N96- 15594

DEVELOPMENT OF ADVANCED DIAGNOSTICS FOR CHARACTERIZATION OF BURNING DROPLETS IN MICROGRAVITY

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1. Introduction

Diagnostic techniques currently used for microgravity research are generally not as advanced as those used in earth-based gravity experiments. For example, most microgravity tests involving single burning droplets make use of imaging techniques for determining the droplet size, and hence, the droplet vaporization/burning rate. The measurement resolution of these cameras are generally not very good (order of 100 microns), and since typical TV cameras have a frame rate of only 30 fps, the amount of data that can be collected during the short period of low-gravity achievable in drop tests and flight tests is small. Furthermore, diagnostic techniques for measuring the instantaneous radial temperature profile (or temperature gradients) within the burning droplet do not exist.

Over the past few years, Aerometrics has been researching and developing a *rainbow thermometric* technique for measuring the droplet temperatures of burning droplets. This technique has recently been integrated with the *phase Doppler interferometric* technique to yield a diagnostic instrument that can be used to simultaneously measure the size, velocity, and temperature of burning droplets in complex spray flames [1]. Also, the rainbow thermometric technique has been recently integrated with a *point-diffraction interferometric* technique for measuring the instantaneous gas phase temperature field surrounding a burning droplet [2]. These research programs, apart from being very successful, have also helped us identify other innovative techniques for the characterization of burning droplets. For example, new techniques have been identified for measuring the instantaneous regression rate of burning droplets. Also, there is the possibility of extracting the instantaneous radial temperature distribution or the temperature gradients within a droplet during transient heating.

What is important is that these diagnostic techniques have the potential for making use of inexpensive, light-weight, and rugged devices such as diode lasers and linear CCD arrays. As a result, they can be easily packaged for incorporation into microgravity drop-test and flight-test facilities. Furthermore, with the use of linear CCD arrays, data rates as high as 10-100 kHz can be easily achieved. This data rate is orders of magnitude higher than what is currently achievable.

2. Program Objectives

In this research and development program, a compact and rugged diagnostic system will be developed that can be used to measure instantaneous fuel droplet diameter, droplet regression rate, and the droplet internal temperature profiles or gradients at very high data rates in microgravity experiments. This is a one year R&D program that commenced toward the end of August 1994. The principle behind the measurement of each of these parameters is briefly described in the following sub-sections.

Rainbow Thermometry

The occurrence of rainbows can be understood with the help of the simple geometrical optics based theory proposed by Descartes several hundred years ago. Using geometrical optics assumptions, the scattering of light by spherical particles can be described as a combination of diffraction, external reflection, refraction, and refraction occurring after multiple internal reflections. Furthermore, adopting van de Hulst's notation [3, *p=0* refers to externally reflected light, *p=1* refers to refracted rays, *p=2* refers to rays that emerge from the droplet after undergoing one internal reflection, and so on. For each order scattered ray, the scattering angle bears a definite relationship to the incident angle. The location of the primary rainbow can then be understood to correspond to that scattering angle at which the angular relationship for *p=2* goes through an extremum. At the rainbow angle, the scattered intensity achieves a local maximum. To one side of the rainbow angle is a shadow region into which no rays emerge and to the other side is a lit region. Similarly, the secondary rainbow corresponds to the scattering angle extremum for *p=3* rays. For example, for water droplets, the primary and the secondary rainbows occur at scattering angles of 137.9^o and 128.8^o, respectively. The dark region between the primary and the secondary rainbow is historically known as Alexander's dark band. Rainbows of order greater than *p=3* can also be present, but in general, are very weak in intensity.

Several characteristics of the rainbow cannot be adequately explained with the geometrical optics based theory, for example, the presence of supernumerary arcs on the lighted side of the primary and secondary rainbows. They occur as a result of interference between two different rays of the same order emerging in the same direction. Thus, at any given angle slightly greater than the rainbow angle, the scattered light includes rays that have followed two different paths through the droplet. To further complicate the situation, the interference of the internally reflected rays with externally reflected (*p=0*) rays gives rise to high frequency intensity oscillations that are superimposed upon the supernumerary fringes. Over the years, several theories have been developed to explain such rainbow characteristics. These theories include Airy's theory [4], the Lorenz-Mie theory [3], the complex angular momentum theory [5,6] which provides an approximation to the Lorenz-Mie theory, and a theory based on Huygen's principle [7]. Of these, only the Lorenz-Mie theory provides an exact solution for the scattering of electromagnetic waves by a spherical particle.

Rainbow thermometry takes advantage of the fact that the rainbow angle is a function of the refractive index of the droplet. Therefore, by measuring the rainbow location with the help of a linear array detector such as a CCD, the refractive index of the droplet can be determined. Since refractive index varies with temperature, the droplet temperature can also be inferred if the relationship between the refractive index and temperature is known *a priori.* A typical measured (using a linear CCD array) dependence of the rainbow location on the droplet refractive index is presented in Fig.1.

In describing the principles of rainbow thermometry we have so far assumed that the droplet is homogeneous. However, during the transient heating period, the droplet is inhomogeneous and exhibits a radial temperature distribution. Theoretical light scattering studies [8] have shown that during the transient droplet heating period, the rainbow position actually moves in a direction opposite to the expected direction of motion. This could lead to erroneous measurements. The measured variation of the rainbow location during the transient heating period of a burning *n*-heptane droplet is presented in Fig.2. Recent experimental and theoretical studies in this area also suggest that the rainbow angle is a direct measure for the refractive index gradients (temperature gradients) near the surface, as long as the gradients are practically linear in the outer region of the droplet [9]. In the current research and development program we are attempting to use the fully digitized time dependent rainbow signature, in conjunction with theoretical light scattering models for inhomogeneous droplets, for reconstructing the temporal evolution of the droplet internal temperature profile or gradient.

Drop Size Measurement

The spatial frequency of the supernumerary fringes that can be observed in the rainbow signature is a function of the droplet diameter. Therefore, in this research program the droplet size information will also be obtained from the time dependent rainbow signature.

Droplet Regression Rate Measurement

As mentioned earlier, the interference of internally reflected rays with external reflections gives rise to high frequency oscillations that are superimposed upon the supernumerary fringes. These high frequency oscillations are extremely sensitive to small changes in the droplet diameter. A typical example of resonance scattering by spherical particles is presented in Fig.3. The dotted line in Fig.3 was computed using the Lorenz-Mie theory for droplet diameters between *60.0* to *61.0* μm and having a refractive index of *1.354*. The computed scattered intensities correspond to a point detector placed at a scattering angle of 142.5^{o}. The solid line in Fig.3 is the result of applying a FFT-based digital filter to the raw signal. The presence of a dominant resonant frequency is obvious in the presented result. In this research program, the measured rainbow signature will also be used to observe the time dependent variation of the high frequency oscillations which will subsequently be used to extract the instantaneous droplet regression rates.

3. Progress to Date

Optical System Development

The development of a breadboard/prototype optical system has been completed. A photograph of the developed optical system is shown in Fig.4. The optical transmitter basically consists of a He-Ne laser beam which is focused to form a measurement probe volume using an appropriate lens. The optical receiver is placed in the backscatter direction at a scattering angle of approximately 145° depending upon the refractive index of the fuel that is being studied, Fig.5. A schematic of the rainbow receiver system is presented in Fig.6. It consists of a front lens for collecting and collimating the scattered light in the backscatter direction and a second lens for focusing the collimated light on to a slit which acts a spatial filter. A third lens is placed behind the slit to image the collected light on to a linear CCD array camera. The other important components of the rainbow receiver include two photomultipliers. PMT#1 is used in conjunction with an automatic exposure control circuitry for the CCD, and PMT#2 is used along with an independent gating circuitry.

Electronics/Opto-electronics System Development

The major components of the electronics/opto-electronics system are presented in Fig.7. It includes an imaging board for housing the CCD array, a gate controlling system, and a data acquisition/signal processing module for the rainbow signal. Prototype, printed circuit boards have been developed and tested for this purpose. The imaging board is located in the rainbow optical receiver and houses a 2048 pixel linear CCD array. As per the manufacturer specification, the maximum clock rate is *60 MHz*. However, for the current research program a clock rate of 20 MHz is being used. This yields an effective data rate of approximately 10,000 per second. To increase the dynamic range of the rainbow system, an automatic exposure control circuitry has also been built into the gate control electronics. The automatic exposure control system integrates the output of PMT#1 and compares the integrated value to an adjustable exposure level for determining the optimal CCD exposure time for each droplet. This not only helps in preventing CCD saturation but also ensures uniform output signal levels for droplets of different size.

The CCD output is then sampled and digitized by a dedicated rainbow signal processor, Fig.7. As discussed earlier, the rainbow signals contain high frequency components which would be undesirable if the rainbow peaks are to be determined directly. However, these may be minimized by using a suitable digital filter. The rainbow signal processor has a digital peak detector which can accept either the ADC output or the digital filter output. The rainbow peak location and intensity of the rainbow are available for transfer to the data acquisition computer for further analysis and post processing. The rainbow signal processor also provides a digital output of each CCD pixel. The digital output can be interfaced to a frame grabber so that large amounts of rainbow signals can be fully digitized and saved for further post-processing.

Droplet Temperature Measurement

The performance of the developed optical/electronic system has been tested by using it to measure the temperature of heated kerosene droplets. For these experiments, a drop-on-demand generator was modified such that fuel droplets could be generated at elevated temperatures. The liquid (within the drop-on-demand cavity) was raised from room temperature (24 ^{o}C) to about 100 ^{o}C in increments of about 5 ^{o}C. The measurements were performed at approximately 3 cm below the drop-on-demand nozzle. The CCD pixel number corresponding to the measured rainbow peak is presented in Fig.8 as a function of the cavity temperature. The data presented in Fig.8 shows a measurement uncertainty of +/- 5°C. This uncertainty results from the high frequency oscillations that ride on the rainbow signal. By digitizing the complete rainbow signal and filtering out the high frequency oscillations, the measurement accuracy can be significantly improved.

Drop Size Measurement

The developed system has also been used to demonstrate the feasibility of measuring the droplet size from the supernumerary fringe pattern. A drop-on-demand generator was used to create water droplets of unknown size but in the range of about 150 - 200 μm. The digitized rainbow signal for this case is shown in Fig.9. The presence of low frequency and high frequency oscillations can be clearly observed in this figure. The effect of applying a low pass FFT filter to this signal is shown in Fig.10. The high frequency oscillations have been completely eliminated. The measured data is compared to a theoretically computed, low pass filtered, rainbow signal for a 185 μm water droplet. The agreement between the measurements and theoretical predictions is excellent suggesting that the diameter of the experimentally generated droplet is 185 μm.

Sensitive Measurement of the Change in Drop Size

Preliminary measurements have also been conducted to examine and demonstrate the feasibility of using morphology dependent resonances as a sensitive means for measuring small changes in the drop size. For the droplet combustion studies, this information can be used to measure the instantaneous droplet regression rates, and hence, the droplet vaporization rates. During the course of this program it was observed that the voltage applied to the drop-on-demand generator could be varied to cause small changes in the droplet diameter. Therefore, in this study, the voltages were slowly varied to examine whether it would produce a measurable change in the high frequency pattern. A high pass FFT filter was applied to the rainbow signal to extract the high frequency oscillations from the measured data, see Fig.11. In Fig.12, the extracted high frequency oscillations for two slightly different voltage settings are compared. In order to visually detect any differences in the pattern, we have zoomed in to a region in the neighborhood of the main rainbow. The data presented in Fig.12 shows that the two wave patterns are approximately 90^{o} out of phase. Using the Lorenz-Mie theory calculations, it was determined that this phase shift corresponds to a change in droplet diameter of approximately 0.05 μm. This clearly shows that the high frequency waveform can be used as a sensitive means of measuring the droplet regression rates in droplet combustion experiments. On the other hand, Fig.13 compares the low frequency oscillations for the same two voltage settings. The two patterns are identical which suggests that the low frequency oscillations cannot be used to measure small changes in the droplet diameter.

Theoretical Modeling

One of the planned tasks for this program involves enhancing the currently available Lorenz-Mie theory to account for light scattering by radially inhomogeneous particles using the algorithm developed by Wait [10]. As a first step toward this end, we have developed a model to describe the light scattering by a two layered spherical particle. The model makes use of the algorithm developed by Toon and Ackermann [12]. This model has been used to determine regions of the droplet that actually contribute to the rainbow signature. Our simulations suggest that the inner 50% of the droplet radius does not contribute to the rainbow signature. It is only the rays that pass through the top 50% (from the surface) that influence the rainbow. To demonstrate this, the theoretically simulated rainbow signal for 100 μm homogeneous water droplet has been compared with that of a 100 μm stratified droplet (inner 50% has a refractive index of 1.40 and the outer 50% has a refractive index of 1.33). The rainbow signatures computed for the two cases are identical as shown in Fig.14. These results are also important because in flight testing the fuel droplet is suspended by a tether which includes a bead of about 100 μm in diameter. It is important to know how the presence of the tether influences the measurement. The stratified sphere light scattering mdel can be used as a first approximation to study this effect.

4. Planned Work for the Future

As mentioned earlier, the primary objective of this program is to develop a compact and rugged diagnostic system that could be in microgravity experiments involving droplet combustion. It is anticipated that the developed diagnostic can be used to extract valuable information such as droplet size, droplet regression rate, and internal temperature profiles/gradients. With data rates as high as 10 kHz, large amounts of data can be obtained that will enable detailed studies of the transient heating characteristics of different fuels during the combustion process. Such information is important in the development and validation of reliable theoretical drop combustion models. To achieve this objective we have planned work in several different areas during the coming months. Improved light scattering models to describe the scattering by inhomogeneous droplet and the data acquisition and post-processing software have to be developed and tested. Detailed measurements will be undertaken with various evaporating and burning droplets. Since flight testing of the developed instrument is also planned, a suitable optical system will need to be designed, developed, and tested.

Acknowledgement

This work has been supported by the NASA Lewis Research Center under Contract NAS3-27261.

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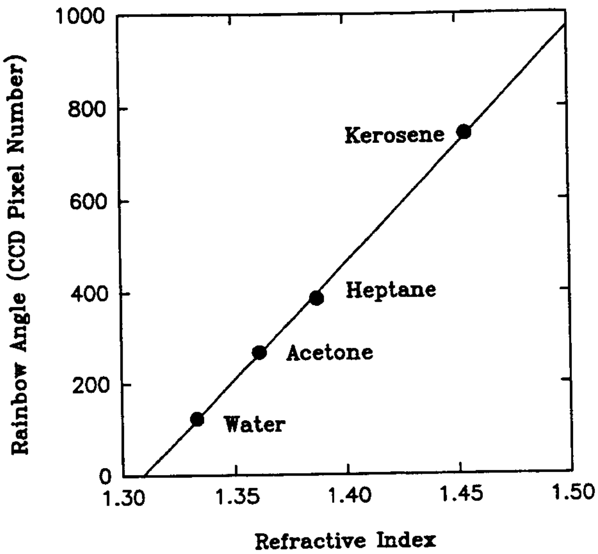

Figure 1: Calibration of the rainbow refractometer. Droplets (approximately *120* μ*m* in diameter) were generated using a monodisperse droplet generator. The CCD pixel number is a direct measure of the rainbow angle.

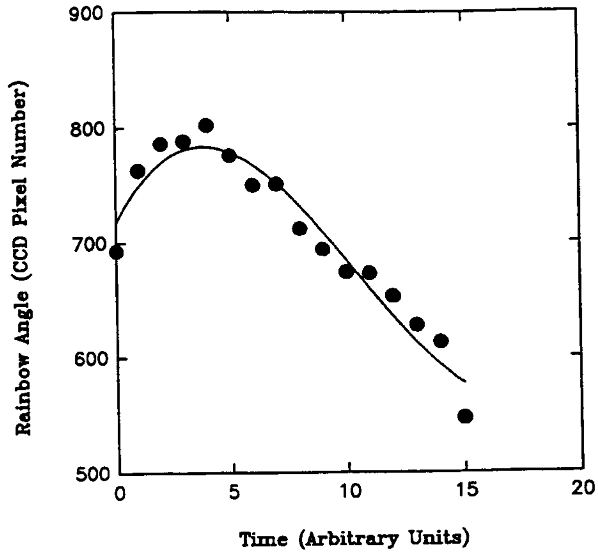

Figure 2: Measured variation of the rainbow position during the transient heating of a n-heptane droplet.

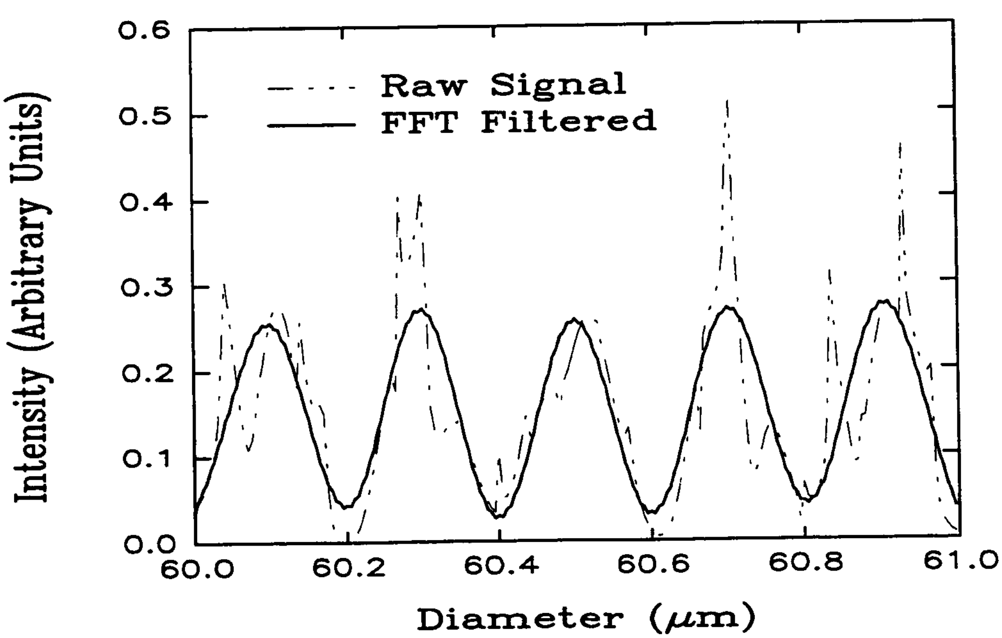

Figure 3: Computed and digitally filtered resonance structure exhibited by spherical particles (*m=1.354*) in the size range *60.0* to *61.0* μ*m*. The measurements were performed assuming a point detector is placed at a scattering angle of *142.5*°.

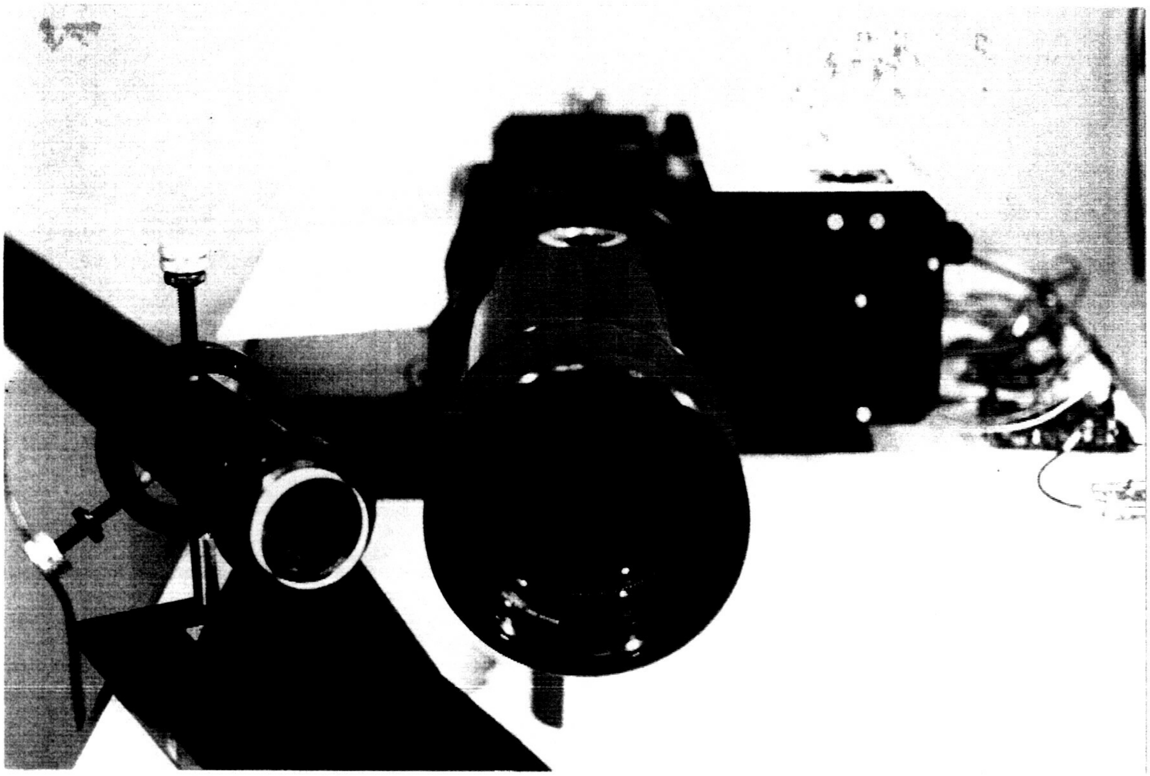

Figure 4: Photograph of the developed prototype diagnostic system.

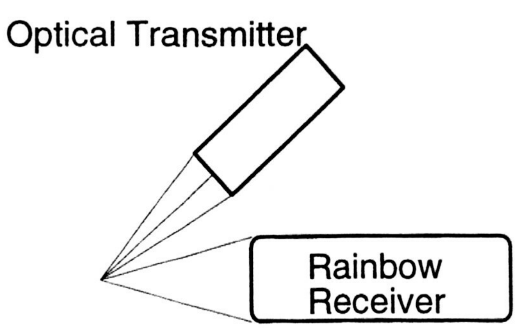

Figure 5: Schematic of the optical system layout.

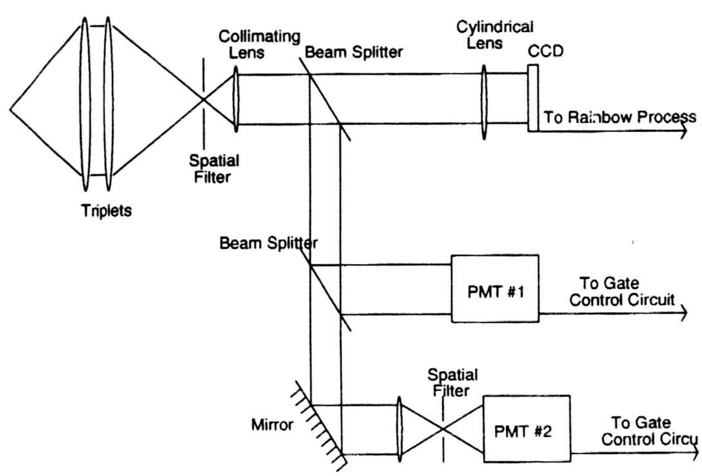

Figure 6: Schematic of the rainbow receiver

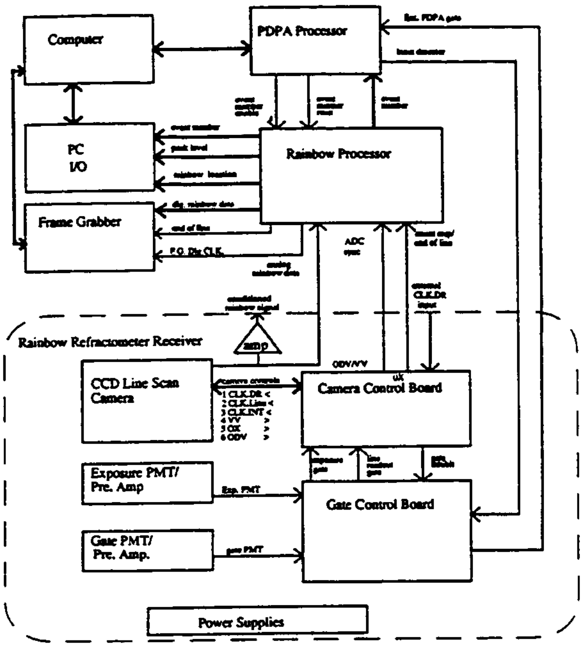

Figure 7: Schematic of the electronics/electro-optics system of the integrated diagnostics.

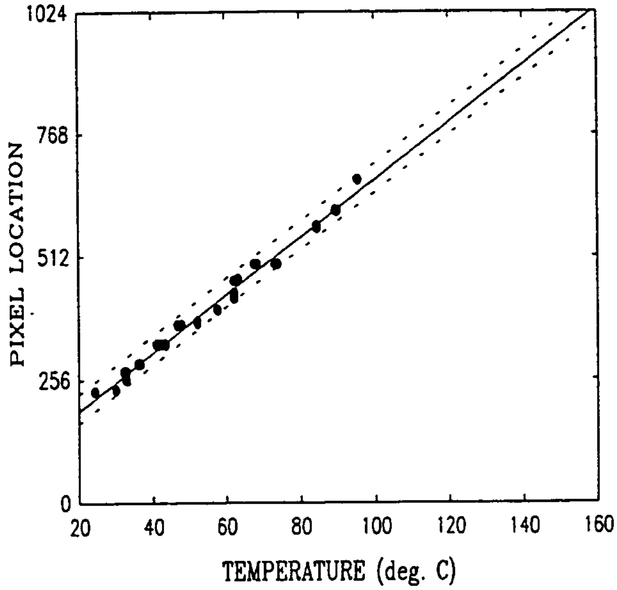

Figure 8: Variation of the measured rainbow location with temperature.

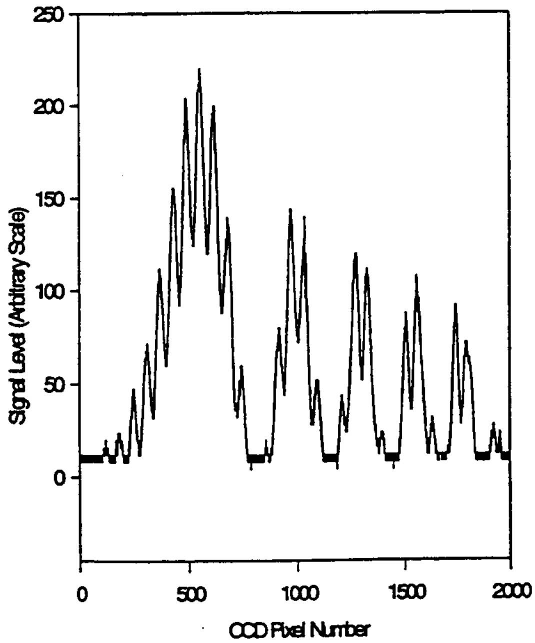

Figure 9: Measured rainbow signal for a water droplet.

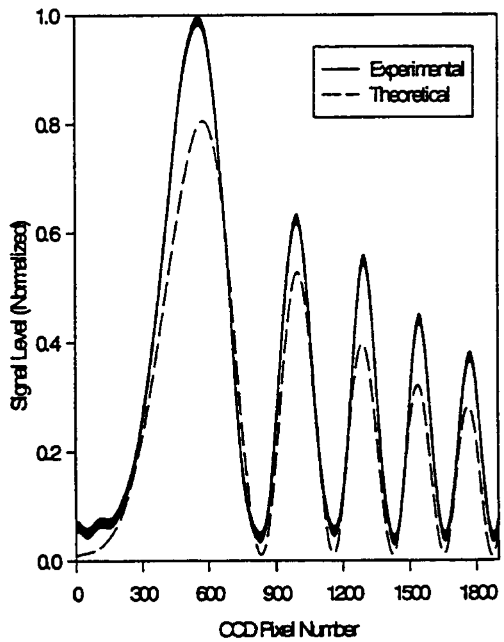

Figure 10: Comparison of experimental and theoretical rainbow signature for a 185 µm water droplet.

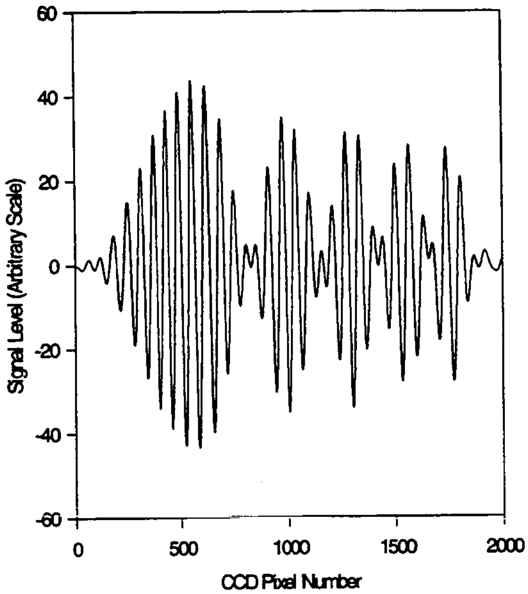

Figure 11: High pass filtered experimental rainbow signal.

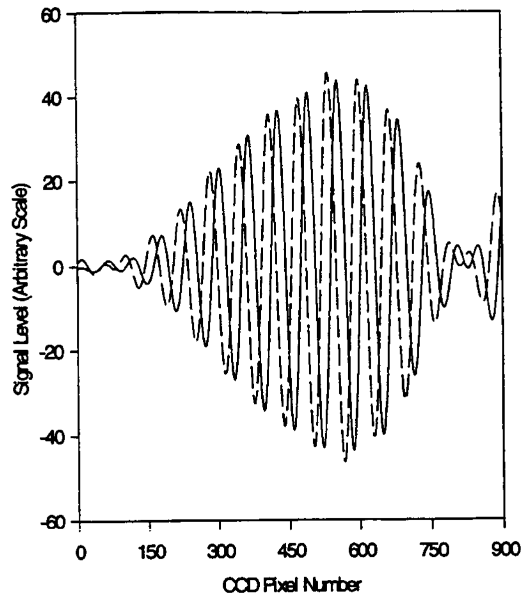

Figure 12: High pass filtered rainbow signal for two different voltage settings on the drop-on-demand generator.

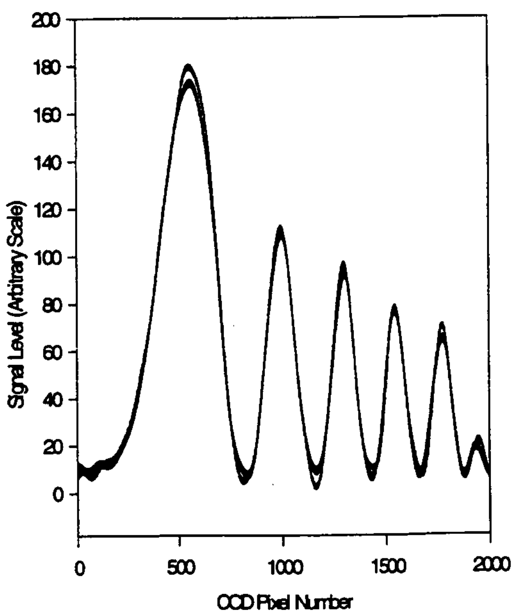

Figure 13: Low pass filtered rainbow signal for the two different voltage settings on the drop-on-demand generator.

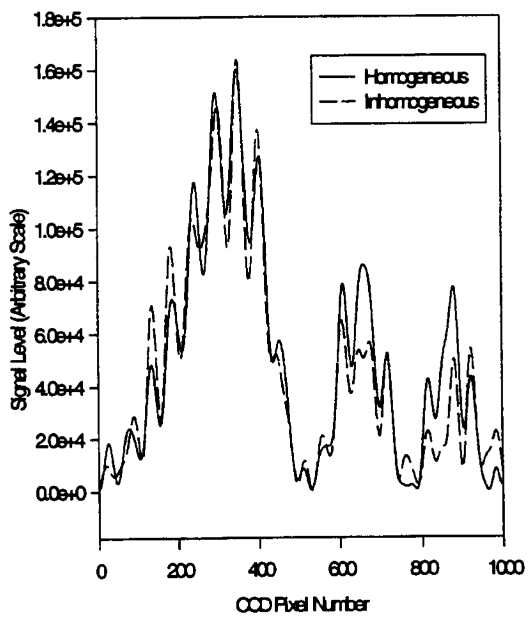

Figure 14: Computed rainbow signals for a homogeneous water droplet and for a stratified droplet for which the outer 50% shell is assumed to have a refractive index of 1.33 and the inner 50% core is assumed to have a refractive index of 1.40. The outer diameter is 100 µm in both cases.