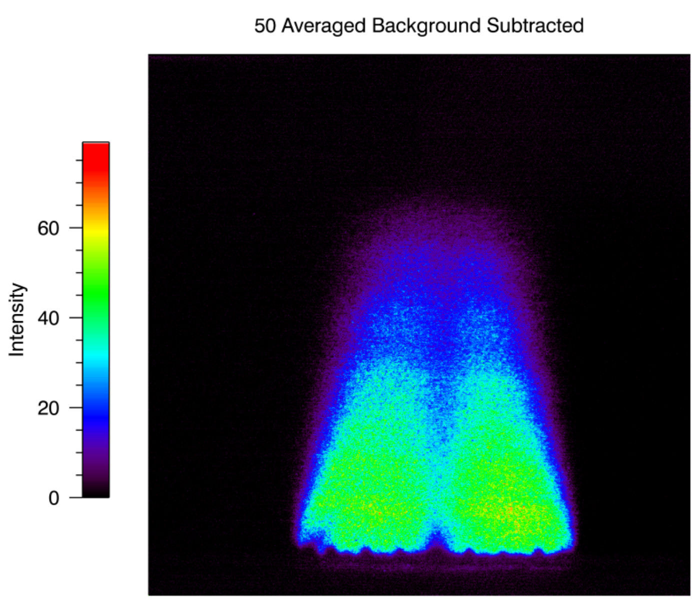

Figure 15.—Average of 50 background subtracted images taken in DIF mode with MCP bracket pulsing on at the $R_2(7)$ OH line, collected in methane flame at $\phi = 0.75$, excited by the OPO.

Saturation of the Interline CCD

The saturation properties of the interline CCD were studied by using a uniform light source. Saturation is defined as the limit of the intensity of light to which the CCD can respond. Knowing the saturation limit will allow identification of images where this intensity limit has been exceeded. Both the exposure time and the gain setting affect the camera chip response to light. Typically, the exposure time is set to a time that will allow saturation at the higher gain settings. Increasing the gain, thus allows detection of small signal intensities like the PLIF signal. Figure 16(a) is a plot of the maximum signal in the image versus the gain of the camera. Figure 16(b) is a plot of the average signal versus the gain. These plots show that the camera has a nonlinear response and saturates near 20,000 counts, which is less than the expected 65,535 counts (the maximum digital readout for a 16-bit camera). For the data shown in these plots, the exposure time of the camera was set to 20 ms and the controller gain was set to 1. According to the camera manufacturer this controller gain setting is meant to be used when the pixel binning feature is used. Figure 17(a) and (b) show the same plots as Figure 16 but with the controller gain set to 2. The data in Figure 17 were collected with a 10 ms exposure time to show more of the range of the response to the increase in light. With the controller gain set at 2 the maximum signal is the expected digital limit of 65,535 counts. According to the camera manufacturer the controller gain = 2 is to be used for amplifying small signals when not using the binning feature of the camera. Therefore controller gain of 2 is useful for PLIF imaging.

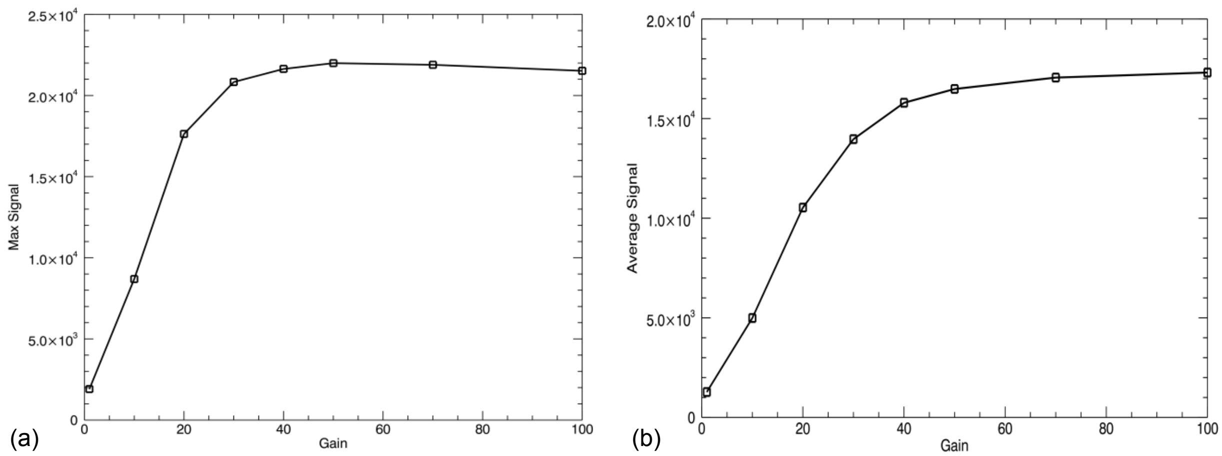

Figure 16.—Saturation curves for controller gain = 1. (a) Maximum signal versus gain setting and (b) average signal versus gain setting. Intensities collected with interline CCD with an exposure of 20 ms.

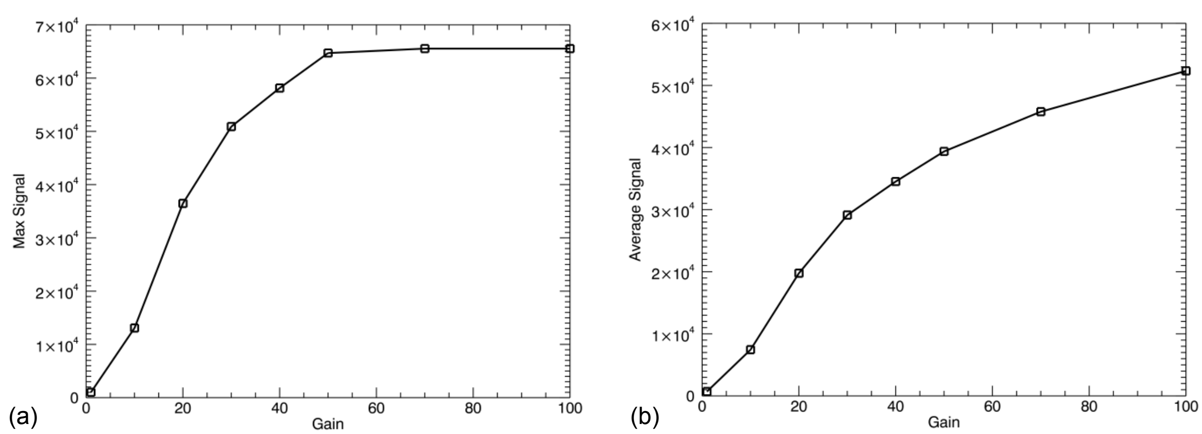

Figure 17.—Saturation curves for controller gain = 2. (a) Maximum signal versus gain setting and (b) average signal versus gain setting. Intensities collected with interline CCD with an exposure of 10 ms.

Recommendations and Important Findings

The measurements that were presented in this work were made to characterize new equipment and find the best settings to collect PLIF signal. The UVX produced a higher fluorescence response than the OPO. If the OPO is to be used for its other advantages, it is recommended to use the $R_2(7)$ line because it produces the most OH PLIF signal. Another important observation is that the OPO produces a more uniform laser sheet than the UVX. The interline CCD camera settings recommended for the best signal response are MCP bracket pulsing on and the controller gain = 2. The DIF mode has been checked and it seems to work properly. Further study of the DIF mode in an environment with a changing luminous background is needed to assess if it is advantageous over the standard collection mode. This work is supported by the Subsonic Fixed Wing project under NASA's Fundamental Aeronautics Program.

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14. ABSTRACT
Planar laser induced fluorescence (PLIF) is used by the Combustion Branch at the NASA Glenn Research Center (NASA Glenn) to assess the characteristics of the flowfield produced by aircraft fuel injectors. To improve and expand the capabilities of the PLIF system new equipment was installed. The new capabilities of the modified PLIF system are assessed by collecting OH PLIF in a methane/air flame produced by a flat flame burner. Specifically, the modifications characterized are the addition of an injection seeder to a Nd:YAG laser pumping an optical parametric oscillator (OPO) and the use of a new camera with an interline CCD. OH fluorescence results using the injection seeded OPO laser are compared to results using a Nd:YAG pumped dye laser with ultraviolet extender (UVX). Best settings of the new camera for maximum detection of PLIF signal are reported for the controller gain and microchannel plate (MCP) bracket pulsing. Results are also reported from tests of the Dual Image Feature (DIF) mode of the new camera which allows image pairs to be acquired in rapid succession. This allows acquisition of a PLIF image and a background signal almost simultaneously. Saturation effects in the new camera were also investigated and are reported.

15. SUBJECT TERMS
Laser induced fluorescence; Lasers; Cameras

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