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Correction of Imaging Errors in Spatially Resolved Laser Scattering Experiments in Flames

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Abstract. Imaging errors in spatially resolved measurements using laser scattering techniques in flames are discussed. An experimental method based on Fourier deconvolution to correct the measurements for the imaging errors is presented. The method is especially important when large gradients are recorded with low *f*-number lenses in order to obtain a sufficient signal-to-noise ratio. The technique is demonstrated experimentally on OH profiles measured by laser-induced fluorescence in an atmospheric acetylen-oxygen flame.

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During the last two decades different laser scattering techniques have become important tools in the diagnostics of combustion processes and gas flows. As described in, e.g., [1], these methods have been used for nonintrusive spatially and temporally resolved measurements of gas temperature, species concentration and gas velocity. Perhaps the most important feature of some of these techniques is the possibility to make simultaneous multiple point measurements, either along a line or in a plane. This was first reported by Hartley on Raman measurements in a gas jet [2]. Later planar imaging of Raman scattering in a flame was performed [3]. Furthermore, Rayleigh scattering has been used for imaging experiments of temperature [4] and gas concentration fields [5]. During the last few years laser-induced fluorescence (LIF) has been developed to yield spatially resolved information. The technique was first demonstrated on OH in flames both in one [6] and two dimensions [7, 8] and has later been developed for species detection using multiphoton excitation, dual species detection and temperature and velocity measurements [9, 10].

Except in the very early imaging experiments, which utilized a photographic plate, a diode array/matrix or a vidicon camera has been used as a detector. In almost all reported experiments a simple quartz or glass lens has been used to image the scattered laser radiation onto the detector area. To our knowledge, however, the images have not been compensated for imaging errors due to, e.g., lens aberrations, focusing errors or diode array interchannel spreading. Such imaging errors generally produce a smoothing of the image which may lead to significant errors especially if sharp peaks or large gradients are recorded. In a recent paper it was noticed that a large aparture collection lens introduced a considerable distorsion of the LIF image of OH and thus an incorrect concentration profile [11]. By using small aparture lenses most of this distorsion can be avoided but the signal-to-noise ratio decreases and significant errors on large gradients may still be introduced by small focusing errors.

The present paper describes an experimental method using Fourier deconvolution [12] to correct the recorded profiles for the imaging errors. With the deconvolution method correct images can be obtained even if large aperture simple lenses are used. The technique is especially useful when large gradients are imaged with low *f*-number lenses in order to record weak signal intensities in wavelength regions where camera lenses with low aberrations are not readily available.

1. Experimental Method and Discussion

The technique was tested on laser-induced fluorescence radiation from OH in an atmospheric pressure welding flame (C_2H_2/O_2). Since the experimental set-up was similar to the one described in [11] only a brief description will be given here. An excimer/dye laser system (Lambda Physic EMG 102 and FL 1002) was operated at ~ 50 μJ per pulse at 307 nm, corresponding to the $R_2(7)$ transition in the $v''=0 \rightarrow v'=0$ vibrational band of the $A^2\Sigma \rightarrow X^2\Pi$ electronic transition in OH. The laser-induced fluorescence radiation was collected with different lenses having various diameters and imaged through an interference filter onto a gated proximity focused PARC OMA III intensified detector consisting of ~ 1024 diodes, each 25 μm × 2.5 mm. Figure 1 shows typical spatially resolved LIF intensity profiles for two simple quartz lenses: a 100 mm diameter $f/1.5$ (upper profile) and a 22 mm diameter $f/7$ (lower profile). In these recordings care was taken to obtain optimum focusing and 100 shots were averaged. The images are demagnified ~ 2.5 times. The effect on the upper profile due to the smoothing introduced by the large aperture lens is clearly demonstrated. The peak amplitudes of the profiles have been normalized for comparison and the somewhat larger peak separation of the lower profile is due to a small difference in magnification. The asymmetry in the profiles is due to absorption of the exciting laser beam [11].

In order to correct the LIF recordings for the imaging errors the whole imaging system, i.e. the lens and the diode array detector, was viewed as a linear system and the Fourier optical method for incoherent imaging described in [12] was applied. Denoting the upper fluorescence profile in Fig. 1 $g(x)$ and the impulse response of the corresponding optical system $h(x)$, it is well known that

$$g(x)=h(x)*f(x), \quad (1)$$

where $f(x)$ is the correct spatially resolved fluorescence and $*$ is the convolution operator. If the impulse response $h(x)$ is known, $f(x)$ can be retrieved by

$$f(x)=\mathscr{F}^{-1}\left\{\frac{G}{H}\right\}, \quad (2)$$

where $\mathscr{F}^{-1}$ is the inverse Fourier transform and the capital letters G and H denote the Fourier transforms of g and h, respectively. $h(x)$ was determined by measuring the response of the imaging system to a point source which was experimentally generated either by focusing the laser beam on a diffuse scatterer or by inserting a thin (25 μm) wire in the laser beam. The insert in Fig. 1 shows the recorded impulse response of the $f/1.5$ lens and the detector. In this measurement the signal intensity was kept at the same level as in the LIF measurements which was well below the saturation limit of the detector. Although the halfwidth of the impulse response is small, a large amount of the total intensity is localized in a broad base, which yields a significant smoothing of the recorded LIF profiles.

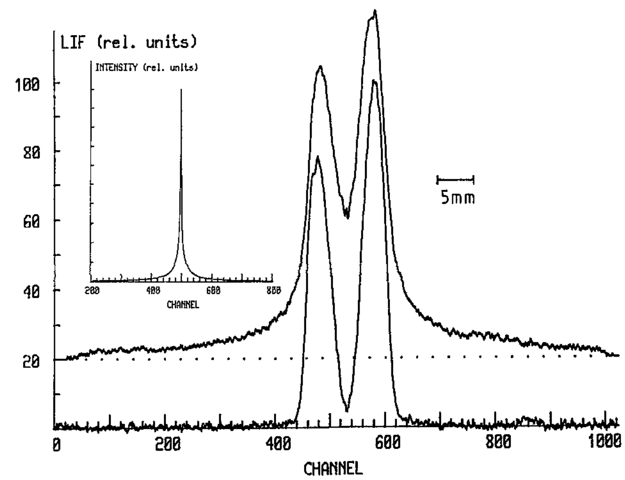

Fig. 1. The LIF profile recorded with a $f/1.5$ (upper profile) and a $f/7$ (lower profile) lens. The insert shows the impulse response recorded with the $f/1.5$ lens

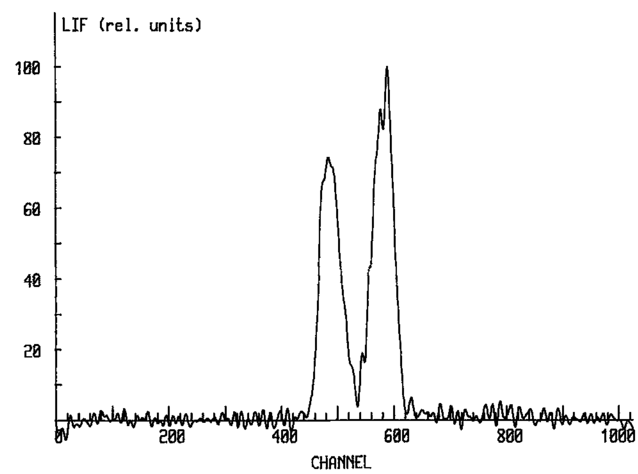

Fig. 2. The upper LIF profile of Fig. 1 deconvolved with the impulse response in Fig. 1

In Fig. 2 the deconvolution of the upper curve in Fig. 1 is shown as obtained from (2). It is apparent that the shape of the LIF profile is significantly altered by the deconvolution. The peak amplitude of the deconvolved profile is approximately 2 times higher than the peak of the recorded profile when the total intensity, i.e. the area under the profiles, is kept constant.

The deconvolution of the lower profile in Fig. 1 with its impulse response results in a profile very similar to Fig. 2. Due to the smaller imaging errors in

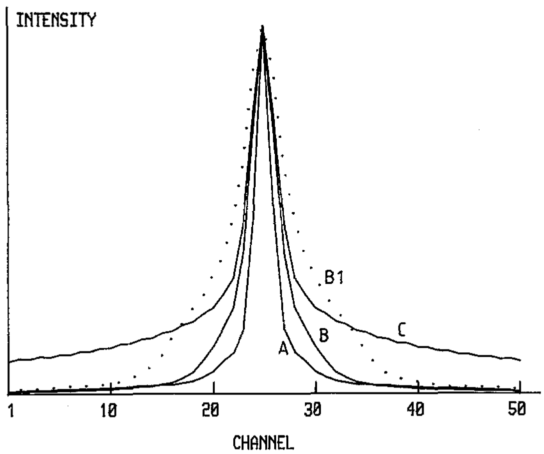

Fig. 3. Impulse responses recorded with a Nikon lens (A), the $f/7$ lens (B) and the $f/1.5$ lens (C) (full lines). Curve B1 (dotted line) shows a slightly defocused impulse response recorded with the $f/7$ lens

this recording the peak amplitude increased only ~10%. However, only a small focusing error results in larger corrections (see below). The high-frequency noise level is lower than in Fig. 2 because the impulse response of the $f/7$ lens is sharper than that of the $f/1.5$ lens (Fig. 3) which results in larger high-frequency components in the transfer function H. Since the deconvolution involves a division with H in (2), high-frequency noise in G is strongly magnified if G is divided by small values in H. This is a generally recognized problem in all deconvolution operations [13]. However, for all the lenses used in this study the impulse responses were sharp enough that a rectangular lowpass frequency filter at 1/5 of the Nyquist frequency was sufficient to eliminate excessive high-frequency noise. In the spatial domain this filter corresponds to the elimination of all gradients that rise or fall in less than ~3.5 channels.

The two methods to record $h(x)$ discussed above are experimentally simple. The focused beam method presupposes that the focus spot is sufficiently small to be considered a point source and that the scatterer really is diffuse. The wire method presupposes that the wire is sufficiently thin and that the wire is aligned parallel with the diodes of the detector. To verify the experimental methods, control measurements of the impulse responses were recorded separately. The point source in the control measurements was either an illuminated 10 μm pinhole or a thin glowing wire, both yielding equivalent results. The experimental and control impulses responses were very similar.

The peak amplitude and the shape of the deconvolved profile is, of course, dependent on the frequency filter discussed above. Thus, the cutoff frequency has to be chosen not to influence the major features of the profile while still eliminating the high-frequency noise. With the chosen cutoff frequency the absolute error in the deconvolved peak amplitude is estimated to be ~10%, which was deduced from the control measurements above. For the large aperture lens the errors are mainly due to noise and experimental errors in the impulse response measurement. For the small-diameter lens the errors are mainly due to incorrect background subtraction in the impulse response measurement which leads to long tails in the impulse response. Since the area under the peak of the impulse response is small for these lenses, the long tails may contribute significantly to the total impulse response.

The impulse response $h(x)$ is, in general, dependent on the position along the laser beam. However, for the optical arrangements used in this study the impulse response was found to change very little with position. Thus, it was sufficient to record one centrally positioned impulse response for the deconvolution.

In the method described above the lens and the intensified diode array detector were viewed as one linear system. To estimate the influence of the detector on such optical systems, a thin glowing wire was imaged with a 50 mm Nikon lens on the diode array detector. The aperture and distance were adjusted to minimize the image spot size with respect to diffraction and magnification. Figure 3 shows the central part of the recorded impulse response (curve A). The impulse responses of the $f/7$ and $f/1.5$ lenses discussed above are also depicted for comparison (curves B and C, respectively). The peak height of the curves have been normalized. The base of impulse response A is probably mainly due to crosstalk and secondary electron emission in the intensified diode array [14]. Thus its smoothing effect on the image cannot be avoided. Figure 3 clearly shows that the detector impulse response (A) as measured above is negligible compared to that of the large lens (C) but contributes significantly to the small lens impulse response (B).

The dotted curve B1 in Fig. 3 shows the impulse response of the $f/7$ lens when the detector was ~4 mm out of focus. The distance between the detector and the lens was ~220 mm. With this impulse response the peak amplitude correction is ~20%. Consequently, great care has to be taken when focusing in order to avoid significant smoothing also when small diameter lenses are used.

In low light level experiments large aperture lenses are often employed in order to obtain a larger collection efficiency and thereby a better signal-to-noise (S/N) ratio. Using the deconvolution technique the recorded images can be corrected for the severe imaging errors of such lenses. However, due to the larger sensitivity to high-frequency noise in the deconvolution operation with large aperture lenses (cf. above), the full benefit of the increase in collection efficiency on the S/N ratio is not obtained. Thus the S/N ratio may not increase substantially for lens apertures above a certain limit. Lenses with this limiting aperture still result in a significant distorsion of the recorded profile. E.g., in the experimental geometry of this study the peak amplitude correction was $\sim 50\%$ for such lenses.

2. Summary

A method based on Fourier deconvolution for correction of imaging errors in spatially resolved laser scattering experiments in flames has been presented. The method is useful to obtain correct scattering profiles in low light level experiments, e.g., Raman scattering, where large aperture lenses often are required in order to obtain a sufficient S/N ratio. Furthermore, the results indicate that small focusing errors may introduce significant errors when profiles with large gradients are recorded. Thus care must be taken when imaging measurements of systems with unknown gradients, e.g., in turbulent combustion, are performed. Although the technique was demonstrated on 1–D images in this paper it can simply be extended to 2–D imaging. However, this requires 2–D Fourier transformation which consumes considerably more computer time.

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