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THESIS

DUAL-BEAM MULTIPLE-WAVELENGTH
LIGHT TRANSMITTANCE MEASUREMENT
FOR PARTICLE SIZING
IN ROCKET MOTOR PLUMES

by

Kevin B. Taylor

June, 1993

Thesis Advisor: David W. Netzer

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13. ABSTRACT (Maximum 200 words)

A multiple-wavelength light transmittance measurement system previously used in a laboratory environment to study particles in solid rocket propellant exhaust plumes was modified for use in the field, where high levels of vibration can degrade the accuracy of data. The system was converted from a single light beam configuration to a dual beam configuration which was capable of obtaining a complete set of 1024 reference and scene measurements in 10.0 ms. Modifications included designing, building and testing a new analog-to-digital data converter trigger circuit, and a rotating-wheel light chopper. Optical components including beam splitters, lenses, and a fiber optic cable were installed, and existing data collection system software was modified. The new system was tested by measuring soot from an oxy-acetylene torch to prove the design concept. Test results and system performance were documented. Recommendations for further modifications, improvements and applications are presented.

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Dual-Beam Multiple-Wavelength
Light Transmittance Measurement
for Particle Sizing in
Rocket Motor Plumes

by

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Submitted in partial fulfillment
of the requirements for the degree of
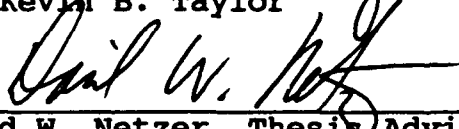
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ABSTRACT

A multiple-wavelength light transmittance measurement system previously used in a laboratory environment to study particles in solid rocket propellant exhaust plumes was modified for use in the field, where high levels of vibration can degrade the accuracy of data. The system was converted from a single light beam configuration to a dual beam configuration which was capable of obtaining a complete set of 1024 reference and scene measurements in 10 ms. Modifications included designing, building and testing a new analog-to-digital data converter trigger circuit, and a rotating-wheel light chopper. Optical components including beam splitters, lenses and a fiber optic cable were installed, and existing data collection system software was modified. The new system was tested by measuring soot from an oxy-acetylene torch to prove the design concept. Test results and system performance were documented. Recommendations for further-modifications, improvements and applications are presented.

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Most of all, I would like to thank my wife Peggy for her unflagging support and encouragement. I would have never finished this without her there. Thanks to my daughter Amy for lifting me up every single day with her smiling face.

I. INTRODUCTION

During a recent war, a need for exhaust plume signature prediction and identification for liquid propellant rocket engines was realized. Since radiation emissions are greatly effected by particles in the plume, knowledge of their size, optical properties, and concentration provides valuable information which is needed to predict the exhaust signature. Liquid rocket propellants, unlike solid rocket propellants, do not normally contain any added metals which can enhance the signature of the plume. However, the exhaust can contain significant amounts of carbon particles, which result from the combustion of hydrocarbons. Soot can produce increased visible and infrared signatures.

Several methods for measuring particles in exhaust plumes exist. The most common procedures are particle sample withdrawal followed by optical measurements or in situ methods based on the transmission and/or scattering of light [Ref. 1]. Soot particles produced by liquid propellants are predominately in the submicron range [Ref. 2,3]. Measurement of these small particles can be accomplished using multiple-wavelength light transmission techniques [Ref 4].

Recent research at the Naval Postgraduate School by Vaughn [Ref. 1] and Kim [Ref. 5] successfully used multiple-

wavelength light transmission measurements for submicron aluminum oxide particles in the plumes of solid propellant rockets. This technique measured the transmittance at six wavelengths. The measured ln-transmittance ratios were compared to the extinction coefficient ratios obtained from a Mie-based computer code. The Beer-Lambert law for the exponential decay of light intensity through a uniform particle field could then be used to obtain the particle concentration [Ref. 4].

The apparatus used in these investigations, while accurate for small rocket motors in a controlled laboratory environment, would probably be greatly effected by vibrations caused by larger motors [Ref. 2]. The apparatus, as originally configured, collected all reference measurements for transmittance calculations prior to rocket motor ignition, which were then averaged to get a mean value. Light measurements through the plume were then collected after motor ignition, which were also averaged. Transmittance was obtained from the averaged values [Ref. 1,5].

Vibrations from a large motor firing can cause variations in the intensity of the light source and/or the alignment of the optical components, thus invalidating the averaged pre-run reference measurements [Ref. 2]. One way to overcome this limitation is to collect reference measurements simultaneously with plume measurements. Transmittance can then be calculated

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at any instance of time, thus negating the effects of vibration and other variations during the burn time. These individual transmittances could then be averaged, if desired.

Another limitation of the light transmission and collection equipment was that it had only been tested across short distances (less than two feet) [Ref. 1,5]. Use of the apparatus on full scale rocket motors would require transmission lengths of fifteen feet or more.

The purposes of this investigation were to (1) modify the multiple-wavelength light transmission apparatus and associated data collection equipment used by Vaughn [Ref. 1] to obtain near-simultaneous reference and plume measurements, (2) extend the light transmission distance and (3) validate the modifications by measuring soot particles from a test source.

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II. THEORETICAL BACKGROUND

A. INTRODUCTION

Multiple wavelength light transmission measurement techniques have been used extensively in recent years to study the nature of small particles. The theory behind these techniques is discussed in detail by Few [Ref. 2,6], Cashdollar [Ref. 4] and Vaughn [Ref. 1].

Recent particle sizing techniques using light transmission measurements are varied applications of the Mie theory for the light scattered by particles [Ref. 1,2]. For particles much smaller than the wavelengths of the incident light the Rayleigh approximation is often used. The techniques have been refined over the years, but the basic approach is that a collimated light beam is transmitted through a particle field [Ref. 2]. Particle size information is then provided by the wavelength dependence of the angular scattering and extinction of the light beam [Ref. 2].

The technique used in this experiment focused on using the extinction of light of multiple wavelengths to determine mean particle size and the particle index of refraction.

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B. LIGHT TRANSMISSION/EXTINCTION THEORY

The transmission of light through a uniform particle cloud is given by the Beer-Lambert law [Ref. 4]:

$$T=\exp(-QAnL)=\exp\left(-\frac{3QC_mL}{2\rho d}\right) \tag{1}$$

where T = fraction of light transmitted,

Q = dimensionless extinction coefficient,

A = cross sectional area of a particle,

n = number concentration of particles,

L = path length,

C_m = mass concentration of particles,

ρ = density of an individual particle,

d = particle diameter

Mie scattering theory considers the interaction of a plane electromagneteic wave with a spherical object. Computation of Q as a function of particle size, light wavelength, and complex index of refraction is possible, and further extensions of the theory have been applied to nonsperical particles [Ref. 1,2,4].

This extension holds if the nonspherical particles are approximated by spherical particles whose diameters provide the same volumes as the nonspherical particles. [Ref. 1,2,6]

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For a polydisperse system of particles, Dobbins [discussed Ref. 4] revised the transmission law to obtain:

$$T = \exp\left(-\frac{3\overline{Q}C_m L}{2\rho d_{32}}\right) \qquad (2)$$

where $\overline{Q}$ is the average extinction coefficient and d_{32} is the volume-to-surface mean (Sauter mean) particle diameter [Ref. 1,4].

Taking the natural logarithm of equation (2) yields:

$$lnT = \overline{Q}\left(-\frac{3C_m L}{2\rho d_{32}}\right) \qquad (3)$$

A multiple-wavelength light beam has identical L, ρ, C_m, and d_{32} for each wavelength through the plume. Therefore, the ratio of the ln-transmissions at any two wavelengths is equal to the ratio of the calculated mean extinction coefficients for the same wavelengths [Ref. 1,4]:

$$\frac{lnT(\lambda_i)}{lnT(\lambda_j)}_{experimental} = \frac{\overline{Q}(\lambda_i, d_{32})}{\overline{Q}(\lambda_j, d_{32})}_{theoretical} \qquad (4)$$

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Cashdollar's computer code [discussed in Ref. 1,4], utilizing Mie theory, was used to generate the values of $\bar{Q}$.

Transmittances at the various wavelengths are determined experimentally. Previous transmittance measurements by Vaughn [Ref. 1] and Kim [Ref. 5] used a single light beam, as discussed in Chapter I. In a dual beam system, as used by Few [discussed in Ref. 2], a calibration measurement of the ratio of scene beam (S) intensity to reference beam intensity (R) is conducted prior to the introduction of soot particles, yielding [Ref. 2]:

$$R_{cal} = \frac{I_S(\lambda)}{I_R(\lambda)} \tag{5}$$

The same intensity ratio is then recorded with soot particles present in the scene beam. The transmittance of light at each wavelength is obtained as the ratio of the sample ratio to the calibration ratio [Ref. 2]:

$$T(\lambda) = \frac{R_{sample}(\lambda)}{R_{cal}(\lambda)} \tag{6}$$

The procedure for determining soot particle diameter requires calculation of Q for various assumed values of λ, d_{32}, m=a-ib (complex index of refraction), and an assumed particle size distribution. If the assumed values are correct, calculated Q ratios will match the measured ln-transmission ratios for each of the wavelengths utilized. [Ref. 1,4]

Studies by Cashdollar [Ref. 4], Few [Ref. 2], and others [discussed in Ref. 2,4] report that the complex index of refraction of soot has a real part (a) value of 1.8 to 1.9. The complex part (b) has values ranging from 0.3 to 0.66. Additionally, the studies report that small particles in plumes often have a monomodal log-normal distribution. In this case the distribution is characterized by d_{32} and σ (standard deviation). [Ref. 1,4]

Since there are four unknown variables (d_{32}, σ, a, and b) a minimum of four independent ln-ratios are needed. Increased numbers of ln-transmission ratios increase the ability to find the best fit between experiment and theory. The values of d_{32}, σ, a, and b are found by finding the best fit (in the least-squares sense) between the calculated and measured results. [Ref. 1,2]

III. EXPERIMENTAL APPARATUS

A. GENERAL ARRANGEMENT

Figure 1 shows the general arrangement of the light transmission and collection equipment. A variable beam splitter, directly in front of the light source, was used to split the light into scene (through-plume) and reference beams for transmittance measurements. The reference beam was redirected through a chopper and focused into a fiber optic cable, which was routed around the particle cloud. The scene beam passed directly through the chopper, a collimating lens, and then through the plume. The chopper provided alternating light measurements for the reference and scene beams. A second beam splitter was used to direct the reference beam from the fiber optic cable into the spectrograph.
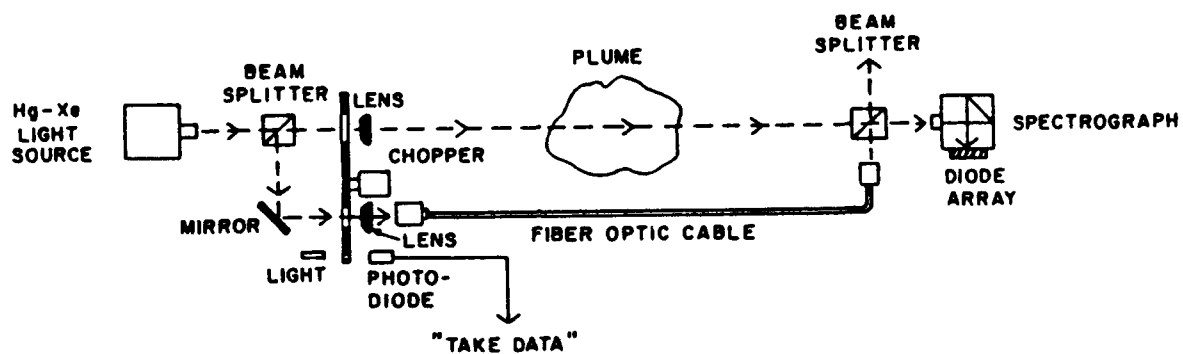
Figure 1
General Arrangement

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A 200 Watt Mercury-Xenon bulb (Oriel Corp. #6291) was used as the light source in this experiment. It produced intensity peaks at wavelengths of 253.4, 302.2, 312.6, 334.2, 366.3, 404.7, 435.8, 546.1, and 577.0 nm. The bulb was mounted in a Oriel lamp housing with a F/1 condenser and a UV grade fused silica 1.5 inch lens. The lamp was powered by an Oriel power supply. [Ref. 7]

An Oriel model 77400 Multispec spectrograph was used to collect the reference beam and scene beam light intensities. A 25μm wide input slit restricted the the amount of stray light entering the spectograph. The transmitted light was then projected onto a 1024 element diode array. Figure 2 shows the optical pattern within the spectrograph.

The diode array was an EG&G Reticon G series solid state line scanner with 1024 elements. Spectral response of the array is in the UV/IR range (approx. 200 - 1000 nm wavelength). The diode array was controlled by a Reticon RC100 motherboard which provided all clock, start, video amplifier, and blanking requirements. [Ref. 8]
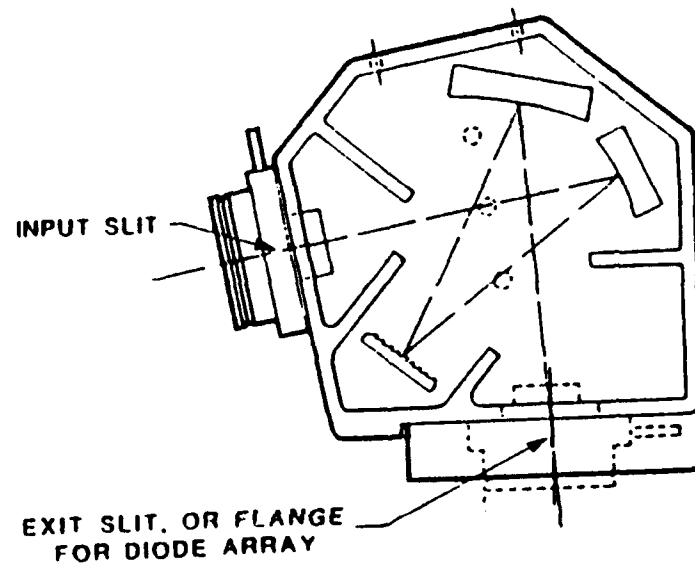
INPUT SLIT

EXIT SLIT, OR FLANGE
FOR DIODE ARRAY

Figure 2
Multispec optical arrangement
[Ref. 7]

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C. LIGHT CHOPPER

A detailed drawing of the light chopper disk is provided in Appendix A. The two sets of large apertures were designed to provide alternating reference and through-plume (scene) light measurements. The aperture arc length provided a transmission time of slightly more than the sweep time of the diode array (2.04 ms) when the disk was rotated at 1000 rpm. The small apertures on the outer radius provided a "take data" command signal to the Data Acquisition/Control System and were aligned with the leading edges of the large apertures. The light chopper provided 1024 transmittance values each 10.0 ms.

The chopper disk was driven by a Vexta model FBL-215A 24 volt DC speed control motor. The motor speed was controlled by a precision potentiometer. Speed was monitored by checking the frequency of the "take data" command from the chopper disk.

D. FIBER OPTICS

The reference beam was routed around the particle cloud using an Oriel, 600 μm diameter, UV/VIS single fiber optic cable. Cable length was 5 meters. Light was collected into the cable using an Oriel model 77780 Fiber Optic Input Accessory with a fused silica F/2 lens. Output from the cable was directed onto the second beam splitter using an Oriel model 77644 Collimating Beam Probe with fused silica lens.

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E. OTHER OPTICS

Two types of beam splitters were used. The first type was a rotating disc, variable beam splitter which allowed for proportioning appropriate intensities of light into the scene and reference beams. A fused silica 50/50 polka-dot beam splitter was placed in front of the spectrogaph. It was used to redirect the reference beam into che spectrograph entrance slit.

IV. DATA ACQUISITION SYSTEM

A. OVERVIEW

Data and clock/timing signals from the diode array were sent to a Hewlett Packard 6942A Multiprogrammer where the data were converted from analog to digital and stored on memory cards for processing. The multiprogrammer was programmed by a HP 9836S desktop computer. Figure 3 is a block diagram showing the general arrangement of the data acquisition system.
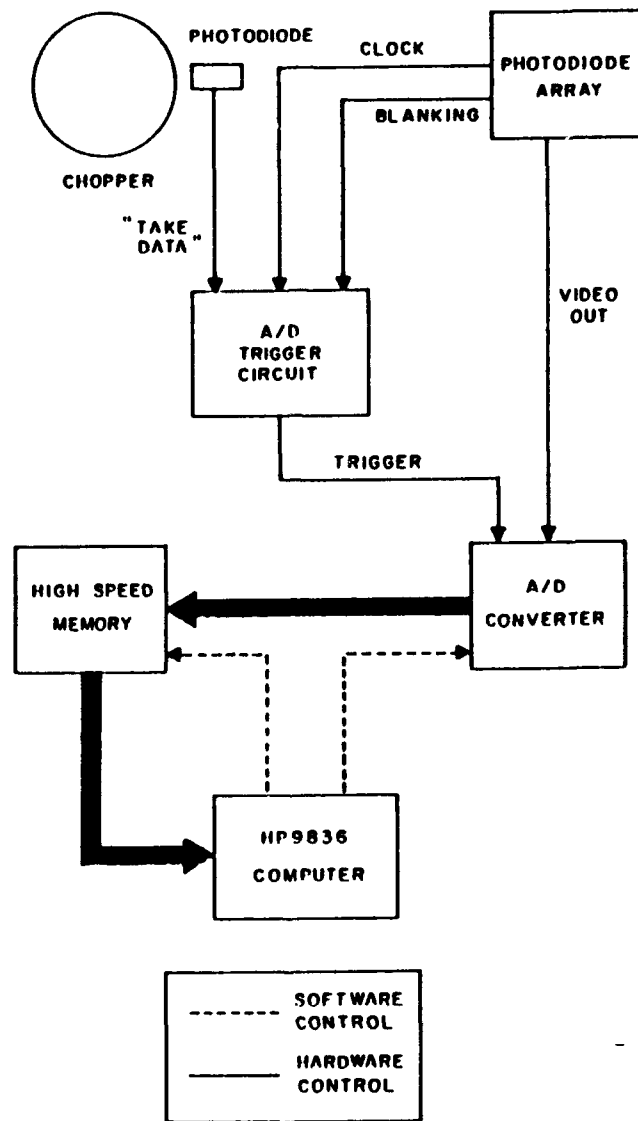
Figure 3
Data Aquisition System
[Adapted from Ref. 9:p. 40]

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B. MULTIPROGRAMMER

The HP6942A Multiprogrammer is a self-contained system which has a wide variety of data acquisition applications. The system can accomodate up to sixteen I/O cards which are programmable by a desktop computer through the HP Interface bus. The cards can be addressed and controlled by the computer via the Multiprogrammer backplane or can be controlled by external triggers through rear card edge connectors. [Ref. 10:pp. 1-1, 2-1, 3-1, Ref. 1: p. 39]

The system used in this experiment was configured with one HP69759A 500 KHz A/D Converter card, one HP69791A High Speed Memory card and four HP69792A Memory Expansion cards.

1. 500 KHz A/D Card

The 500 KHz A/D card, when triggered, converts input voltages into 12-bit, twos-complement binary values within 2.0 μs. It may be triggered internally by program command or externally by a lockout input at the edge connector. Digital output is available at the edge connector at a rate of 500 KHz. [Ref. 11]

The system was configured to receive analog data from the diode array and send digital data to memory at the edge connector. Additionally, it was configured for external triggering from the A/D trigger circuit.

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2. High Speed Memory and Memory Expansion Cards

The High Speed Memory card can store up to 65,536 16-bit words at high speed. Data can be written to, or read from, the card by the computer via the backplane or an external device via the card edge connector. Memory Expansion cards are added to the Memory card by a special chaining cable. Each expansion card can store up to 196,608 16-bit words. With four expansion cards, the total memory available was 851,968 16-bit words. [Ref. 12]

Memory was programmed to operate in a First In/First Out (FIFO) mode. This allowed the cards to act like a data buffer with data written to sequential memory locations. [Ref. 12]

Data from the A/D card was written to memory via the edge connector. Data was then read from memory to the computer hard disk by the computer via the Multiprogrammer backplane.

C. A/D TRIGGER CIRCUIT

1. Purpose

The most critical part of the Data Acquisition System was the A/D trigger circuit. The circuit design had to insure that the Diode Array Clock signal (500.0 KHz), the Diode Array Blanking Pulse signal (484.5 Hz), and the "Take Data" command (200.0 Hz) from the chopper were properly combined. The resultant trigger signal was required to be a group of 1024 pulses (at 500 KHz) which were synchronized with the start of a diode array sweep and the leading edge of a chopper disc aperture. Figure 4 is a diagram showing how the signals were combined.
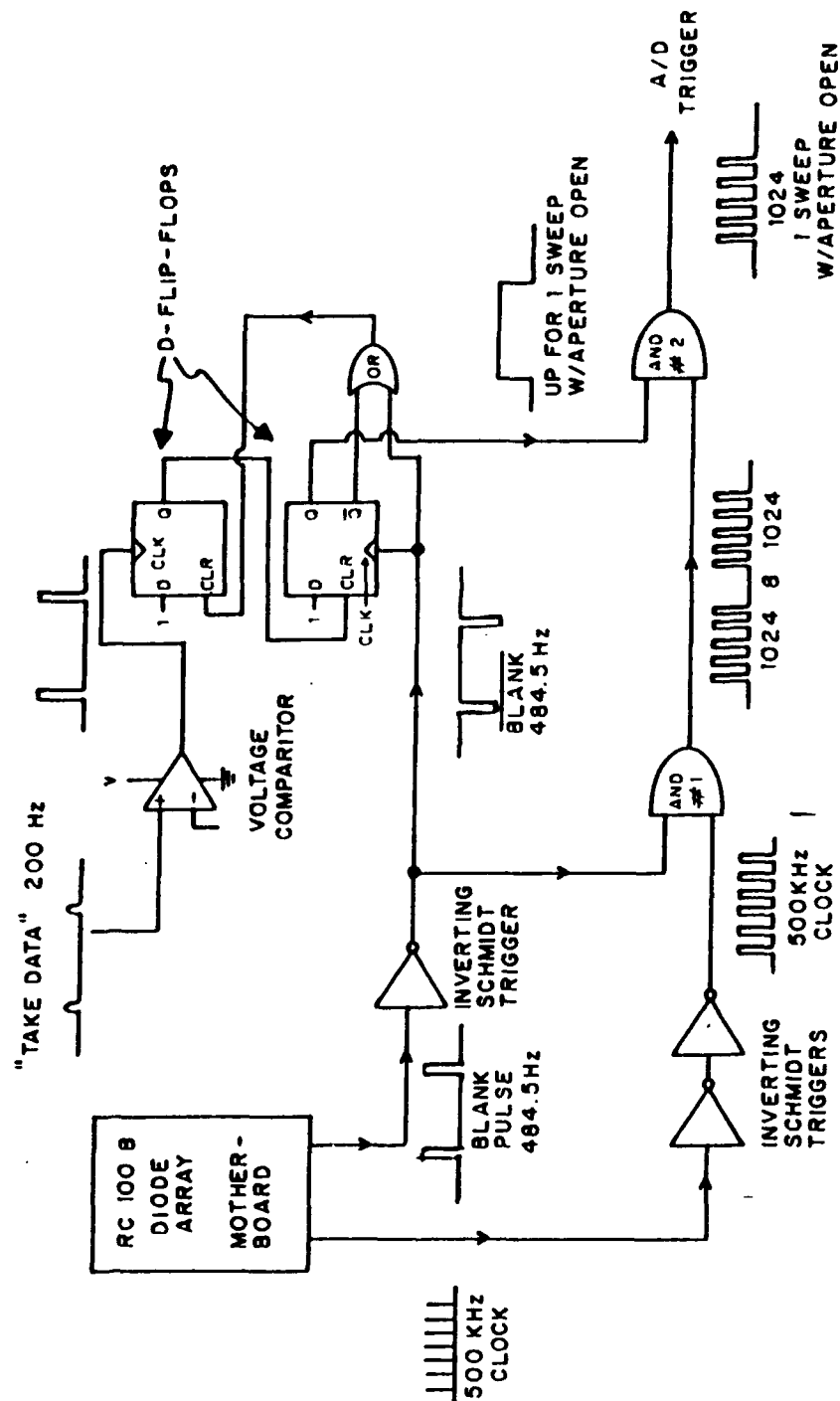
Figure 4
A/D Trigger Circuit

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2. Modifications

During previous applications a Timer/Pacer card was programmed as an input to the A/D trigger signal, and a circuit card for the trigger was constructed [Ref. 1:p. 41, Ref. 9:p. 42]. Since the Timer/Pacer portion was deleted and the chopper "Take Data" signal (an analog voltage signal from a photodiode) was added, a new circuit card had to be designed and constructed, as previously discussed.

The new circuit card was installed and successfully tested. Figure 5 is a timing diagram of the A/D trigger circuit. A detailed drawing of the new circuit card is provided in Appendix B.

Figure 5
A/D Trigger Timing Diagram

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V. SYSTEM TEST PROCEDURE AND RESULTS

A. TEST PROCEDURE

1. Initial Alignment

The system was initially constructed with the light source and spectrograph at a 10.0 ft. separation. The optics were then aligned and diode array voltages check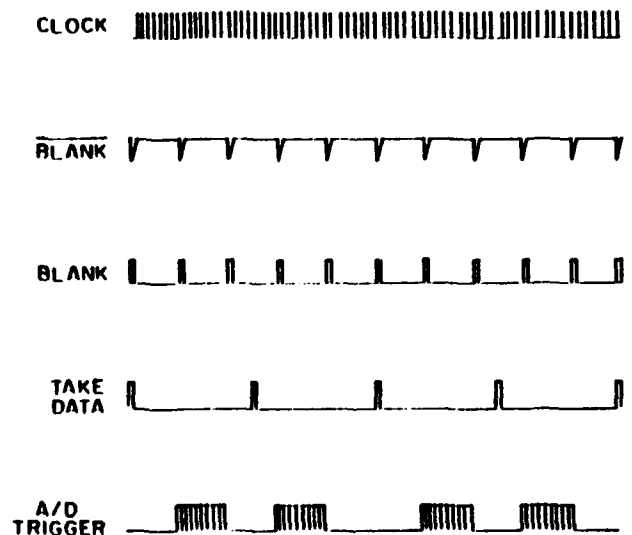ed for both the reference and scene beams. The variable beam splitter was adjusted to provide optimum light intensities for both beams.

It became readily apparent that the 200 watt light source provided insufficient radiant power to overcome both being passed through two beam splitters and the losses in the fiber optic cable. With the best beam splitter adjustment and system optical alignment diode array peak voltages were barely discernable above base noise levels. The data acquisition system was unable to record usable readings for transmittance calculations.

2. Test Configuration and Procedure   -

Due to time and cost constraints, it was not possible to obtain a more powerful light source. The system was reconfigured so that sufficient diode array voltages were obtained to prove design concept. The variable beam splitter was removed and light was directed through the chopper into the fiber optic cable. The beam splitter at the entrance to

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the spectrograph was removed and the output of the fiber optic cable was directed into the spectrograph. Reference beam intensities were obtained and averaged. It was then assumed that reference beam intensities were constant for the remainder of the system test.

The system was then configured to obtain test data from a particle source. The fiber optic cable was removed and the scene beam was directed through the chopper and directed onto the spectrograph inlet slit. Additionally, the spectrograph was moved to distance of approximately 4.0 ft. from the light source in order to insure sufficient scene beam intensity. Calibration (no plume) intensities were recorded prior to the introduction of soot particles. The smoke cloud from a fuel-rich oxy-acetylene torch flame was directed into the scene beam and intensities were recorded.

B. TEST RESULTS

1. Data Reduction

The first step in data reduction was to obtain calculated extinction coefficient (Q) ratios using the Mie-scattering computer code. Q was determined as a function of d_{32}, σ, m, and wavelength. Five wavelengths were observed during the test (λ_1 = 366.3, λ_2 = 404.7, λ_3 = 435.8, λ_4 = 546.1, and λ_5 = 577.0 nm) which provided ten independent ln-transmittance ratios.

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Three values of m were used in the calculations. The first, m = 1.8 - 0.3i, is similar to the value derived by Kunitomo and Sato for various soots and the value measured by Chippett and Gray for propane and acetylene soots. The second, m = 1.95 - 0.66i, is the complex index of refraction of carbon measured by Senftleben and Benedict. The third, m = 1.8 - 0.6i, is an average of the index for carbon and the index for propane and acetylene soots measured by Dalzell and Sarofim. Two values of σ were used, 1.5 and 2.0, which are typical of soot particle size distributions. [Ref. 4]

The measured intensities were then converted into ln-transmittance ratios. The average of six sweeps of the diode array were used to determine the reference beam intensities for five observed wavelengths. The intensities for the scene beam, both with and without particles, were similarly calculated using the averages from two sweeps of the diode array. The transmittances for each wavelength were then calculated as discussed in Chapter II. The natural logarithms were computed and the ten independent ln-transmittance ratios (for five wavelengths) were obtained.

The next step in data reduction was to look for rough trends in data to reduce the amount of required regression analysis. Values for d_{32} were calculated using the measured ln-transmittance ratios and various specified values of m and σ as shown in Table 1. The refractive index

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m = 1.8 - 0.6i with σ = 1.5 or 2.0 provided a poor correlation since six of the ten measured ln-transmittance ratios were lower than the minimum calculated extinction coefficient ratios. Additionally, m = 1.95 - 0.66i with σ = 2.0 yielded poor results. These three data sets were eliminated from further consideration. Calculations of mean d_{32} indicated a likely value ranging from approximately 0.10 to 0.17 microns.

TABLE 1

Calculated d_{32} for Specified m and σ Values

ln - ratios	m = 1.8 - 0.3		m = 1.95 - 0.66		m = 1.8 - 0.6	
	sigma = 1.5	sigma = 2.0	sigma = 1.5	sigma = 2.0	sigma = 1.5	sigma = 2.0
0.4884	0.14	0.06	0.06	••	••	••
0.5865	0.15	0.09	0.1	••	••	••
0.6106	0.18	0.125	0.125	0.085	0.12	0.065
0.6296	0.14	0.07	0.09	••	••	••
0.7332	0.21	0.17	0.155	0.12	0.15	0.115
0.7758	0.135	0.08	0.09	••	••	••
0.7872	0.22	0.2	0.155	0.12	0.16	0.115
0.7999	••	••	••	••	••	••
0.8328	0.09	0.06	0.06	••	••	••
0.9135	0.2	0.12	0.12	0.08	0.12	0.065
mean diam.	0.163	0.108	0.106	0.101	0.138	0.09
std dev.	0.04	0.047	0.036	0.019	0.018	0.025

Note: all values of d_{32} are in microns

•• indicates ln-transmittance ratio below
   minimum extinction coefficient ratio

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Now that a likely range of values for d_{32} was obtained, the ratios of calculated mean extinction coefficients for assumed values of m, σ, and d_{32} were plotted against observed values of the ln-transmittance ratios. If the ratios had corresponded exactly with each other, the data points would have formed a 45 degree line passing through the origin. Short of this, the best fit of data would have the least scatter about this line, and would form a line with a slope approximately equal to one. [Ref. 1]

The best fit of data was found by applying a linear least-squares fit to the data. The regression analysis function in Microsoft Excel was ideal for this purpose. The correlation coefficient, r, is a measure of the relationship between the ln-transmittance ratios and the extinction coefficient ratios. The square of the correlation coefficient expressed as a percentage was used to measure how closely the data points matched the regression line. The r^2 values closest to one indicated the best linear correlation between data. The x - coefficient (slope) of the regression analysis indicated how closely the slope of the least-squares fit matched a 45 degree line. [Refs. 1, 13]

Figures 6, 7 and 8 are plots of the regression lines for m = 1.8 - 0.3i (σ = 1.5), m = 1.8 - 0.3i (σ = 2.0), and m = 1.95 - 0.66i (σ = 1.5), respectively. Particle diameter (d_{32}) was varied from 0.09μ to 0.18μ in each case.
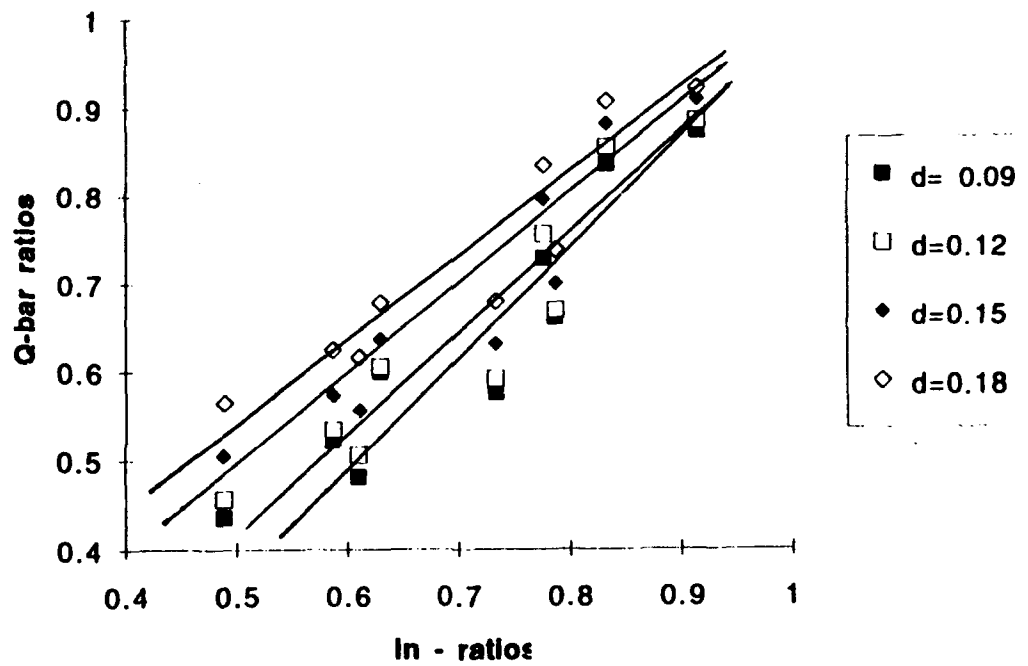
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Figure 6
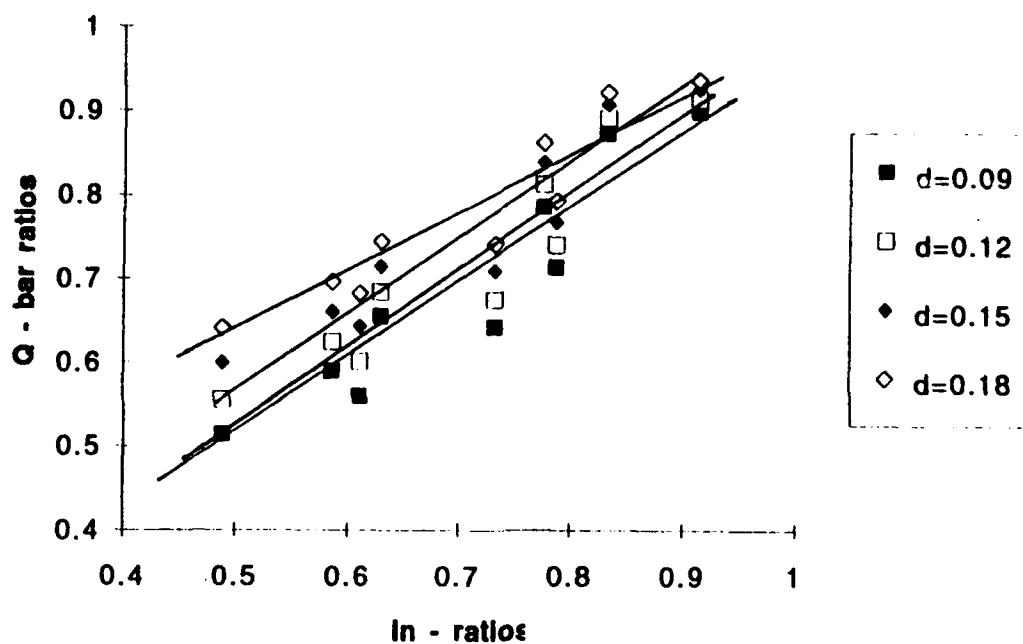Least Squares Fit
$m = 1.8 - 0.3i$ ($\sigma = 1.5$)
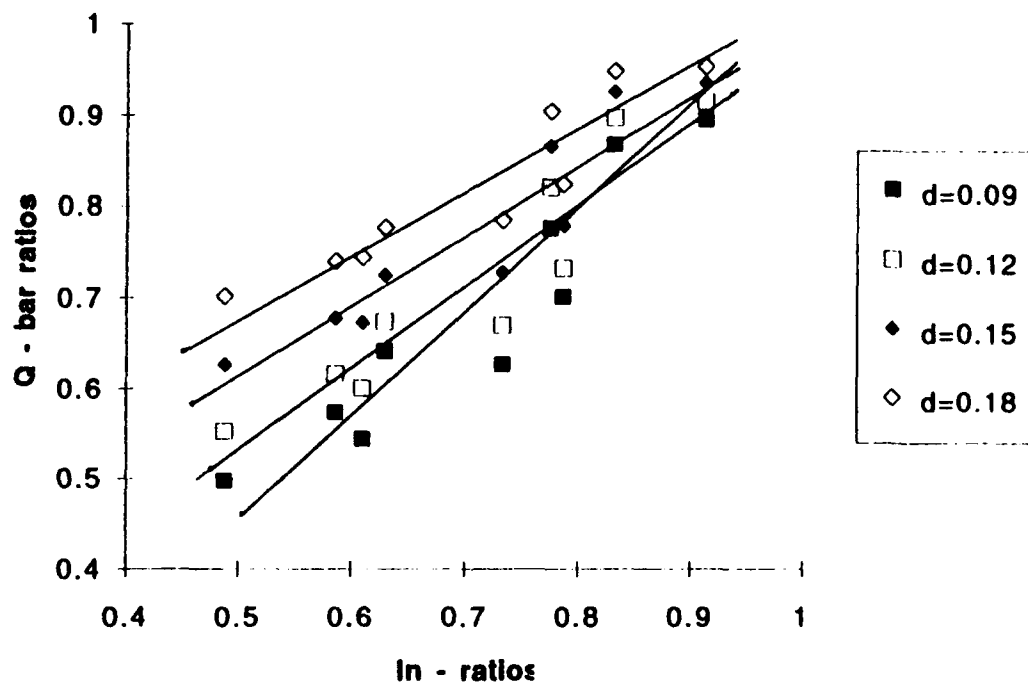
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Figure 7
Least Squares Fit
m = 1.8 − 0.3i (σ = 2.0)

Figure 8
Least Squares Fit
m = 1.95 − .66i (σ = 1.5)

2. Data Analysis

As previously noted, Table 1 data indicated that
$m = 1.8 - 0.6i$ with $\sigma = 1.5$ or 2.0 and $m = 1.95 - 0.66i$ with
$\sigma = 2.0$ provided poor correlation. No correlations were
obtainable using a ratio of $\ln T(\lambda_5 = 577.0\mu)$ over
$\ln T(\lambda_4 = 546.1\mu)$. This apparently resulted because the
wavelengths were so closely spaced [Ref. 5].

Table 2 lists the r^2 and x-coefficient values obtained
in each case. The best r^2 value was 0.8839 for $d_{32} = 0.12\mu$,
$m = 1.8 - 0.3i$, and $\sigma = 2.0$. All other r^2 values were within
2.0 percent. The best x - coefficient value was 0.995 for
$d_{32} = 0.15\mu$, $m = 1.8 - 0.3i$, and $\sigma = 1.5$. This was
significantly closer to 1.0 than any of the other results,
indicating that d_{32} is probably closer to 0.15μ than 0.12μ.
The poor correlations indicate the possible existence of a bi-
modal particle distribution in which the second mode is at a
larger diameter as a result of soot agglomeration in the fuel-
rich post-flame region, where the measurements were made.

It must be noted that the system recorded many more
sweeps of the diode array than were actually used. Better
results will be obtained by using all available data to
calculate measured transmittances.

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TABLE 2

Summary of r^2 and x - coefficient Values

diameter	m = 1.8 - 0.3 sigma = 1.5		m = 1.8 - 0.3 sigma = 2.0		m=1.95-0.66 sigma = 1.5	
	r -squared	x - coefficient	r - squared	x - coefficient	r - squared	x - coefficient
0.09	0.8809	1.0538	0.8837	0.9406	0.8806	0.9715
0.12	0.8759	1.0486	0.8839	0.8789	0.8753	0.8999
0.15	0.8739	0.995	0.8838	0.8057	0.8705	0.7783
0.18	0.8699	0.8919	0.8834	0.7317	0.8643	0.6408

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3. System Performance

With the exception of an inadequate light source, system performance appeared to be excellent. The A/D trigger circuit and light chopper functioned as designed. One shortcoming in system software was noted. If the data acquisition program was actuated during an A/D trigger pulse group, then the recorded data was obtained out of sequence. This problem was mitigated by slowing the chopper rotation frequency, and thus the frequency of the "take data" signal. This resulted in longer nulls between A/D trigger pulse groups and, therefore, less chance of actuating the data acquisition program during a trigger group. The slower chopper rotation rate, and resulting slower data acquisition rate, could result in degraded performance in a high vibration environment.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The system design concept was proven valid. The goals of obtaining rapid measurements of reference and scene beam intensities and of extending the distance between light source and spectrograph were not achieved. Installation of a stronger light source will make these goals possible. Poor correlation of the data obtained from a fuel-rich oxy-acetylene flame was probably the result of the existence of a multimodal particle size distribution.

B. RECOMMENDATIONS

Recommendations for further system development and applications are:

(1) Obtain a more powerful light source. Minimum power should be 1000 watts.
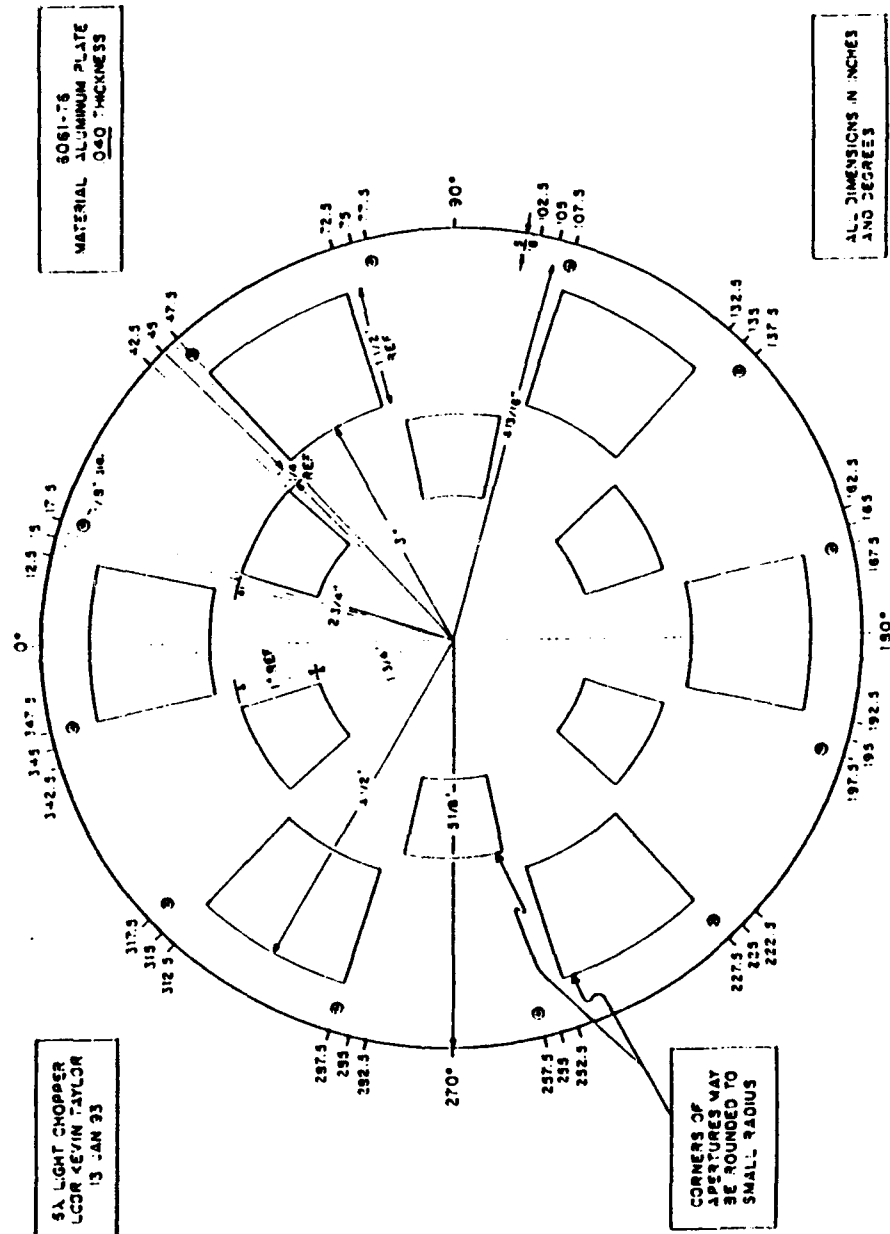
(2) When adequate intensities are obtained in both the scene and reference beams, test the system on a particle source with known characteristics.

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(3) Conduct tests in environments with varying amplitudes and frequencies of vibration to determine system limitations.

(4) If the system is sensitive to vibrations with amplitudes and frequencies expected in the field environment, it may be necessary to reduce the number of diodes swept (since only approximately 10 of the 1024 are needed). This will result in a increased sweep rate (since T_{sweep} = # diodes in array / 500 Khz). Additionally, a chopper capable of rotating at higher speeds will provide a higher data acquisition rate, since a higher "take data" signal frequency would result. The data acquisition program and/or the A/D trigger circuit would require modifications to eliminate the problem of triggering the A/D card in the middle of a trigger pulse group.

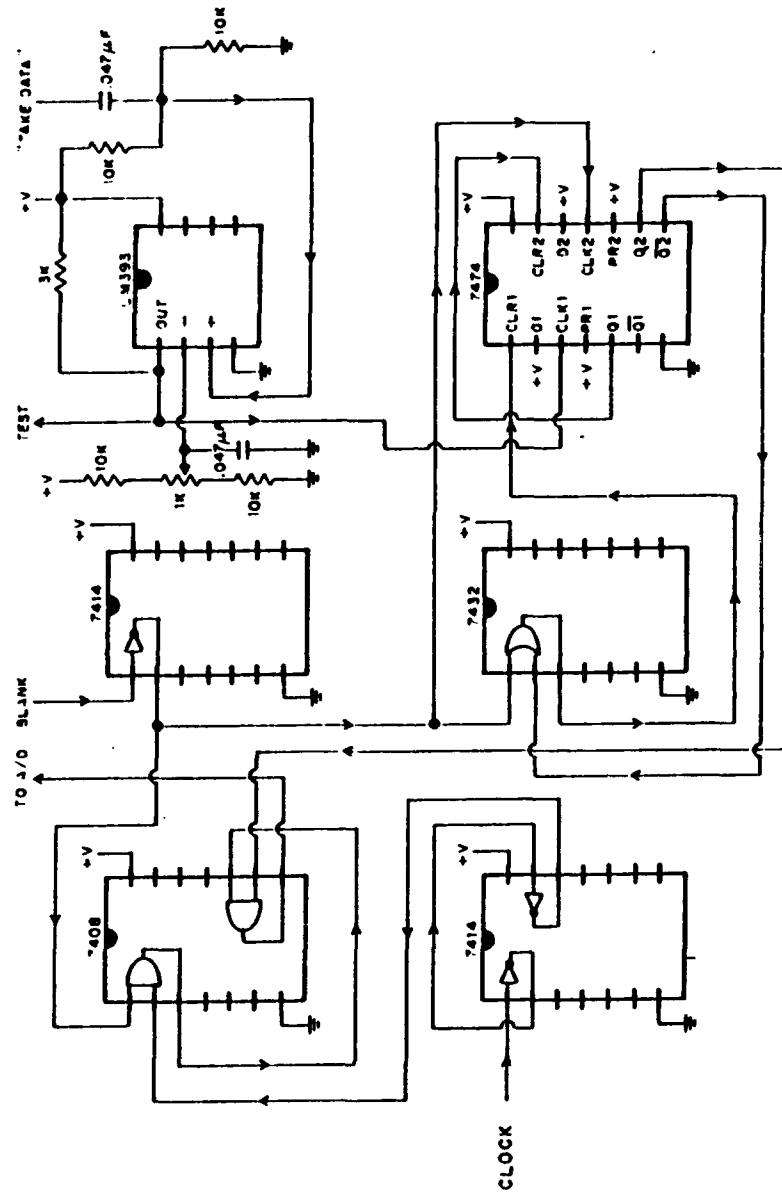(5) Obtain the fiber optic cable and lenses required to extend transmission distance to that required for testing over longer distances (~40 ft).

APPENDIX A

LIGHT CHOPPER DISC DESIGN

MATERIAL
6061-T6
ALUMINUM PLATE
.040 THICKNESS

ALL DIMENSIONS IN INCHES
AND DEGREES

SA LIGHT CHOPPER
LCDR KEVIN TAYLOR
13 JAN 93

CORNERS OF
APERTURES MAY
BE ROUNDED TO
SMALL RADIUS

A/D TRIGGER CIRCUIT CARD SCHEMATIC

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APPENDIX C

DATA ACQUISITION PROGRAM

```
20    !********** ACQUIRES MULTIPLE SCANS OF DIODE ARRAY ******************
30    !********           AND STORES THEM ON DISK          ***************
40    !**********  BERT HANSEN, KEN GRAHAM,KELLY HARRIS 1984  ************
41    !**************************************************************
50    !**********  REVISED FOR USE WITH 500KHZ A/D AND STORAGE ***********
51    !*********        ON HARD DRIVE BY JOHN VAUGHN 1992      ***********
61    !********** REVISED FOR DUAL BEAM APPLICATION ********************
70    !*************     BY KEVIN TAYLOR 1993    *******************
71    DIM C(1:8192),D(1:8192),Z(1:8192)
120   LOCAL LOCKOUT 7        ! DISABLES FRONT PANELS OF DATA ACQUISITION SYSTEM
130   REMOTE 709
140   OUTPUT 709;"AR"                      ! ANALOG RESET OPENS ALL CHANNELS
270   GOSUB Initiate
410   PRINT USING "@"
420   PRINT " DATA WILL BE STORED ON HARD DRIVE WITH FOLLOWING FILE NAMES:"
430   PRINT USING "///"
440   PRINT "   CALIBRATION ---- A "
450   PRINT " PARTICLE SAMPLE ---- B "
452   OUTPUT 709;"DC11,2"   ! OPEN SHUTTER
460   PRINT USING "//"
743   PRINT "TAKING  DATA"
744   !WAIT 3
754   GOSUB Multiprog         !Takes calibration data
755   GOSUB Purge
761   GOSUB Storedata
700   PRINT USING "/////////"
990   PRINT "          INTRODUCE PARTICLES THEN PRESS KEY # 9 TO TAKE DATA"
1000  ON KEY 9 LABEL " TAKE DATA" GOTO 1011
1010  Standby:GOTO Standby
1011  Part=1
1012  PRINT USING "///"
1014  PRINT "TAKING PARTICLE DATA"
1015  WAIT .1
1020  GOSUB Multiprog                            ! TAKE PARTICLE DATA
1040                                             !PARTICLE DATA FILE NAME
1057  GOSUB Storedata
1081  OUTPUT 709;"AR"                    !A/D is in slot 1
1082  LOCAL 7                            !Mem Card      2,3
1090  GOTO 3000                          !Timer/pacer     8
1100  Multiprog:                             !Mem Exp Cards   4,5,6,7
1101  .Cdelay=0
1103  OUTPUT 709;"DC11,2"
1117  Cdelay=Cdelay+1
1127  IF Cdelay<5 THEN
1137    GOSUB Initiate
1147    GOTO 1117
1157  END IF
1305  IF Part=0 THEN
1309    PRINT USING "///"
1311    PRINT "CALIBRATION DATA IS STORED ON MEMORY CARDS "
1312    WAIT 3
1314  END IF
1320  IF Part=0 THEN GOTO 1590
1330  PRINT USING "///"
1404  PRINT "PARTICLE DATA IS STORED ON MEMORY CARDS "
1590  RETURN
```

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```
1600 Storedata:!
1601  PRINT USING "///"
1602  PRINT "DATA IS BEING TRANSFERED FROM THE CARDS TO THE COMPUTER"
1603  PRINT USING "/"
1605  PRINT "WHEN THE TRANSFER IS COMPLETE THE FIRST 5 ENTRIES OF EACH FILE"
1606  PRINT "                    WILL BE DISPLAYED"
1607  OUTPUT 723;"WF2.3,76T"                              !FIFO-IN WITH LOCKOUT
1608  OUTPUT 723;"MI";2;8192;"T"
1609  ENTER 72305;Z(*)
1612  IF Part)=1 THEN GOTO 1700
1613  PRINT "NEGATIVE VOLTAGE LOOP"
1615  FOR I=1 TO 8192
1616  IF Z(I)<32000 THEN
1617  C(I)=Z(I)*.0005
1618  GOTO 1630
1619  END IF
1621  C(I)=(65535-Z(I))*.0005
1630  NEXT I
1650  GOTO 1782
1700  Part=Part+1
1701  PRINT "NEGATIVE VOLTAGE LOOP"
1710  IF Part(1 THEN GOTO 1607
1720  FOR I=1 TO 8192
1730  IF Z(I)<32000 THEN
1740  D(I)=Z(I)*.0005
1741  GOTO 1751
1742  END IF
1750  D(I)=(65535-Z(I))*.0005
1751  NEXT I
1760  Part=1
1775  PRINT USING "///"
1782  Lucky$=CHR$(65)
1783  ASSIGN @Path2 TO Lucky$
1784  OUTPUT @Path2;C(*)
1785  IF Part=0 THEN GOTO 1790
1787  Lucky$=CHR$(66)
1788  ASSIGN @Path2 TO Lucky$
1789  OUTPUT @Path2;D(*)
1790  FOR I=65 TO 65+Part
1791    Lucky$=CHR$(I)
1792    ASSIGN @Path2 TO Lucky$
1793    PRINT "RDAT ";CHR$(I)
1794    FOR J=1 TO 5
1795      ENTER @Path2;M
1796      PRINT M
1797    NEXT J
1798  NEXT I
1799  WAIT 3
1801  OUTPUT 723;"WF2.3,56T"                              !FIFO-IN WITHOUT LOCKOUT
1802  RETURN
```

```
1840 Initiate:!
1880   OUTPUT 723;"WF,2.3,256,2.3,56,T"!Initialize the Mode register
1881   OUTPUT 723;"WF,2.1,30,2.2,0,T"!Set reference 2(low order word)
1882   OUTPUT 723;"WF,2.1,31,2.2,0,T"!Set reference 2(high order word)
1883   OUTPUT 723;"WF,2.1,26,2.2,177777,T"!Set reference 1(low order word)
1884   OUTPUT 723;"WF,2.1,27,2.2,17,T"!Set reference 1(high order word)
1885   OUTPUT 723;"WF,2.1,22,2.2,0,T"!Reset Read Pointer(low order word)
1886   OUTPUT 723;"WF,2.1,23,2.2,0,T"!Reset Read Pointer(high order word)
1887   OUTPUT 723;"WF,2.1,20,2.2,0,T"!Reset the Difference counter(low order word
)
1888   OUTPUT 723;"WF,2.1,21,2.2,0,T"!Reset the Difference counter(high order
word)
1889   OUTPUT 723;"WF,2.1,24,2.2,0,T"!Reset the Write pointer(low order word)
1890   OUTPUT 723;"WF,2.1,25,2.2,0,T"!Reset the Write pointer(high order word)
1891   OUTPUT 723;"CC,2,1T"!Send a clear card instruction
1892   PRINT USING "3/"
1893   OUTPUT 723;"WF,2.3,56T"        !SET MEMORY CARD TO FIFO-IN MODE
1894   OUTPUT 723;"CY",2,"T"          !ACTIVATE CARD
1895   OUTPUT 723;"WF1.1,11,1.2,0T"   !DISABLE MUX(Need to enable mux if ever
                                      !switch back to 1417A connector cable)
1896   OUTPUT 723;"WF1.1,12,1.2,0T"   !DSBL OUTPUT FALSE
1897   OUTPUT 723;"WF1.1,13,1.2,0T"   !ENBL EEN FALSE
1898   OUTPUT 723;"WF1.3,0T"          !RESET A/D MODE BITS
1899   OUTPUT 723;"WF1.1,2,1.2,1T"    !SET EXTERNAL TRIGGER
1900   OUTPUT 723;"WF1.1,1,1.2,0T"    !DISABLE INTERNAL TRIGGER
1901   OUTPUT 723;"WF1.1,3,1.2,0T"    !TRIGGER POLARITY SELECT INPUT DISABLED
1902   OUTPUT 723;"WF1.1,4,1.2,1T"    !EXT LOGIC SENSE ACTIVE HIGH
1903   OUTPUT 723;"WF1.1,5,1.2,1,T"   !EXTERNAL LOCKOUT-INPUT ENABLED
1904   OUTPUT 723;"WF1.1,7,1.2,0T"    !MULTIPLE EXTERNAL TRIGGER RESPONSE
1905   OUTPUT 723;"WF1.1,20,1.2,1T"   !PROGRAM GAIN X10(FOR LSB OF .0005)
1908   RETURN
1916 Purge: !
1920   FOR I=65 TO 66
1930     Lucky$=CHR$(I)
1940     PURGE Lucky$
1950   NEXT I
1960   FOR I=65 TO 66
1970     Lucky$=CHR$(I)
1980     CREATE BDAT Lucky$,8192,16
1981     ASSIGN @Path2 TO Lucky$
1982   NEXT I
1983   PRINT USING "///"
1985   PRINT "HAD TO PURGE AND CREATE BDAT FILES"
2000   RETURN
3000   END
```

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LIST OF REFERENCES

1. Vaughn, John K., *Measurement of Submicron AL₂O₃ Particles in Rocket Plumes*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1992, pp 1-34.

2. Few, J., Lewis, J., Hornkohl, J., *Optical Measurements of Turbine Engine Exhaust Particulates*, University of Tennessee Space Institute-Center for Laser Application, Report No. NAPC-PE-221C, July 1991, pp 1-8.

3. Few, J., Lewis, J., Hornkohl, J., *Optical Particle Sizing in the Exhaust of an AGT 1500 Combustor*, University of Tennessee Space Institute-Center for Laser Application, Report No. AC DIV-PE-235C, July 1992, pp 1-7.

4. Cashdollar, K., Lee, C., Singer, J., *Three-Wavelength Light Transmission Technique to Measure Smoke Particle Size and Distribution*, Applied Optics, Vol. 18, No. 11, June 1979, pp 1763-1769.

5. Kim, H., *Multiple-Wavelength Transmission Measurements in Rocket Motor Plumes*, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1991, pp 3-8,40.

6. Few, J., Hornkohl, J., *Measurement and Predication of Jet Engine Particulate Effluents*, University of Tennessee Space Institute-Center for Laser Application, Report No. NAPC-PE-195C, February 1990, pp 1-11, 17-20.

7. Oriel Corporation, *Light Sources, Monochronometers, Detection Systems*, Catalog, Vol. II, Statford, Connecticut, 1990, pp. 82-94.

8. EG & G Reticon, *Reticon Linear Diode Arrays*, Application Notes, No. 121, Sunnyvale, California.

9. Harris, R., *An Apparatus for Sizing Particulate Matter in Solid Rocket Motors*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1984, pp 40-41.

10. Hewlett-Packard Corporation, *Data Capture with the 6942A/6944A Multiprogrammers*, Application Note 316-5, December 1984.

11. Hewlett-Packard Corporation, *H-P 500 Kilohertz Analog-to-Digital Converter Card Model 69759A*, Operating Manual, June 1984, p 1-2.

12. Hewlett-Packard Corporation, *H-P High Speed Memory Card Model 69791A and Memory Expansion Card Model 69792*, Operating Manual, March 1984, pp 1-1,1-2.

13. Microsoft Corporation, *Microsoft Excel User's Guide 2*, Redmond, Washington, 1992, pp 41-45.

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