Phase Doppler Interferometry Volume Flux Calculation Optimization and Comparison with Nominally Point Mechanical Patternation Techniques

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Abstract

Characterization of the volume flux distribution for a spray is a first order determinant for evaluating spray performance. The phase Doppler interferometer instrument has been well established as a means for accurately and reliably measuring drop size and velocity distributions in sprays. Utilizing these spray characteristics combined with local number density (concentration), the phase Doppler interferometer can provide a nonintrusive, in situ volume flux measurement. With the advancement of the phase Doppler Interferometry technique, the evaluation and comparison of instrumentation capable of measuring volumetric flux is an important step in validating these data for a wide range of industrial spray applications.

In the current study, experimental results of volume flux were acquired using Mechanical Patternation (MP) and Phase Doppler Interferometry (PDI) techniques. The baseline measurements in the present study were obtained using mechanical patternation of a hydraulic, low capacity, flat fan spray nozzle. Through controlled testing methods, the Artium PDI system, which incorporates the Artium AIMS *auto setup* software, was shown to very accurately determine the volume flux for the spray nozzle at multiple locations within the spray plume as well as D_{30} and velocity results. Additionally, the effect of receiver lens selection, slit aperture, and PMT gain were examined. Volume flux agreements as high as 98.8% were acquired between the MP point method and the PDI, when appropriate setup methods were implemented.

Introduction

Drop size and velocity information is very important when characterizing sprays; however, in many cases spray pattern volume flux distribution is also a primary focus when characterizing sprays. The liquid volume flux distribution may be collected or estimated with several measurement techniques including Mechanical Patternation (MP) and Phase Doppler Interferometry (PDI). Mechanical Patternation can be time consuming and does not provide high spatial resolution. Furthermore, the flux measurement is dependent upon the drop size, number density and drop velocity and these three parameters can vary from point to point throughout the spray. For example, a large number of small drops may produce a similar flux to a much smaller number of large drops (a diameter cubed relationship). Whether it is a spray coating application or a combustion process, all details of the spray matter. Thus, it is very useful to advance the PDI technique to where number density and volume flux can also be measured with very high confidence. Over the past 25 years, numerous efforts associated with measuring number density and volume flux have been reported (e.g. see [4],[7],[10],[11]) with varying degrees of success. A recent study by (Schwarzkopf et al. [7]) indicated that the flux could be measured to within 30% of the expected value, provided the instrument setup parameters were carefully calibrated. That study found that the detector gain had a "sweet spot" at which the integrated flux measurements over the extent of the spray plume agreed with the flow rate into the atomizer. This method required careful tuning of the instrument parameters and cannot be easily generalized between various sprays or instruments.

The phase Doppler method has been shown through extensive evaluations over the past 25 years to be capable of measuring drop size distributions and velocity reliably even in challenging spray environments including combusting sprays. The focus of this investigation is to experimentally examine the volume flux distribution results provided by mechanical patternation and phase Doppler interferometry. The results will be compared using reasonable conversions of the recorded fundamental information. Schemes used for data conversion and comparison from one

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method to the other will be discussed. Mechanical patternation provides the most direct measurement of the volume flux and will therefore serve as the baseline measurement method for comparison with the phase Doppler results.

Equipment and Methods

Spray Nozzle

The spray nozzle that was investigated for this study was a Spraying Systems Co. hydraulic, flat spray nozzle. The TPU650050 type nozzle provided a steady flow (3.75 mL/s), nominally uniform spray pattern that was deemed suitable for this investigation. All volume distributions were collected spraying water downward at 50mm from the nozzle exit orifice plane, operating pressure was monitored and maintained at 4bar for all tests.

Volume flux ($cm^3/cm^2/s$), which is a vector quantity, provides a measurement of the liquid volume (cm^3) that passes through a probe area (cm^2) normal to the direction of the flow velocity, per unit time (s).

Mechanical Patternation

In order to accurately collect the local volume flux, mechanically, a sharp-edged tube with a known surface area opening was used. Additionally, an attached graduated cylinder was used to collect liquid and compare with individual PDI measurement points. This Collection Tube (CT) was precisely machined to have a 2mm diameter opening. Figure 1 provides an image of the collection tube volume flux device used in this investigation.

The mechanical CT method drawbacks include droplet splash-back and reverse-air flow due to volume displacement inside the graduated cylinder. Droplet splash-back was minimized by utilizing a sharp-edged, steep-sloped collection tube opening. Reverse air flow (exiting through the CT opening) was minimized by including a relief opening below the deflector plate (white sloped component in Figure 1). Additionally, flow that is not primarily normal to the CT opening surface will result in a proportional error due to the spray direction; therefore, the collection tube was angled at each collection location to match the mean approaching droplet trajectories and to maintain the 2mm cross-sectional collection area perspective.

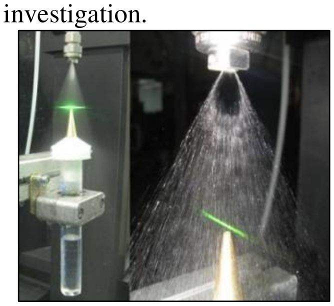

Figure 1. CT (Point)

Phase Doppler Interferometry

The Phase Doppler interferometry technique was first proposed in 1984 by Bachalo and Houser [1]. For these investigations, the Artium Technologies PDI was the focus instrument. This technique measures the size, velocity, angle of trajectory, and time of arrival of each particle passing through an optical measurement volume formed by pairs of intersecting laser beams. The technical explanation of the Phase Doppler technique can be reviewed in a number of publications including Bachalo 1985 [2]. The ability to measure accurately requires the reliable detection and measure of the size, velocity, and transit time of each droplet. In addition, an accurate in situ measurement of the sampling cross sectional area must be made before one can accurately calculate the local volume flux at a "point".

The Artium PDI system utilizes a unique digital signal burst detection method which reliably detects droplets, even in complex environments. This is an advance over the earlier Fourier transform burst detection method invented by Ibrahim and Bachalo (U.S. Patent 5,289,391). This detection system is also critical to the in situ approach for measuring the effective diameter of the sample volume as a function of drop size. The Fourier transform based signal processor uses quadrature down-mixing to position the signals in an optimum range for processing. The real and imaginary (shifted by 90 degrees) components of the signals are sampled and a full complex Fourier transform is used to obtain the signal frequency and phase. Each of the three signals for the phase measurements is sampled in this manner and the phase differences computed at the same frequency for each signal. Three phase differences are computed, AB, AC, and BC for detectors A, B, and C from the Channel1 velocity component. These three phase differences are compared for consistency as one of the validations for each droplet signal detected. The approach has proven to be very effective in detecting and eliminating sizing errors due to the well-known trajectory problem.

The Artium AIMS software incorporates an *auto-setup* feature that serves to optimize the frequency and phase shift processing. The auto-setup feature acquires a small number of signals produced by droplets passing through the measurement volume and is discussed in detail in Bachalo, et al. [patent pending]. User-to-user setup differences that have been known to produce varying results and accuracy in PDI data results, often relying upon the operator's individual experience and understanding of the PDI principals, have been significantly minimized with this approach. There remain three important hardware parameters which are not set by the AIMS software (as yet) and were varied for this study: Receiver lens focal length, High Voltage Gain, and Slit Aperture Width. The detector gain and slit aperture selection in the receiver are currently undergoing automation by Artium and will be available in the near future. These three parameters have the combined effect of determining the effective width of the receiving sensor and the amplification of the signal prior to signal acquisition and processing. The laser transmitting lens focal length was 1000mm for all tests; the receiving unit focal length was 1000 and 500mm (for separate tests) and was oriented at the 40° off-axis forward scatter position.

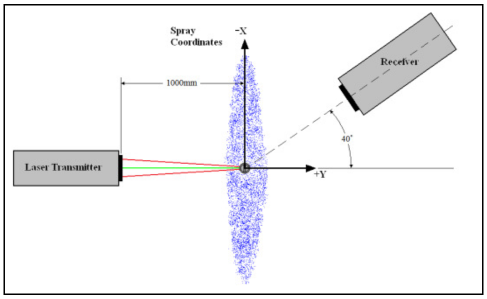

Figure 3. PDI orientation diagram

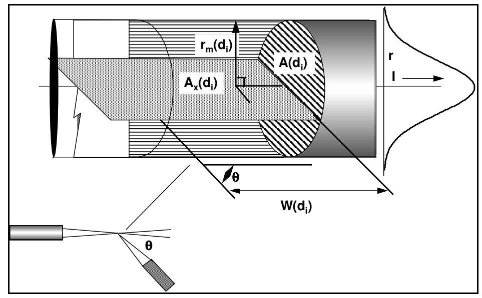

Figure 4. Schematic-formation of the PV for the PDI

Probe Volume Description

A review of the structure of the Probe Volume (PV) formed with the PDI is necessary due to the importance of the PV cross section to the number density measurement and the volume flux calculation. Using an off-axis receiver position and a slit aperture in the receiver, the focused and overlapped beams are intersected by a projection of the slit aperture [W(d_i)] (Fig. 4). The focused diameter of the laser beams at the waist, the width of the slit aperture and the magnification of the receiving optics sets the approximate size of the sample volume. This size may change based on light beam attenuation due to spray droplets causing light extinction, by changes in the detector gain, and other factors. Therefore, Bachalo incorporated a means for in situ measurement of the sample volume in early Aerometrics PDPA instruments. This method was later described by Saffman [9], albeit with some differences.

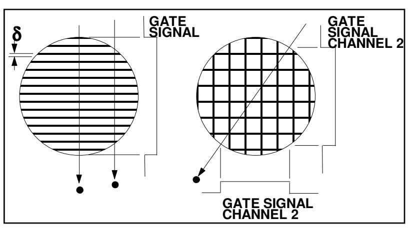

Figure 5. Original Bachalo [1] method - in situ measurements of the probe diameter using fringe patterns

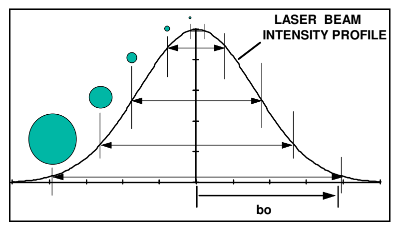

Figure 6. Demonstration of effective sample volume diameter for each drop size class

The in situ sample volume measurement approach utilizes the built in scale, fringe spacing (δ), and the number of cycles in the burst signal to obtain the diameter of the measurement volume. The number of cycles in the Doppler burst signals is recorded for each particle size class. Particles will pass on all possible trajectories through the beam but signals from individual drop size classes with the most cycles will have passed through the diameter of the beam. These signals are used to measure the effective diameter of the PV for that particle size. Burst detector gate signal duration, T, which is the signal burst detector output when the Doppler burst signal is detected, may be used. Gate time is measured for each Doppler burst along with the particle velocity. This approach works well if the flow of drops is essentially in one known direction. If the particles are passing the sample volume at oblique angles or at angles that depend on the drop diameter, then the theoretical description of the sample volume may be unreliable. If a PDI instrument that measures two or three velocity components is used, then each of the three velocity components can be measured and the sample volume can be defined accurately. Figure 5 shows how this works for a two-component system. Gate times and velocities are measured in the two directions to obtain the resultant diameter.

$$D = V \bullet T \qquad (1)$$

Other schemes have been proposed using the beam intensity information (Sommerfeld and Qui [10]). These methods are reported to be independent of the particle angle of trajectory. However, they may be affected by beam distortions and attenuation due to the measurement environment.

Volume Flux Calculation

The determining variables in the volume flux calculation are D_{30} (volume), sample volume cross section, velocity (arrival rate, often size dependent), and number density (concentration). The combination of these variables into the volume flux calculation is demonstrated in Equation 2. The various input variables for Equation 2 equate to the mean drop volume times the drop count, over the effective probe area times the total acquisition time.

$$VF = \frac{\frac{\pi}{6} D_{30}^3 * N}{PA * t_{Total}} \qquad (2)$$

Drop size and velocity are direct measurements by the PDI based on the Doppler difference frequency and detector phase shifts; see Bachalo and Houser [1] for a description of these techniques.

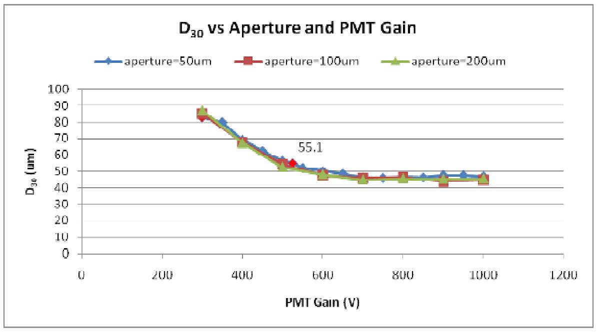

Figure 7. Aperture Effect on D_{30}

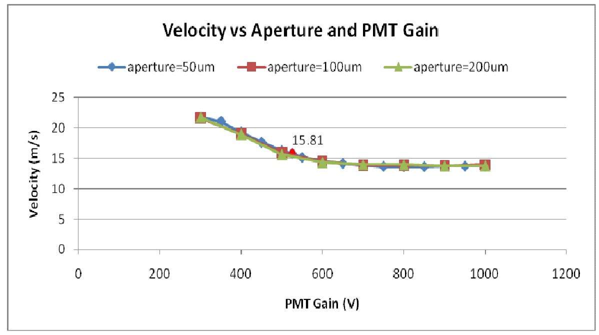

Figure 8. Aperture Effect on Axial Velocity

Figures 7 and 8 demonstrate the important *in*sensitivity to detector gain of the PDI D_{30} and Axial Velocity results over a range of aperture and high voltage gain settings. Previous results (e.g. Schwarzkopf, et al. [7]) showed a significant change in measurements with detector gain implying that the user must carefully set this parameter to obtain reliable measurements and repeatability. With the new PDI, provided the gain is set above a threshold level (600V in this case), the results can be seen to be very consistent. The aperture setting has no effect on drop size or velocity calculations that were investigated. The benefit of easy aperture selection will generally become apparent when reaching a high spray particle number density; reducing the aperture will improve the signal quality and minimize the coincidence errors.

The effect of receiving lens selection has two primary effects, a linear change in drop size measureable range and a linear change in effective probe volume. Both effects are due to the effective change of receiver component spacing projected from the PV toward the receiver lens (change of effective detector spacing and slit aperture). Figures 9 and 10 provide the results of a receiver lens change from 500mm to 1000mm focal length.

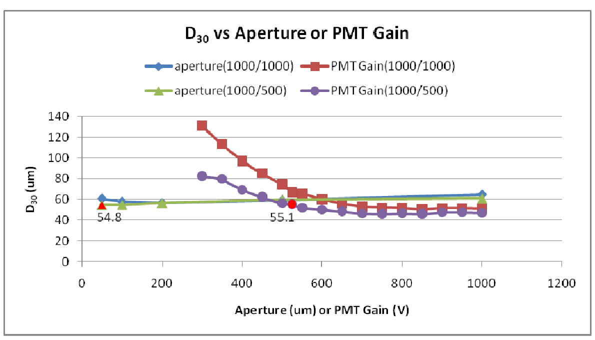

Figure 9. Receiver Lens Effect on D_{30}

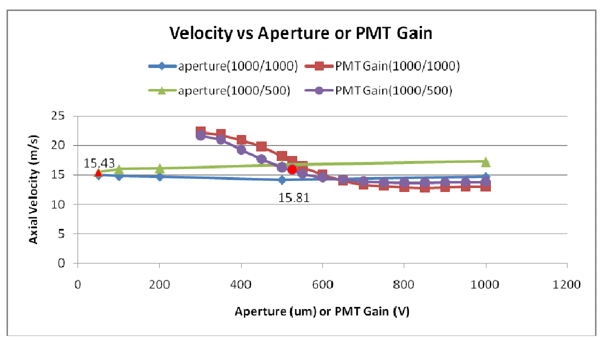

Figure 10. Receiver Lens Effect on Axial Velocity

The effective *differences* in the D_{30} and Velocity results with the 1000mm receiver lens focal length in Figures 9 and 10 are due to the reduced signal quality, primarily, for smaller droplets. However, when an appropriate aperture (50 um) and PMT gain (600 mV) are used with the 1000mm lens, the differences in calculated D_{30} and Velocity are 9.1% and 4.9%, respectively.

The quality of the volume flux results will depend heavily upon number density (and associated PV calculation). This becomes difficult in practice due to the variable probe volume (PV) calculation, or effective measurement volume, which is dependent upon drop size *and* velocity (transit time within the PV), laser beam and scattered light attenuation, droplet angle of trajectory, and overall signal quality. The effects of these factors on the uncertainty of the PV calculation, and ultimately local volume flux, may result in large differences in volume flux; see Figure 12.

Due to confidentially arrangements, the exact details of proper correction of the PV and droplet trajectory effects will not be disclosed herein. However, the dramatic errors in Volume Flux calculation will be demonstrated and shown to be substantially improved through appropriate applications of setup and processing methods.

Results and Discussion

Extensive measurements over the spray pattern were performed and repeated to evaluate the PDI measurement capability. The volume flux distribution results demonstrate very good agreement with the correct setup parameters. Auto-setup was used throughout the tests which set the signal processing parameters for each measurement location. The PMT voltage was set at 525-800V based on the results shown in Fig. 9 and 10, in order to cause a small number of intensity saturated Doppler bursts. The primary challenge in the setup process was accommodating the rather large spray angles (±40°); the effect of non-normal droplet trajectory is seen in the PDI-1 vs. PDI-2 results (Fig 12).

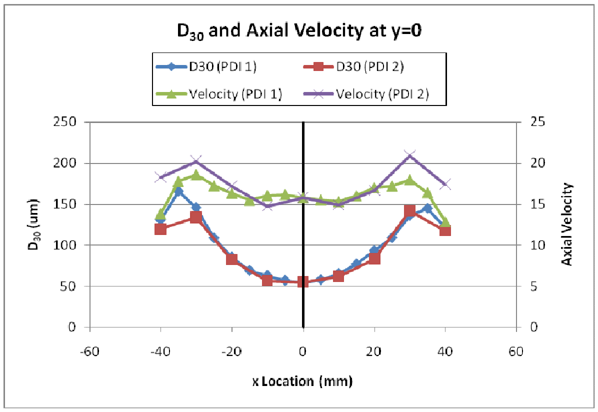

Figure 11. D_{30} at y=0

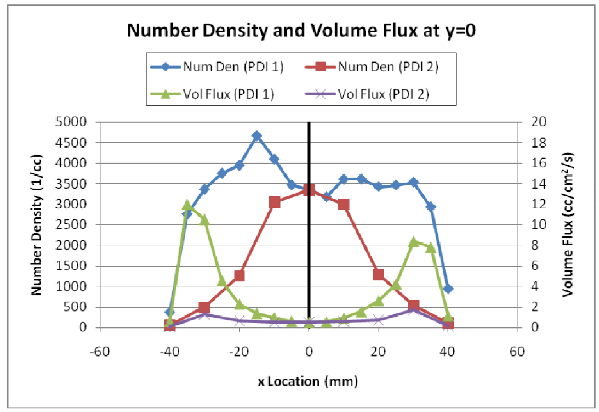

Figure 12. Axial Velocity at y=0

The results presented in Figures 11 and 12 represent PDI results at discrete location across the y=0 axis of the spray plume. "PDI 1" data represents data acquired without droplet trajectory considerations. "PDI 2" data results represent the much improved (volume flux) results capable with phase Doppler interferometry when droplet trajectory is properly considered. The D_{30} and Axial Velocity distributions do not exhibit dramatic changes based on droplet trajectory. At first sight, the shape and behavior of the PDI 1 volume flux data looks believable and consistent with the shape of the D_{30} plots. However, the volume flux distributions did not agree with the CT data that was obtained at selected points in the spray except at the x=0 location. These local PDI flux values increased to as much as 7 times higher than the CT measurements with increasing droplet radial velocity. After revising the in situ sample volume measurement approach to account for increasing droplet angle of trajectory, the results showed a significant improvement. Figure 13 focuses on the volume flux distributions acquired by the PDI 2 setup and the CT results. Note that at the center, where the spray is exactly vertical, the PDI volume flux measurements are in excellent agreement with the CT data, whereas the PDI data at all points is only in good agreement with the CT(angled) results. The CT results with an angled collection tube demonstrate agreement greater than 97%, see Table1.

Table 1. Volume Flux Results and % Difference at discrete locations along y=0

	Volume Flux (cc/cm²/s)							% Difference						
	x location (mm)							x location (mm)						
	-30	**-20**	**-10**	**0**	**10**	**20**	**30**	**-30**	**-20**	**-10**	**0**	**10**	**20**	**30**
PDI 1	10.481	2.264	0.914	0.523	0.914	2.671	8.391	689%	267%	81%	2.4%	50%	289%	474%
PDI 2	1.290	0.680	0.485	0.522	0.586	0.704	1.716	2.9%	10.3%	3.9%	2.6%	4.1%	2.4%	17.5%
CT	0.751	0.586	0.551	0.536	0.551	0.586	0.751	44%	5.0%	9.2%	0.0%	9.9%	14.8%	49%
CT (angled)	1.329	0.616	0.505	0.536	0.612	0.687	1.461	0%	0%	0%	0%	0%	0%	0%

The results provided in Table 1 demonstrate the greatly improved agreement between the CT and PDI when droplet trajectory considerations are combined with correct system parameter setup. The disagreement between "PDI 2" and "CT (angled)" is within the uncertainty associated with the collection angle orientation of the CT(angled).

Summary and Conclusions

The significant problem of measuring droplet number density and volume flux as well as drop size and velocity was re-visited. Using the newly developed Artium PDI 2D MD instrument with its automated setup features, very good PDI results as compared to the collection tube (CT) were acquired. The first step was to demonstrate the relative insensitivity to detector gain which was varied over nearly an order of magnitude and showed little or no change in the measured D_{30} and velocity values across the spray. This is important since it is very time consuming to optimize the detector gain at each measurement location. In past experiments with earlier models of the PDPA and PDA, volume flux was shown to be very dependent on the detector gain settings. The initial results for droplet number density and volume flux looked consistent but were found to have a large disagreement with CT data, except for the spray center point location. This provided the information that allowed the diagnosis and solution to the problems associated with in situ measurements of the sample volume when there is a significant spray angle (radial droplet trajectory). In fact, the error in the sample volume size increased monotonically with flow angle. Reconciliation of this problem resulted in exceptional agreement with the CT (angled) data.

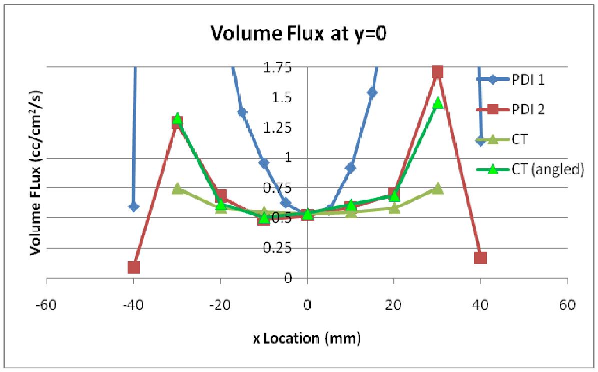

Figure 13. Volume Flux at y=0, PDI and CT data

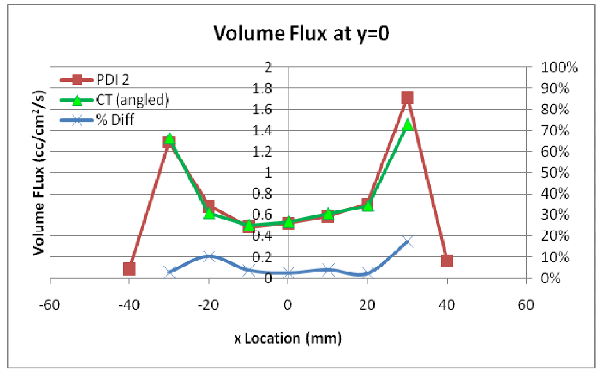

Figure 14. Final Volume Flux at y=0 with % Difference

The CT data is trusted as this device measures over a small area in a similar location and at the same time as the PDI (Fig. 1). Essentially no integration (except over time) is required to make the comparisons.

Some additional work and refinement of the PDI and especially the in situ sample volume measurement techniques promises to lead to an improved PDI instrument that is capable of measuring the number density and volume flux as reliably as mechanical patternators or more so. Furthermore, flux is a vector quantity and the PDI is able to resolve the flux components and primary flow direction; this is not easily done with mechanical patternators. The reliable measurement of drop size, velocity, and volume flux from a single instrument represents a significant step forward in spray characterization.

Acknowledgements

The contributions and review by Dr. William Bachalo, president of Artium Technologies, played a key role in the substance and quality of this work.

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