Measurement of Two-dimensional Concentration Fields of a Glycol-based Tracer Aerosol Using Laser Light Sheet Illumination and Microcomputer Video Image Acquisition and Processing

by

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Submitted to the Department of Architecture on 17 January, 1992
in partial fulfillment of the requirements for the degree
Master of Science in Building Technology

ABSTRACT

The use of a tracer aerosol with a bulk density close to that of air is a convenient way to
study the dispersal of pollutants in ambient room air flow. Conventional point
measurement techniques do not permit the rapid and accurate determination of the
concentration fields produced by the injection of such a tracer into a volume of air. An
instantaneous two dimensional distribution would aid in the characterization of flow and
diffusion processes in the volume studied, and permit verification of theoretical models.

A method is developed to measure such two dimensional concentration fields using a laser
light sheet to illuminate the plane of interest, which is captured and processed using
current microcomputer-based video image acquisition and analysis technology. Point
concentrations, determined optically using extinction of monochromatic illumination
projected through the aerosol onto a photo detector, are used to calibrate the captured
video images to determine actual concentration values. Accuracy, reproducibility, and
maximum rate of data acquisition are evaluated by means of theoretical models of
ambient air flow in a sealed box with point-injection of the tracer, and in a duct of
circular cross section with constant air velocity under both constant and pulsed injection
scenarios.

Thesis Supervisor: James W. Axley
Title: Associate Professor
This thesis is dedicated to the notion that reason and the scientific process are highly correlated to personal and interpersonal integrity and respect.

In deepest gratitude to my sister and parents for their continued support, encouragement, and love.

Special thanks to the following people:

The BT K-ε turbo party squad: Cruisin' Dave, Kurt, Arlene, and Cyane; and their respective spouses and significant others, and even Bernoulli.

My roomates Guy and Jamie.

And to Ron Jerit, no bag of hammers.
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii

ACKNOWLEDGEMENTS .............................................................................................. iii

## 1 OVERVIEW

1.1 OBJECTIVE ...................................................................................................... 1
1.2 SCOPE .................................................................................................................. 1
1.3 MEASUREMENT METHOD
   APPARATUS ............................................................................................................ 2
   TEST PROCEDURE .................................................................................................... 2
1.4 RESULTS ............................................................................................................... 3

## 2 INTRODUCTION

2.1 DEFICIENCIES OF PRESENT METHODS
   Invasiveness ............................................................................................................. 4
   Poor Spatial and Temporal Resolution ................................................................ 4
   Complexity and Expense ....................................................................................... 4
   Need for Field Measurement ................................................................................. 4
2.2 STRATEGY ............................................................................................................. 5
2.3 BASIC AEROSOL SCIENCE
   CLASSIFICATION .................................................................................................... 6
   PHYSICAL PROPERTIES
     Size Distribution .................................................................................................. 6
     Shape ..................................................................................................................... 7
     Concentration ....................................................................................................... 7
   TRANSPORT PROPERTIES
     Convection ............................................................................................................ 8
     Diffusion ............................................................................................................... 8
     Settling .................................................................................................................. 8
   AGGLOMERATION AND SURFACE EFFECTS
     Agglomeration ..................................................................................................... 8
     Surface Effects ..................................................................................................... 9
   OPTICAL PROPERTIES
     Rayleigh and large particle extinction ................................................................ 10
     Mie theory .............................................................................................................. 10
2.4 AEROSOL SELECTION CRITERIA .......................................................................... 10

## 3 BACKGROUND .................................................................................................... 12

3.1 TRACER AEROSOL
   CANDIDATE TRACERS ............................................................................................ 12
   SELECTED TRACER ................................................................................................. 12
3.2 DEVELOPMENT OF CONCENTRATION RELATION
   INTRODUCTION ........................................................................................................ 14
1 OVERVIEW

1.1 OBJECTIVE

The dispersal of airborne contaminants within enclosed environments such as vehicles, buildings, laboratories, etc. has become the focus of increasing attention in the building technology community. Improved knowledge of the subject has potential application to the improvement of building air quality and HVAC ventilation effectiveness.

Ideally, the quality of air within enclosed environments should be evaluated in terms of distribution of contaminant concentration, both instantaneous and over time, within the environment. Air quality requirements may be thus tailored to include contaminant concentration and distribution rather than the relatively crude criteria in use today, such as rate of air exchange, allowing more precise and efficient allocation of energy and material resources to meet those requirements. In addition, improvements in developing and measuring minimum contaminant environments, such as clean rooms, become possible if more comprehensive measurements of contaminant concentration distribution can be produced and evaluated.

Current technologies for measuring airborne contaminant dispersal in rooms, based on point sampling methods, have several inherent disadvantages, including the invasive nature of the procedures used, poor spatial and temporal resolution of measured results, and complexity and expense of their use.

The objective of the work presented in this thesis is to examine the use of low power laser light sheet illumination and video image processing to address the above issues. Similar techniques have recently been used successfully for various flow visualization studies [6, 14]. This approach indicates the use of aerosols as surrogate tracers for molecular and very small particulate contaminant species, since the threshold for detection of scattered light is within the range accessible by common video and laser illumination systems. Aerosol systems clearly approximate the behavior of the gaseous medium in which the particles are suspended, although to what extent remains a relevant subject for detailed investigation.

In the study of airborne contaminant dispersal, relevant areas of knowledge include aerosol science, small particle statistics, fluid dynamics, and optics. The detailed characteristics of air, and the aerosol systems of contaminants and tracers introduced to approximate the behavior of contaminants for measurement and study, are major areas of concern. The detection and quantitative measurement of a tracer aerosol proves to be nontrivial and optical techniques provide useful methods in both microscopic and macroscopic domains. The relation of measured to desired parameters, and evaluation of the efficacy of a particular approach in terms of repeatability of measurements and accuracy
vis a vis theoretically predicted solutions, is the final step in producing potentially useful results for further study and potential application to real-world systems.

1.2 SCOPE

The scope of the project includes the selection of tracer aerosol, development of generation and injection apparatus and techniques; implementation of laser light sheet and video image acquisition and analysis techniques; selection/development of a reference measure of tracer aerosol concentration; development of calibration procedure to relate the acquired lab data to the standard concentration values based on theory; and evaluation of accuracy and repeatability of the method. Tests are performed in a compartment under well-mixed, no-flow conditions to establish reference concentration. Continuous and pulsed injection tests are performed in a duct of circular cross section under steady flow conditions to evaluate the method by comparing experimental results with predictions based on convection/diffusion theory.

1.3 MEASUREMENT METHOD

The main purpose of using tracer materials to measure flows is the convenience with which they may be detected relative to the actual contaminant species. A number of different tracer visualization techniques exist [12], but the most straightforward approach to the study of building air flows is optical scattering. Scattering is highly dependent on particle size, with the highest scattering efficiency at particle sizes between 1 and 10 microns [17]. Illumination of a tracer aerosol sample may be likewise accomplished by various means, a laser source being chosen for the present work (see 4.3). The method is designed to provide a path to full-scale field measurements in that the equipment used is largely standard, operates on the commonly available 120 volts, and requires no special laboratory infrastructure (e.g. liquid coolant or special ventilation).

APPARATUS

An apparatus is developed to investigate contaminant dispersal fields of a tracer aerosol in two dimensions. A dynamic laser light sheet produced using an oscillating mirror is used in conjunction with a CCD video camera, microcomputer image acquisition hardware (a frame grabber board), and image processing software. A relation is developed to link the acquired video data to quantitative measures of tracer concentration by studying uniformly distributed dispersal fields in an enclosed volume under stagnant flow conditions. See 4, EQUIPMENT.

TEST PROCEDURE

The procedure for obtaining data relevant to the objective of correlating concentration to video pixel value involves the following:

- Generation and injection of tracer and establishment of the flow regime to be measured
- Illumination of the sample field
• Acquisition of video data
• Digitization of the image
• Image processing
• Analysis of results

Each of these will be discussed in detail in subsequent sections on equipment and the actual tests performed. This procedure was applied to each of the three test scenarios.

1.4 RESULTS

The use of tracer aerosols to simulate molecular and very small particulate contaminants is evaluated relative to the behavior of the studied tracer as well as inherent properties of aerosol systems. Frame capture rate and spatial resolution are far superior to current point sampling techniques, and the resolution of illumination values within the boundaries imposed by clipping is artificially limited in this work only by image acquisition hardware and software selected for the work. Absolute concentration values are measured optically and related to captured video data for a sealed compartment, and relative values are obtained for pulsed injection duct tests. The limits under which absolute and relative relations can be established between concentration field and corresponding video frame data are articulated.

The inherent time-dependence of any aerosol size distribution function, and issues of Schmidt number (a measure of the relative importance of particle diffusivity to eddy diffusivity) similitude lead to limitations in the efficacy of the surrogate tracer approach. In particular, a unique relation of number concentration to scattered illuminance (video pixel value) is not possible due to the time dependence of the aerosol system, and violation of Schmidt similitude criterion limits the conditions under which tracer aerosols are useful in simulating the behavior of molecular and very small particle contaminants.

In addition, accurate reference concentration measurements of the tracer aerosol pose theoretical and practical difficulties; and the generation, transport control, and disposal of the tracer aerosol pose significant challenges vis a vis hardware required to support these functions.

The practical limitations of the apparatus are evaluated. The dynamic range of sensitivity bounded by clipping in the captured images due to over-illumination saturation and under-illumination signal-to-noise ratio covers a relatively small portion of the concentration range indicated by extinction measurements taken simultaneously with the video data acquisition and by visual inspection. This may be improved by the use of more advanced CCD technology currently available, and technology not yet available will continue this trend. The quantity of illumination available for scattering and video acquisition is limited by power requirements of the laser, leading to an available viewing field on the order of less than a meter. This limitation is inherent in laser systems, but alternate forms of illumination schemes have the potential to overcome this.
INTRODUCTION

2.1 DEFICIENCIES OF PRESENT METHODS

Well developed technologies for measuring point concentration (e.g. gas chromatographers with infrared detectors, particle counting samplers) are often used to determine contaminant concentration in situations where the spatial and temporal variation of concentration are not significant factors. These devices sample a very small volume compared to scales of interest in building technology, and register the presence of particles over periods of time long compared to the time scale of some typical building flow variations. The need to measure distributed concentration fields instantaneously compared to scale parameters relevant to room air distribution studies represents a new use for which these devices were not intended and are not well suited. Some of their limitations are discussed below.

Invasiveness - Point sampling methods require the installation of collection devices at each point within a room where a measurement is desired. This is normally achieved by using either local grab-sampling pumps or syringes or a network of tubing routed to a central pump and valve control unit. The physical presence of these sampling devices may alter the airflow distribution and thereby alter the contaminant dispersal patterns being measured within a room. These devices and the associated instrumentation may also compromise movement of personnel and furnishing of the rooms being studied and, thereby, limit the study of dispersal within the space.

Poor Spatial and Temporal Resolution - To accurately characterize the dispersal of contaminant within a room using a point-sampling approach, multiple samplers must be deployed and simultaneously sampled. This presents significant data acquisition difficulties. Typically twelve or fewer sampling devices have been used and, due to instrumental limitations, sampled at approximately one-minute intervals. Thus, point sampling techniques provide only a crude approximation of spatial distribution and are practically limited to the study of stationary dispersal fields.

Complexity and Expense - The complexity of instrumentation increases with the number of samplers, because each sampler typically requires a separate input channel. The relatively large number of point measurements required for an adequate description of a two dimensional dispersal field, and the associated data acquisition hardware and computer provisions, is prohibitive. In addition, the invasiveness problem is exacerbated as the quantity of samplers is increased.

Need for Field Measurement - It is useful to be able to quickly measure concentration distributions in the field. Point measurement techniques are seldom used in the field due to their inherent complexity, lack of resolution, and cost.
2.2 STRATEGY

Figure 1 Schematic diagram of project strategy

Figure 1 shows a schematic view of the present work, where the arrows indicate functional dependencies of the elements of the project. In the first phase of work, each of the elements was identified, and implementation of the critical path elements and dependencies was established through assembly and testing of lab apparatus under the most controlled conditions, a sealed volume with no flow. Candidate tracer substances were evaluated and an aerosol material and generation scheme were selected. Parameters affecting the selection of laser light sheet generation components were evaluated, including laser power, mode, wavelength, and control, and components were selected; galvanometer frequency, input signal generation, and amplification; desired sheet geometry and constraints affecting the ability to implement these.

Following phases further advanced the state of the work by testing two scenarios of progressively higher complexity, namely a straight circular duct with constant air velocity under continuous, and then pulsed, injection of tracer aerosol. Results from these tests were compared to predictions from convection-diffusion theory.
2.3 BASIC AEROSOL SCIENCE

Many parameters have been developed to characterize aerosols, in the general categories of physical, transport, optical, and time-dependent properties. Those relevant to the present work include the single parameter particle size, the size distribution function, shape, state, and refractive index of transparent translucent material. Characterization of inherently time-dependent properties of aerosol systems is described by several parameters.

CLASSIFICATION

Aerosols may be divided into categories based on their process of creation, condensation versus dispersion, and again by the state of the particles, solid versus liquid. Condensation aerosols are formed from supersaturated vapors or non-volatile reaction products, while dispersion aerosols are formed by grinding or atomization [11]. The terminology used to describe aerosols is not standardized; several names are available for various kinds of aerosol systems, generally indicating particle size range or state, concentration, and/or macroscopic scale of the system. Table I below is based on terminology proposed by Fuchs [11].

PHYSICAL PROPERTIES

Table I Typical classification of aerosols

<table>
<thead>
<tr>
<th>Process \ Phase→</th>
<th>Solid</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation</td>
<td>smoke</td>
<td>mist,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fog</td>
</tr>
<tr>
<td>Dispersion</td>
<td>dust</td>
<td>mist</td>
</tr>
</tbody>
</table>

Particle size - The absolute size of the suspended particles determines to a large extent the transport and optical properties of an aerosol system. Polydisperse aerosols have a wide range of particle sizes, while monodisperse aerosols are more amenable to single size characterization. If at least 90% of the particles fall within a range of 1μm, the system is typically considered monodisperse [11]. The optical particle size parameter, \( x = \frac{\pi d_p}{\lambda} \), where \( d_p \) is the diameter of a spherical particle and \( \lambda \) is the wavelength of the illumination used to measure the particle, is useful in the development of the theory as a dimensionless representation of the size of a single spherical particle. Other parameters, such as the volume or mass of a particle, are sometimes used to describe its size. Solid particles, especially those created by dispersive processes, often require more complex notions of single parameter size characterization due to their irregular shapes.

Size Distribution - The primary characteristic of a polydisperse aerosol system is its size distribution function defined by:

\[
dN = n(d_p, \lambda) d(d_p)
\]  

(1)
where $d\mathbf{N}$ is the number concentration (i.e. number of particles per unit aerosol volume) of spherical particles in the size range $d_p$ to $d_p + d(d_p)$. $n_p(d_p)$ is the particle size distribution function, $d_p$ is particle diameter, and $r$ and $t$ are respectively the location and time coordinates at which the function is to be defined [10]. It is useful to consider this as a continuous function for purposes of theoretical development. For example, various moments of the distribution function have physical significance, corresponding to number concentration, number average particle diameter, surface area, etc. [10]. However, in the laboratory, the size distribution function must be considered as a discrete function due to the practical limits of measurement equipment. The measured size distribution is of necessity limited in resolution of particle size values for dimensions of concern in the study of aerosols which has significant relevance to the interpretation of measured data from bulk aerosol samples, e.g. extinction efficiency.

A discrete particle size distribution function, $n_d(d)$, may be defined in an analogous manner by breaking the total range of particle sizes present into a series of $i$ sub-ranges defined by upper and lower bounds $d_{i,lower}$ and $d_{i,upper}$. Each value of the discrete distribution is then defined as the ratio of the number of particles per unit volume of aerosol that fall within the $i$th sub-range and $d_i$ is taken, by convention, to be the geometric mean of the limits of the size range:

$$d_i = \frac{1}{\left(\frac{1}{d_{lower}} + \frac{1}{d_{upper}}\right)}$$

Shape - Small liquid phase particles tend to be spherical in shape, and agglomerate into larger spheres. Solid phase particles may have arbitrary shape, are often oblong or irregular, and often contain voids or interstices between formerly separate particles.

Concentration - Typical measures include number concentration, volume concentration, and mass concentration. In the case of mists (liquid particles) the latter two are equivalent, assuming constant mass density of the material, because particle shape can be assumed to be spherical with no internal voids. Number concentration is defined as follows: if $\delta N$ is the number of particles in a volume $\delta V$ surrounding the point at which concentration is to be defined, $\delta N/\delta V$ is called the average concentration of particles within the volume $\delta V$. Definitions of mass and volume concentrations follow similar lines. The notion of concentration is meaningful within a volume range limited on the low end where the number of particles is statistically relevant, and on the high end where the concentration gradient within the volume is negligible.
TRANSPORT PROPERTIES

The motion of particles suspended within a gaseous medium can be characterized as either dispersive or convective. The predominance of one or the other (or neither) of these mechanisms in a given flow regime is dependent on the fluid properties and aerosol properties of the specific flow regime under study. It is indicated by the Peclét Number $Pe=LU/D$ where $L$ is a characteristic length, $U$ is the characteristic velocity of the fluid, and $D$ is the dispersal coefficient.

Convection - Transport of an aerosol due to bulk motion of the gaseous medium, i.e. in a non-stagnant flow field, is referred to as convective transport. This mode of transport dominates in steady or unsteady laminar or turbulent flow regimes.

Diffusion - Brownian motion of aerosol particles will tend to reduce the gradient of the number concentration within a study volume. This dominant transport mode in a stagnant flow field (no flow) is termed particle diffusion, $D$. In practice, however, it is nearly impossible to produce a truly stagnant flow field because very small thermal gradients will induce small scale convective turbulence. Small scale turbulence induced either by buoyant or viscous shear forces effectively disperses particles and is referred to as eddy diffusion.

Settling - The diffusive forces in air, i.e. from Brownian collisions, will counteract gravitational settling forces for particles smaller than approximately 10μm in diameter [11]. That is, smaller particles will remain in suspension, and larger particles will fall due to gravity. Settling of larger particles is dependent on the size of the particles. Table II [10] shows the Stokes settling velocity $c_s$ as well as other transport properties of aerosols of various values of $d_p$. $v$ represents the kinematic viscosity of air and $\rho_p$ the mass density of particle substance.

AGGLOMERATION AND SURFACE EFFECTS

Agglomeration - By nature, the number concentration of aerosol particulates in a given sample changes over time. The inherent convective and diffusive motion of such particles leads to collisions between aerosol particles, which then combine to form larger particles. The local transport mechanisms that induce these collisions are particle diffusion due to Brownian motion, differential settling, eddy diffusion, Coulomb forces, and possibly interparticle van der Waals forces.

Each of these mechanisms affects the collision frequency, which is expressed by $\beta N_p^2$, where $\beta$ is called the collision frequency function, and is a function of the

---

1 A temperature gradient $\Delta T=0.01^\circ$K in a chamber with characteristic size 1m will induce a convective flow velocity of 1cm/sec, which is the (gravitational) settling rate for particles of $d_p=10\mu$m [11].

2 There are certain self-preserving size distributions [10].
above factors as well as the sizes of the colliding particles, and \( N_i \) and \( N_j \) are number concentrations of particles of sizes \( i \) and \( j \) respectively. Table III [10] shows the time required to reduce the concentration of a monodisperse aerosol to 1/10th the original value (\( N_0 \)).

Surface Effects - The collision of aerosol particles with vessel walls and other obstructions, e.g. diagnostic devices, and their subsequent elimination from suspension, can be a significant factor affecting the concentration of a sample. The mechanisms producing this are particle and eddy diffusion for the case of turbulent flow in a duct. From boundary layer theory for uncharged particles, the deposition rate can be shown to depend on

- The area available for mass transport
- The characteristics of the fluid and flow regime, e.g. Reynolds number
- The relative importance of particle versus eddy diffusion, indicated by the Schmidt number \( \nu/\mathcal{D} \).

Surface deposition is not expected to be significant for the flow regime used in the duct tests because of the favorable volume/surface ratio.

### OPTICAL PROPERTIES

Loss of illuminance transmitted through an aerosol sample is defined as extinction. The two components of extinction are scattering, the retransmission of light incident onto a particle in another direction; and absorption, the conversion of incident illumination to other forms of energy such as heat or mechanical motion. Each of these components is represented by an efficiency factor \( K \), and the total extinction efficiency is defined as \( K_{\text{ext}} = K_{\text{scat}} + K_{\text{abs}} \), where \( K_{\text{scat}} \) and \( K_{\text{abs}} \) are the scattering and absorption efficiency factors, respectively. The extinction properties

### Table II  Aerosol transport properties

<table>
<thead>
<tr>
<th>( d_p ) (( \mu m ))</th>
<th>( \mathcal{D} ) (cm(^2)/sec)</th>
<th>Schmidt No. ( \nu/\mathcal{D} )</th>
<th>( c_s ) (cm/sec) (( \rho_p=1\text{g/cm}^3 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>.01</td>
<td>( 5.24 \times 10^{-4} )</td>
<td>( 2.87 \times 10^{2} )</td>
<td></td>
</tr>
<tr>
<td>.02</td>
<td>( 1.34 \times 10^{-4} )</td>
<td>( 1.12 \times 10^{3} )</td>
<td>( 1.61 \times 10^{2} )</td>
</tr>
<tr>
<td>.05</td>
<td>( 2.35 \times 10^{-5} )</td>
<td>( 6.39 \times 10^{3} )</td>
<td>( 2.50 \times 10^{2} )</td>
</tr>
<tr>
<td>.1</td>
<td>( 6.75 \times 10^{-6} )</td>
<td>( 2.22 \times 10^{4} )</td>
<td>( 8.62 \times 10^{2} )</td>
</tr>
<tr>
<td>.2</td>
<td>( 2.22 \times 10^{-6} )</td>
<td>( 6.76 \times 10^{4} )</td>
<td>( 2.26 \times 10^{2} )</td>
</tr>
<tr>
<td>.5</td>
<td>( 6.32 \times 10^{-7} )</td>
<td>( 2.32 \times 10^{5} )</td>
<td>( 1.00 \times 10^{3} )</td>
</tr>
<tr>
<td>1.0</td>
<td>( 2.77 \times 10^{-7} )</td>
<td>( 5.42 \times 10^{5} )</td>
<td>( 3.52 \times 10^{3} )</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td></td>
<td>( 1.31 \times 10^{2} )</td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td></td>
<td>( 7.80 \times 10^{2} )</td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td></td>
<td>( 3.07 \times 10^{1} )</td>
</tr>
<tr>
<td>20.0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>50.0</td>
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<td></td>
<td>7.58</td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
<td>30.30</td>
</tr>
</tbody>
</table>
of aerosol systems are based on conventional optics and physics, and depend on refractive index $m$ (for particles made of clear liquids), particle size, wavelength of incident illumination, and the absorption properties of the material of the suspended particles. The tracer aerosol relevant to this work, a clear liquid, is believed to have a negligible absorption, and $K_{\text{abs}}$ is taken as equivalent to $K_{\text{ext}}$.

Rayleigh and large particle extinction - The extinction properties of aerosol systems are derived from the optical properties of the constituent particles, which are highly dependent on their general size range. The domain where particle size is small compared to the wavelength of incident radiation (i.e. $x=\pi d_p/\lambda >> 1.0$) is described by Rayleigh theory. On the other end of the size spectrum, geometric optics applies where it is relevant to think in terms of a ray whose width is large compared to its wavelength and yet small compared to the size of the particles in question. This applies to particles greater in size than approximately 50 times the wavelength of the radiation.

Mie theory - Many aerosols, including the tracer aerosol used in the present work, lie between the particle sizes described above, thus those theories are not applicable. Mie Theory treats the scattering of light by single homogeneous spherical particles of arbitrary size and refractive index. It presents a solution of the Maxwell equations with the appropriate boundary conditions. More detail is presented below in 3.2.

### 2.4 AEROSOL SELECTION CRITERIA

Optimal characteristics for a tracer aerosol to be most useful in measuring two-dimensional concentration distributions include strong light scattering. In addition, the chosen tracer should closely follow the flow regime being studied if the aerosol is used to simulate molecular or very small particle dispersal. Both of these are dependent primarily on the size of the particles involved; in general, smaller particles will follow the flow better since they are less susceptible to settling and to lateral accelerations due to strong velocity gradients in the flow field, and larger particles would appear to be favorable from a scattering point of view simply because of the larger projected area from which to scatter light (although for $d_p$ greater than the sheet thickness scattered illuminance is reduced, requiring increased sheet thickness (and laser power) to achieve similar scattered illuminance). In the size range where particles remain suspended in air there is an optimal size range for light scattering, based on Mie theory, of $x=3$ where $x$ is

<table>
<thead>
<tr>
<th>$N_0$ (cm$^{-3}$)</th>
<th>$t_{1/10}$ (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}$</td>
<td>1.2 sec.</td>
</tr>
<tr>
<td>$10^9$</td>
<td>12 sec.</td>
</tr>
<tr>
<td>$10^8$</td>
<td>2 min.</td>
</tr>
<tr>
<td>$10^7$</td>
<td>20 min.</td>
</tr>
<tr>
<td>$10^6$</td>
<td>3.5 hr.</td>
</tr>
<tr>
<td>$10^5$</td>
<td>35 hr.</td>
</tr>
</tbody>
</table>
the size parameter described above (see Figure 4). The aerosol must be stable, i.e. remain in suspension and visible, long enough to accommodate the time scale of the flow regimes being considered. In addition the aerosol must be serviceable in a laboratory environment, and potentially in the field as well. This means primarily that it must be non-toxic to personnel, and the environment; non-staining and easily cleaned from surfaces after deposition; inoffensive; etc. In addition, the expense and availability of the material, and the practicalities of generation and bulk sample control of an aerosol from the material are considerations.
3 BACKGROUND

3.1 TRACER AEROSOL

CANDIDATE TRACERS

A number of candidate tracers was evaluated for potential use in the present work. These included helium-filled bubbles both with and without fluorescent dyes (fluorescein or rhodamine 6G) added to enhance visibility, lycopodium spores, and 1μm silicon spheres.

Early investigations were conducted using neutrally buoyant helium-filled soap bubbles produced by a Sage Action bubble generator [see appendix]. The bubbles are approximately 3.18mm in diameter. The bubble solution is non-toxic, non-corrosive, and safe. Little residue is left behind. The relatively large size of these bubbles makes them an attractive tracer candidate. They are large enough that individual particles in the concentration field can be identified and counted using the image acquisition system. This property virtually eliminates the problems of correlating light scattering theory to concentration measurements. Helium bubbles are commonly used in flow visualization studies. They are robust enough to survive propellers and fans, indicating that sample control and injection is feasible. However, their typical lifetime of two minutes before bursting is much shorter than the time required for evaluation of room contaminant dispersal, and their large size discounts their value as a surrogate tracer to simulate molecular and very small particulate contaminants. In addition, greater laser illumination is required to achieve detection by the image acquisition equipment, since a laser sheet thickness greater than the diameter of the bubbles, with no loss of illuminance, is required to produce a detectable level of scattering.

The fluorescent dyes were rejected due to safety and serviceability considerations, as they are listed as possible carcinogens [16] and generally known to leave staining residues.

Solid particles were rejected for this work due to the difficulty in generating and injecting solid phase aerosols. In addition, lycopodium is highly flammable, and its irregular particle shape poses theoretical difficulties in determining the size distribution function concentration values of aerosol samples produced from the material.

SELECTED TRACER

The aerosol used in all tests reported in this thesis was produced with a Rosco 1500 Fog Machine, manufactured for theatrical use [see appendix]. A proprietary mixture of low molecular weight glycols is pumped into the machine and heated to its vaporization point. The vapor is then released into the air where it condenses to produce an aerosol. The "fog" produced is non-toxic, non-corrosive, and leaves little residue on surfaces.
The refractive index of the glycol mixture was measured before its use in the aerosol generator, and the refractive index of fluid condensed from aerosol generated by the machine was also measured. The static index of refraction of the unprocessed solution was 1.413 and that of the condensed solution is 1.407. A refractive index of 1.41 is used for all light scattering calculations in this report. The specific gravity of the solution is 1.12 [see appendix], and the liquid solution and condensate are miscible in water.

The size distribution of the aerosol was measured using a Malvern Microsizer particle sizer [see appendix]. This machine projects a collimated laser beam through an aerosol sample, which is scattered by particles within the aerosol sample through a lens and to a photoreceptor matrix. The device calculates a particle size distribution based on Mie theory. Results are shown in Figure 2.

![Tracer Aerosol Size Distribution](image)

Figure 2 Size distributions of the tracer aerosol; the data series represent the same sample at progressive time intervals.

A plot of the measured volumetric mean diameter of the tracer aerosol against time (Figure 3) reveals a steady increase in the particle diameter over the test interval. This corresponds to the continual agglomeration of aerosol particles. The figure indicates, extrapolating a linear increase in the particle diameter of the
volumetric mean particle size with time, that the volumetric mean diameter will reach 10\(\mu m\) at a time of approximately 30 minutes. The linear extrapolation of this curve represents a conservative (low) estimate of the length of time before settling becomes significant because continual particle agglomeration leads to fewer suspended particles, hence slower agglomeration (see Table III).

![Tracer Aerosol Size](image)

**Figure 3** Plot of mean particle diameter vs. time for the same tracer data shown in Figure 2

3.2 **DEVELOPMENT OF CONCENTRATION RELATION**

**INTRODUCTION**

The determination of a two-dimensional concentration field requires a calibration of concentration value in an observed flow field to the measured illuminance of incident light scattered from all points. In addition, temporal and spatial resolution of the measurements must be indicated for a complete description of the concentration field.

A point concentration measurement method was developed using measured optical extinction and Mie theory. The scattered illuminance determines the pixel value reported by the video acquisition hardware at pixel location corresponding the observed point in the flow field. This pixel value is used as the required measure of scattered light, which must be uniquely related to a value of aerosol concentration to establish the desired correspondence. Normalization is required to remove systemic error in the pixel values due to various sources (see 3.3, NORMALIZATION).

Simultaneous measurement of sample concentration and video image acquisition is intended to provide the data required to establish the desired correspondence of pixel value to sample concentration. In addition, effects of the time dependent nature of both size distribution function and concentration of the aerosol sample should be embedded in the method if a useful correspondence is to be established.
DEVELOPMENT

Mie theory may be used to establish a relation between number, mass, or volumetric concentration of an aerosol with a measured extinction coefficient, which is related to extinction efficiency.

The extinction coefficient, \( \gamma \), is defined as the fraction of incident illuminance, \( I \), scattered and/or absorbed within a medium per unit optical path length \( z \):

\[
\gamma = -\frac{dI}{Idz} \quad (3)
\]

Integrating this over a given path length \( <z_1, z_2> \), called the optical path length, gives the reduction in intensity of light passing through an aerosol (Lambert's Law):

\[
I_2 = I_1 e^{-\int \gamma dz} \quad (4)
\]

The integral \( \int \gamma dz \) over the optical path length is referred to as the optical thickness of the aerosol and is given the symbol \( \tau \). If \( \gamma \) remains constant over the path of integration \( \Delta z = z_2 - z_1 \), i.e. if the extinction coefficient remains constant through the portion of the aerosol being measured, then:

\[
I_2 = I_1 e^{-\gamma \Delta z} \quad (5)
\]

and the optical thickness becomes \( \tau = \gamma \Delta z \). Thus the extinction coefficient may be determined photometrically by measuring the relative loss of light intensity:

\[
\gamma = \frac{\ln \left(\frac{I_1}{I_2}\right)}{\Delta z} \quad (6)
\]

The extinction efficiency, \( K_{ext} \), is defined as the ratio of light energy lost along the optical path (due to scattering and/or absorption) to the light energy intercepted by a particle, \( I(\pi d_i^2/4) \). For an aerosol cloud with a discrete distribution of particle sizes, \( n_i \), the attenuation of light, \( dI \), over an infinitesimal optical path length \( dz \) is related to the corresponding discrete distribution of extinction efficiency of the particles as:

\[\text{Also referred to as the attenuation coefficient or turbidity.}\]
\[
dl = - \left( \sum_i \frac{\pi d_i^2}{4} \frac{\kappa_{\text{ext}} n_i}{\lambda} \right) \frac{d\lambda}{d\zeta}
\]

where \( n_i \) is the number of particles of (geometric mean) diameter \( d_i \) per unit volume. The approximation is due to the use of discrete particle size distributions. The extinction coefficient is thus related to these discrete distributions as:

\[
\gamma = -\frac{dl}{d\zeta} = \left( \sum_i \frac{\pi d_i^2}{4} \frac{\kappa_{\text{ext}} n_i}{\lambda} \right)
\]

If the distribution of particles is described in terms of the relative number distribution \( N_i = \frac{n_i}{N} \), where \( N \) is the total number of particles per unit volume, it follows that:

\[
\gamma = n_N \left( \sum_i \frac{\pi d_i^2}{4} \frac{\kappa_{\text{ext}} n_i}{\lambda} \right)
\]

Alternatively, the distribution may be described in terms of a relative volumetric distribution \( V_i \), the volume of particles of size \( d_i \) per total volume of particles, \( V \), per unit volume of aerosol. Then, the extinction coefficient can be described for spherical particles as:

\[
\gamma = V \left( \sum_i \frac{\pi d_i^2}{4} \frac{\kappa_{\text{ext}} V_i}{\pi d_i^3} \right) = V \left( \sum_i \frac{3}{2} \frac{\kappa_{\text{ext}} V_i}{\pi d_i^3} \right)
\]

For an aerosol with particles of constant mass density, \( \rho \):

\[
\gamma = \frac{C}{\rho} \left( \sum_i \frac{3}{2} \frac{\kappa_{\text{ext}} V_i}{\pi d_i^3} \right)
\]

where \( C = \rho V \) is the total mass concentration of particles.

From the Mie Theory of scattering, the extinction efficiency of non-absorbing spheres for single, independent scattering is very closely approximated by [17]:

\[
\gamma = \frac{C}{\rho} \left( \sum_i \frac{3}{2} \frac{\kappa_{\text{ext}} V_i}{\pi d_i^3} \right)
\]
\[ K_{\text{ext}} = 2 - \frac{4}{\phi} \sin \phi + \frac{4}{\phi^2} (1 - \cos \phi) \]  

(12)

where

\[ \phi = 2 \frac{\pi d}{\lambda} (m-1) \]  

(13)

in which \( m \) is the index of refraction and \( \lambda \) the wavelength of the incident light\(^4\).

The single scattering criterion is met when the distance between particles is much greater than their dimension, so that light is scattered at most once before impinging on the photosensor. Single scattering is unambiguously indicated when the measured optical thickness \( t \leq 0.1 \); when \( 0.1 < t < 0.3 \), compensation for multiple scattering may be necessary [17, 10].

Figure 4 shows the form of \( K_{\text{ext}} \) as a function of particle diameter \( d_p \) for the tracer aerosol and illumination wavelength used in the present work. The form of this curve is similar for the range \( 1 < m < 2 \) under visible light, asymptotically approaching \( K_{\text{ext}} = 2 \) as particle size becomes large relative to the wavelength of incident light. This is the double extinction paradox, that a particle removes an amount of light from an incident beam corresponding to twice the area of the particle. The paradox can be explained by noting that diffraction accounts for the additional extinction [10].

From equation (10), volumetric concentration can be related as:

\[
V_{\text{sr}} = \frac{\gamma}{\left( \sum_{i} \frac{3}{2} K_{\text{ext}} \frac{V_i}{d_i} \right)} ; \quad \gamma \Delta z < 0.3
\]

(14)

where the limitation on optical thickness has been included as a reminder that single independent scattering is required for validity. The denominator of equation (14) is found by laboratory measurements using either the exact relation for extinction efficiency \( K_{\text{ext}} \), equation (12), or the approximation \( K_{\text{ext}} = 2 \). The introduction of error, by using the discrete size distribution function obtained in the lab to represent the actual continuous size distribution function, suggests the possibility that the use of the approximate relation may yield a more accurate calculated concentration value than the discrete formula.

\(^4\) van de Hulst uses the slightly different notation \( x = 2 \pi a / \lambda \), where \( a \) represents the particle radius.
Extinction Efficiency
For Selected Tracer

Relative volumetric size distributions of the tracer aerosol used in the studies are shown in Figure 2. The optical thickness of the test sample used to determine this distribution was greater than required for theoretical compliance with the single scattering criterion. Laboratory data, however, indicates that $K_{ext}$ is not highly sensitive to optical thickness (see Figure 3, Figure 13 in 5.1).

The denominator of the expression for $V$ in equation (14), which may be viewed as the total extinction per unit sample volume, was calculated using both the exact and approximate relations for extinction efficiency $K_{ext}$ using the measured size distribution data, and the results are shown in Figure 5. It appears that the total extinction per unit sample volume stabilizes at a value of approximately 1.75$\mu$m$^{-1}$ after the initial period of rapid agglomeration indicated in Figure 2, and before a significant fraction of the particles grow to have a mean diameter of 10$\mu$m, at which point settling may become significant [11]. This indicates that within those time boundaries, a constant volume of material is suspended in the aerosol state, but with a steady decrease in the number concentration of particles.
The value of this function is seen to be insensitive to illumination wavelengths in the visible range, typical indices of refraction, and to the expected range of extinction efficiency indicated by Figure 4. The latter is evident because at $d_p = 34\mu m$ (corresponding to the smallest available value, early in the time series) $K_{ext} = 0.86$. The form of the corresponding curve is similar to the curve for the approximation $K_{ext} = 2$. The value

$$V = \frac{\gamma}{1.75\mu m^{-1}}$$

(15)

correlates strongly to the variation of $V/d$, which is relatively much greater than the variation in the other relevant parameters.

Figure 3 indicates, extrapolating a linear increase in the particle diameter of the volumetric mean particle size with time, that the volumetric mean diameter will reach 10μm at a time of approximately 30 minutes. Thus, as a conservative estimate, equation (15) may be considered useful only between approximately 10 and 30 minutes from the generation of the tracer aerosol.

3.3 IMAGE PROCESSING

Image processing techniques were employed for the purposes of error correction in captured video data (normalization to correct for systemic error, and application of convolutions to mitigate random error); verification of the uniformity of the concentration field in the sealed compartment tests (statistical analysis of pixel data); and to develop the final values to be related to actual concentration values measured by extinction. Normalization and convolution produce data sets of the

---

5 The variation of the absolute size distribution function with time is dependent on the initial concentration of the aerosol test sample. Initial concentrations used for subsequent tests in this report were similar to the initial concentration used here to measure the size distribution of the tracer aerosol.
same form as the raw pixel values, while subsequent analysis operates on the normalized data to derive information in forms that clarify and add meaning, and make manageable the development and presentation of the desired correspondence to the measured concentration data. This analysis takes the forms of statistical operations performed on individual frames, e.g. determination of mean pixel value, standard deviation, and distribution histogram over a captured view; and the comparison of these properties across a related set of captured frames, e.g. a time series of frames captured to record the evolution of an injected pulse of tracer aerosol. The specific operations performed subsequent to normalization are determined by the goals of the analysis.

ERROR CORRECTION

Test data frames were first convolved to reduce the effects of random error, and then normalized to correct for systemic error. shows histograms for an example frame taken during a sealed compartment test. Each of the error correction processes was applied independently to the raw data. The resulting histograms indicate that random noise may be a more significant cause of pixel value error, since correcting for it via convolution results in a greater modification to the original frame data than normalization.

NORMALIZATION

"Raw" captured video data are normalized in order to correct for error introduced from the following sources:

- Uneven illuminance across the laser sheet due primarily to sinusoidal variation in scanner (and thus beam) velocity
- Uneven CCD pixel response, i.e. inherent difference in output from different individual CCD elements from the same incident illuminance
- Obstructions between the sheet and the camera, e.g. dust on the optical window or camera lens
- External interference introduced into the signal enroute from the CCD camera to the frame grabber board
- Optical aberration/loss
- Stray light
- Analog-to-digital conversion

Normalization is accomplished by altering the pixel values at each location in the raw data frame according to data obtained from a normalization frame, also referred to as a blank frame. This is a frame of uniform scattering field (e.g. tracer concentration) illuminated and captured under identical conditions to those of "live" data collection. That is, the apparatus configuration was not modified between capture of normalization frame data and "live" extinction data. The equation for the new pixel value after normalization is:

\[
p_{\text{new}} = \frac{p_{0} \cdot p_{\text{norm frame}}}{\overline{p}_{\text{norm frame}}}
\]

where \(p_{0}\) is the initial captured video pixel value, \(p_{\text{norm frame}}\) is the pixel value at the corresponding location of the blank frame, and \(\overline{p}_{\text{norm frame}}\) is the mean pixel
\[ P_{\text{normalized}} = \frac{P_0}{P_{\text{norm frame}}} \] (16)

value of the blank frame\(^6\).

CONVOLUTION

Sources of random error necessitating corrective convolution of video data include:

- Line noise in the power supplied to equipment
- Electromagnetic interference from nearby electrical devices, e.g., the laser and scanner
- Dark current inherent in CCD’s

Convolution is the process of applying matrix transformations to each pixel in an image, where the values in the transformation matrices for each pixel depend on the values of surrounding pixels. The details of the dependence determine the effect of the convolution; standard convolutions exist for such operations as smoothing, noise reduction, etc., and these were applied to captured frames in the current work.

UNIFORMITY ANALYSIS

The degree to which normalized frames can be considered uniform is determined by the actual uniformity of the tracer field, accuracy of the captured and processed image data in representing the field, and the specific notion of uniformity applied to the data. In fact, the assumption of actual tracer field uniformity is an approximation due to the inherent properties of aerosol systems. Pixel value distribution histograms (across all pixels in a given frame) were used as qualitative guides to correspondence of video data to actual concentration distribution, and to the uniformity of acceptable frames.

Frame data exhibiting video or digitization saturation, or below the sensitivity threshold of the equipment, was regarded as invalid for uniformity characterization because of its lack of correspondence to the concentration field. Histograms with peaks at the detection extremes were regarded as indications of

\(^6\) It was necessary to use the macro capability of the Image 1.40 software to implement this manipulation with adequate precision because the integer math built into the software led to unsatisfactory results. For \( P_{\text{norm frame}} < .5 P_{\text{norm frame}} \), which can occur even for relatively uniform frames at low pixel values (since the standard deviation is not proportional to the average pixel value), the resulting normalized pixel value is 0. A macro was written to perform the normalization using floating point math, resulting in more accurate normalized pixel values.
Figure 6  Histograms of raw, normalized, and convolved pixel data from a typical captured frame of uniform tracer concentration.

Near-normal (Gaussian) histograms in the center 80% of the pixel value scale were taken as qualitative indications of video data correspondence to actual aerosol conditions. The standard deviation and coefficient of variance were examined as indicators of uniformity, using sub-frames of varying sizes within an image to evaluate uniformity with respect to the characteristic dimensions of the concentration field corresponding to the sub-frame sizes.

CALIBRATION TO MEASURED CONCENTRATION

From the compartment tests, the mean value of each normalized frame was used as the single-parameter value corresponding to the concentration of the tracer aerosol at the time of capture, as determined by the extinction measurements made at the time of frame capture. In the compartment tests, the concentration value was dependent on time and initial conditions only, as the dimensions of the sample were controlled and no-flow conditions were dominant.
Although in all duct tests the flow velocity was held constant, additional degrees of freedom existed in the mathematical expressions relating the various parameters describing the behavior of the systems. In the constant-injection duct tests, the aerosol size distribution function changed with space as well as time, although the geometry was constant. In the pulsed injection tests, the geometry of the flow also was variable as pulse diffusion became relevant, and uniform mixing within the plane of observation could not be expected. These additional variables prevented absolute determination of concentration distributions. However, as described above, relative volumetric concentration does not vary greatly with time during the period between 10 and 30 minutes from the time of aerosol generation. Thus, relative concentration can be established (approximately) for samples within these constraints by assuming constant $V_\infty$, and test samples easily conform to these requirements. In these tests, mean pixel values were used as relative measures of concentration.
4 EQUIPMENT

4.1 TRACER INJECTION

The aerosol escapes from the fog machine at a relatively high, somewhat variable, volumetric flow rate (approximately 1500 cfm) and a very low pressure. For tests where control of the injection flow rate was unnecessary, the tracer aerosol was directed from the fog machine into the desired location via a 7.62cm (3 inch) diameter flexible hose. Further modifications were made to allow for aerosol to be captured and released into the test volume for the duct tests at controlled rates of flow. Specifically, a section of .3048m (12 inch) diameter flexible duct (flexi-duct) was mounted in a vertical frame, with inlet and exhaust ports, from the fog machine and to the test duct, respectively, in the bottom (see Figure 18). Injection was performed by collapsing this section of duct, forcing the aerosol into the test duct. Tracer aerosol was produced and stored temporarily in the expanded flexi-duct to both cool the sample to achieve neutral buoyancy and allow the early rapid agglomeration phase to pass. A low speed motor was attached so that a constant, controlled rate of injection could be produced; with this device disengaged, pulsed injection was produced by weighting the top of the flexi-duct and permitting it to descend quickly due to its own weight.

4.2 EXTINCTION MEASUREMENT

Reference concentration measurements were made with a 4mW (compartment extinction tests) and a 2mW (duct tests) HeNe laser operating at a wavelength of 633nm. The beam was directed into a standard photocell across an interval of between ±2cm (duct tests) and ±8cm (compartment tests) to produce an optical thickness low enough to satisfy the single scattering requirement, yet high enough to produce a significant reduction in transmitted illuminance compared to I_o, the reference illuminance with no aerosol present between the laser and the detector.

Extinction measurements were also made by placing a photodetector (similar to the one used with the HeNe laser) within the laser light sheet generated with the Argon Ion laser. In the sealed compartment tests, this data was used solely as a comparison to the HeNe extinction data. In the duct tests, however, the in-sheet extinction measurement provided the concentration values of the tracer aerosol at the location of image acquisition. Details of the Argon Ion laser and light sheet generation technique are presented below.

4.3 LASER LIGHT SHEET

The term "light sheet" refers to an illumination beam geometry that is collimated in one dimension, typically a flat plane. Lasers' primary advantage in flow visualization is their ability to probe flows in a non-intrusive fashion while providing much useful information. The fundamental properties of lasers, coherence, energy density, geometric controllability, and wavelength specificity, are all exploited in various flow visualization techniques. Almost all flow
visualization techniques either depend on properties inherent in laser light or are made more convenient by them. Multi-watt laser powers are the rule where they are reported by authors of flow visualization studies [19, 18, 6], although one study of a 10cm diameter section was done with a 5 milliwatt laser. Typical methods of producing laser light sheets result in generic sheet configurations as indicated in Figure 7.

**STATIC LASER SHEETS**

Laser light sheets are produced by de-collimating a laser beam in one direction through one of two techniques. In their simplest form, laser light sheets are produced by directing the beam through a single cylindrical optic [6]. This diverges the beam in one plane only, producing a triangle of light, which can then be oriented perpendicular or parallel to the direction of the flow being studied. This sheet can be reoriented or translated at a controlled rate to provide multiple views of a single flow field [6]. The parameters of the sheet, base width, divergence angle, and focus (width convergence), can be controlled by replacing the single optic with a series of spherical and cylindrical lenses [14, 15]. A sheet with parallel edges can be produced by adding a cylindrical lens to the end of this optical series whose axis is perpendicular to the sheet. The distance between the parallel edges of the sheet are limited by the size of this last lens. The camera recording the visualization is typically oriented perpendicular to the laser light sheet, i.e. facing the sheet.

---

7 In some studies where properties of laser light were not necessary to study the flow, sheets have been generated with incoherent sources [13]. The technique of flash lamp light slicing is purported to cost less and have fewer infrastructure requirements than a pulsed laser system [9]. The optical arrangements are similar to those for laser light sheets, but the typical water cooling system for lasers in the multiwatt power range is avoided.

8 A unique fiber optic array device is available, in which a circular bundle of fibers on one end is arranged in a narrow linear array on the other end. This device has the advantage of not requiring a laser, but the disadvantage, in the present configuration, of producing a poorly collimated sheet geometry.
Static sheets have the advantage that they can be of simple design, requiring minimally a single cylindrical lens, and are relatively inexpensive.

**DYNAMIC SHEETS**

Dynamic sheets are produced by rapidly sweeping an undiverged, continuous wave, beam. In general, pulsed lasers can't be used in dynamic sheets. The oscillating motion is accomplished by reflecting the beam from a rotating mirror assembly [19], or by driving prisms [7] or mirrors [1] at specified frequencies. A galvanometer, commonly referred to as a scanner when used to direct a laser beam, is a device that translates an applied voltage into the angular displacement of a shaft about its axis. A mirror mounted on the shaft reflects the beam through the scan angle, the included angle of the sheet. This is also referred to as the divergence of the sheet. By specifying the oscillatory time/position function of two reflectors rotating about perpendicular axes, three-dimensional sheets can be generated with arbitrary shapes (e.g. circular conical surface, parallel intersecting planes, parallel non-intersecting planes), yielding quasi-simultaneous views of the same flow through these surfaces [1]. Advanced laser sheet techniques have been used in flow visualization studies.

The scan frequency of a dynamic sheet is typically desired to be as high as possible to approximate a continuous sheet (so that the oscillation period is much less than the required minimum time interval over which illuminance is to be measured). The maximum frequency possible is directly tied to the inertia of the mirror/shaft combination. This inertia must be kept as low as possible to maximize available frequency, and the center of mass of the assembly must remain on the axis of rotation. The scan angle is also desired to be as great as possible for viewing large areas. Increased excursion requires increased scan speed, and thus inertia to mass ratio, to maintain equal frequency. These factors indicate that a smaller mirror size is desirable. In addition, maximum available scanner frequency goes down with excursion. If the sheet width is to be controlled by the diameter of the incident beam (other options are available), required mirror size increases with both sheet width and scan angle. Increased scan angle requires increasing the mirror dimension radially from the axis of rotation, compounding the inertia problem.

9 Various combinations of oscillating prisms, mirrors, slits, and lenses have been used to generate semi-dynamic sheets that pulse with cw mode lasers [2].

10 For example, the sweep frequency can be controlled to obtain stroboscopic effects that can yield velocity information or produce instantaneous-quality views of the flow being studied. By synchronizing the sweep frequency with an aspect of a periodic flow (e.g. supersonic air jet [2]), images can be obtained of these highly transient phenomena.
Sheet position and orientation in space relative to the desired plane (or region) of observation and to the image recording device (CCD camera) is controlled by mounting the scanner assembly using standard optical positioning devices.

The illuminance distribution within the sheet is a function of scan waveform (voltage vs. time), scan angle; beam width; and distance from the source. Clearly, although the illuminance distribution is taken as static, it varies with lateral position as a function of the amount of time the beam spends illuminating a given location relative to the period of oscillation.

The advantages of the dynamic sheet configuration include the uniformity of the sheet along its axis of propagation (to the extent that the width remains constant), and the absence of loss by transmission through multiple lenses. The lateral uniformity is a function of the scan waveform, and high uniformity can be achieved at the expense of scan speed (due to mirror/armature inertia constraints). However, even a sinusoidal scan waveform (allowing maximum scan frequency) is fairly uniform in the central portion of the scan, corresponding to the parts of the sine wave of low curvature.

**SCANNER**

The galvanometer used in the present work was driven with a sinusoidal signal, which allowed a scanning frequency of up to 85% of the natural frequency of the galvanometer/mirror assembly, over 500Hz. This met the quasi-static performance requirement posed by the video camera (see VIDEO SYSTEM below). The mirror had an aperture (width) of ±6mm.

The manufacturer advises, based on experience, that to prevent abnormally rapid deterioration of the scanner bearings, operation should be limited by the following equation:

\[ \theta v^2 \leq 4 \times 10^6 \ deg \ Hz^2 \]

where \( \theta \) is peak-to-peak excursion (½ scan angle), and \( v \) is the scan frequency. Parameters of the apparatus used in the present work were up to \( \theta = \pm 15 \ deg \) and \( v = 600 \ Hz \), for \( \theta v^2 = 5.4 \times 10^6 \), sometimes exceeding the recommended limit.

The scan angle used for the experiments presented here ranged from approximately 15 to 30 degrees, and the wavelength used for the laser sheet in all tests was 514nm (green).

**FIBER OPTIC LINK**

The beam was initially directed through a fiber optic link [see appendix] to its position pointing at the scanner mirror. This device was intended to provide laser collimation and increased flexibility in configuring the apparatus. The device
proved untenable due to losses induced by the fiber optic (±15% loss of transmitted light), unacceptably high divergence, and practical difficulties aligning the beam properly into the fiber optic.

4.4 VIDEO SYSTEM

A Cohu monochrome CCD video camera [see appendix] was used to record images of the aerosol tracer. The CCD imager contains 739 x 484 active picture elements (pixels) over a 6.4mm x 4.8mm area (standard ½ inch format). Rated sensitivity is 0.012 lux, which corresponds to a 30% output signal strength (30 IRE units, or 214.2mV) at the CCD. The spectral response curve and modulation transfer function\(^\text{11}\) are shown in Figure 8.

The integration period of the CCD, the interval during which photons are allowed to accumulate onto the CCD chip before being read to the processing circuitry and output to the frame grabber, is 1/60th second\(^\text{12}\). This both determines the temporal resolution with which images can be captured, and indicates the scanning frequency requirement for quasi-static performance (i.e. the laser must make enough passes back and forth through the scan angle within 1/60th second to approximate a static illumination distribution).

The camera signal was directed to a Data Translation frame grabber board [see appendix], producing 640 x 480 pixel resolution with 256 (8 bits) levels of gray. An Apple Macintosh II computer was used to process the video data. Captured images were processed with Image 1.40 software [see appendix] and stored in tagged image file format (TIFF). Standard statistical analysis and raster graphics transformation functions are available within the software, and it is possible to write macros to accomplish unsupported functions.

\(^\text{11}\) The modulation transfer function (MTF) is a measure of ccd resolution. Its value expresses a normalized depth of intensity modulation as a function of line pair frequency. The MTF depends on the microgeometry of the ccd chip and the physics inherent to the way ccd’s work [Beynon].

\(^\text{12}\) The integration period of this camera may be externally controlled. This option was not investigated in the present work.
Figure 8  CCD camera response curves
5 TESTS

5.1 SEALED BOX CALIBRATION

The objective of this test was to compare concentration of well-mixed tracer aerosol under no-flow conditions (measured by HeNe laser extinction) to mean pixel values of simultaneously captured video frames of the sample (illuminated by the Ar Ion laser light sheet). A time series of measurements was made and frames simultaneously captured, providing representative ranges of concentration values and video frame data. This series shows the decay of concentration with time.

APPARATUS CONFIGURATION AND TEST PROCEDURE

Measurements were made in a test volume approximately 47.0cm x 68.5cm x 67.3cm. The top of the volume was fitted with an optical glass window through which the laser light sheet was projected, and one face was plate glass, allowing the imaging system to record light scattered by the aerosol inside the volume. Edges were sealed to prevent leaks of gas.

Two sealable 7.62cm (3 inch) diameter ports were provided for allowing tracer aerosol to be introduced and exhausted via flexible hoses.

A photometric sensor was mounted to the bottom of the test volume at approximately the centerline of the laser sheet, and was used for one of two extinction measurement series. The other extinction series was produced by a 4mW HeNe laser (633nm) directed onto a similar photocell fixed at 5.2cm from the laser aperture. This apparatus was sealed inside the test volume.

The camera head was mounted approximately 73.7cm from the plane of the laser sheet. A 55mm f/1.2 lens was used, resulting in a field of view approximately 8cm x 5cm, 13cm - 18cm above the bottom of the test volume. The scan angle used was approximately 5 degrees.

With the apparatus configured as shown in Figure 9, reference illuminance measurements were made with no tracer present in the compartment. These served as $I_0$ values in the data sets. Then, tracer aerosol was generated directly into the test volume through a 7.62cm (3 inch) diameter flexible metal hose connecting it to the fog machine. At each interval (which varied between tests), a video frame was captured, and the illuminance onto each of the photodetectors was recorded.

To establish correspondence of aerosol concentration (from the transmitted illuminance readings) to video images, it was assumed that aerosol concentration was uniform throughout the test volume at each measurement interval. Observations of the test volume during the test indicate that this is a good approximation although transient flow structures (concentration variations) were
Sealed compartment apparatus used for extinction/video correlation tests clearly visible within the sheet, especially near the top surface of the test volume. Captured frames, from the small region near the center of the test volume, showed slight evidence of these flow structures, however.

RESULTS/ANALYSIS

Results from a representative data run are used to establish extinction parameters for the tracer aerosol and investigate the form of the correspondence between concentration and video pixel values. The even-field normalization frame used for this test was the frame captured at t=5 min.

Figure 10 shows illuminance values at both photodetectors at each measurement interval. Also shown are additional readings from the Argon Ion laser (sheet) with its output power set to 51mW. This data was collected toward the end of the run.

The top surface of the volume was a single sheet of plexiglass; thus temperature gradients are the expected cause of the flow structures.
when light scattered by the aerosol was comparatively low, and thus video acquisition was near the lower limit of camera sensitivity. With increased absolute scattering, it was hoped to achieve more useful video data. That is, the range of illuminance scattered by the aerosol at a given time in the test should produce a corresponding range of pixel values for the average pixel value of the frame to be most useful. If the illuminance is beyond the sensitivity of the camera (on either the low or high end), the resulting range of pixel values will be clipped, and its mean will not provide a useful correspondence.

![Transmission Through Aerosol Sample](image)

**Figure 10**

Although the optical thickness of the aerosol as measured by the Argon Ion light sheet (Figure 12) does not meet the single scattering criterion, data from the HeNe and its associated photodetector more closely conform to this requirement. However, the form of the resulting curve for the extinction coefficient using data from the Argon Ion laser is the same as for the conformant HeNe data, the curves apparently differing only by a constant. Although the investigation of this finding is beyond the scope of this thesis, it is potentially useful as supplementary information in the study of the mathematical solution to the multiple scattering problem. Additionally, it indicates the potential for a correspondence allowing
multiple scattering data to be used, without solving the extensive mathematics rigorously, to relate extinction coefficient to concentration, to be developed.

Also note in Figure 12 and ? that the measured optical thickness and corresponding extinction coefficient data for 40mW and 51mW Argon Ion configurations is roughly the same. This is as expected from theory, and is some indication that the apparatus was functioning properly. The slight difference, that the values for 51mW are lower than those from 40mW, may be attributable to noise due to extraneous higher order scattering from particles near the detector leading to additional recorded illuminance. Alternatively, absorption between source and detector due to the aerosol material itself may be proportionally greater for the lower laser power, leading to higher values of these parameters for the lower laser power.

![Concentration graph](image)

Figure 11 Correspondence of concentration, measured via HeNe extinction, to mean pixel value of captured frames

Figure 11 shows $V_{∞}$ as a function of time.

Figure 14 shows mean pixel values for each captured frame as a function of time. Raw captured values and normalized values are shown, as well as corresponding
standard deviations. For the raw data, the standard deviation is lower at both ends of the acquisition range, indicating that clipping of values is occurring. That is, at both high and low ends of the range of scattered illuminance of the sample, the ranges of illuminance values producing the mean pixel values are partially outside the measurable range of the video system. The illuminance outside the measurable range is recorded as the limiting value, and the standard deviation is lower than if the full range had been recorded. The highest recorded mean pixel values (±240) are not the highest available (255); this is possibly due to extinction along the viewing axis of the video camera lens, both from the aerosol itself and from the glass barrier enclosing the test volume and the optical system, as well as the uneven nature of the laser sheet illumination. This should be counteracted by the normalization process, which would account for the increased mean value of the normalized data. The reduction in the mean pixel value caused by uneven illumination across the viewing field may account for the rest of the difference. The slight dip in mean pixel value at the beginning of the run may indicate that the aerosol concentration was far enough out of the optical thickness criterion that multiple rather than single scattering was significant.

Mean pixel values are compared to extinction coefficient in Figure 15. Note the relatively narrow band of sensitivity between extinction coefficient values of approximately 1.5 and 2.2 for the HeNe data. Figure 16 shows a comparison of normalized mean pixel value to estimated concentration for those frames where clipping due to saturation or detection threshold was not significant. The good correlation of these results supports the relation developed in section 3.2. Note, however, that in the data run shown, a one-to-one correspondence of concentration to pixel values exists only over a part of the range of acceptable video frames. A different initial sample concentration might optimize the range of correspondence.
Figure 12 Optical thickness of sample data

Figure 13 Extinction coefficient
Figure 14 Mean video pixel values of captured frames

Figure 15 Extinction coefficient correlated to mean pixel value for the specific equipment/aerosol configuration of the test data
5.2 DUCT TESTS

The objective of both constant and pulsed injection duct tests was to measure downstream concentration tracer aerosol in fully developed, turbulent, constant velocity flow conditions for upstream tracer injection; and to compare measured results to predictions based on convection-diffusion theory. Theory applied to constant tracer injection relates bulk mean concentration at the point of injection to bulk mean concentration at the point of measurement downstream, independent of time. Tracer bulk mean concentration downstream for a pulsed injection is time dependent due to the transient nature of the pulse, and the dependency is predictable using one-dimensional convection-diffusion theory.

APPARATUS CONFIGURATION AND PROCEDURE

The configuration of the duct apparatus was driven by parameters required to achieve desired flow characteristics of fully developed turbulence, and in anticipation of predicted convective and dispersive behavior of the system. Based on the properties of the aerosol used in the tests, a 30.48 cm (12 inch) duct was chosen to minimize anticipated surface effects, e.g. loss of concentration due to wall absorption, and to provide a geometric sample scale appropriate to the laser sheet illumination and video acquisition system parameters (sheet width and video field of view dimensions were to be on the order of centimeters). The range
of velocities to be tested was chosen to be within turbulent flow regime conditions. The initial configuration of the duct apparatus is shown in ?.

The initial configuration of duct apparatus is shown in Figure 17. The flow straightening tubes and upstream length of the duct were intended to break up large scale eddies and allow the flow to become completely well-developed prior to the injection of tracer. A dead length of ±3m separated the injection port and the observation window, an optical glass port through which the video camera was exposed to the scattered light from the laser sheet. Tracer aerosol was injected directly from the fog machine into the injection port. Using the standard values for air, density $\rho=1.2\text{kg/m}^3$, and viscosity $\mu=1.82\times10^{-5}\text{kg/ms}$, and a characteristic length $D=.3048\text{m}$, the Reynolds number can be related to flow velocity as

$$ Re=\frac{\rho D v}{\mu} \quad (18) $$

or, solved,

$$ Re=2.01\times10^4 v \quad (19) $$

where $v$ is the flow velocity in m/s. In order to maintain turbulent flow as defined by $Re>2500$, $v$ must be greater than 0.125m/s. The fan/duct configuration was capable of producing flow velocity of up to 2m/s, providing the upper bound for velocities to be tested.

Observation of the equipment in operation, however, indicated that at moderate velocities (±0.6m/s) the flow was in fact not well developed by the time it reached the observation section of the duct. At low velocity, the flow appeared to have a partially laminar structure and a larger scale turbulent structure apparently generated by the fan. This was apparently due to the flow structure produced by the fan, and to a lesser extent by lack of available dead length both between the fan and the injection port and between the injection port and the observation section. In addition, the injection port did not function at the higher flow velocities, a negative pressure gradient having been produced in the injection port tube, forcing the tracer aerosol out the ventilation louvers on the fog machine (rather than into the duct).
The direct injection of tracer proved inadequate for valid data collection due to highly variable flow rate and pressure from the fog machine and thus insufficient control of volumetric flow rate. In addition, the equations developed above for determining the concentration are not valid for size distribution data collected in the highly unstable period immediately following generation of the aerosol.

In order to correct these problems, the configuration of the duct was rearranged to provide increased dead length, and an injection port was devised to hold a sample and then inject it at a controlled rate. The final duct configuration is shown in Figure 18.

The injection port was moved to the upstream end of the duct, and the fan was moved to the downstream end of the duct. The effective dead length between injection and observation points was increased to ±6.0m.

The temporary storage and subsequent controlled injection of the tracer aerosol was accomplished with a collapsible section of flexi-duct with two sealable 7.62cm (3 inch) diameter ports, one each for introduction of tracer into the device and
exhaust of tracer into the duct for measurement. The volumetric flow rate of tracer for the constant injection tests was controlled by collapsing the flexi-duct using a constant-speed motor.

The fog machine was connected to the injection port via a 7.62cm (3 inch) diameter flexible metal hose. The injection port itself was a 7.62cm (3 inch) diameter brass tube, oriented vertically within the duct, with two staggered rows of 1.6cm (%in) diameter holes facing downstream, and one row of similar holes facing upstream.

Reference HeNe extinction measurements were made at the base of this tube, ahead of the location where the tracer aerosol entered the duct, by projecting the laser through the aerosol transverse to the direction of flow (horizontally). The optical path length to the photocell was 1cm. The single scattering criterion was determined to be within acceptable limits ±10 minutes after the generation of the aerosol (see Figure 19).

The mean air flow velocity through the duct, constant for each test run, was set by adjusting the fan speed and measured using a hot-wire anemometer. The probe was traversed across a diameter of the duct near the upstream end, the velocity reading being averaged over the traverse time. This measurement was then repeated several times, and the average of the repetitions was taken as the duct flow speed.

Optical windows were built into the observation section of the duct for both laser sheet and video camera in order to minimize distortion and light transmission losses. The sheet divergence was approximately 10 degrees, and the camera head, with 55mm lens, was placed ±0.5m from the plane of illumination, leading to an image area of approximately 8cm x 5cm. Laser power for all duct tests was 40mW.
Video frames constituting a subset of the total viewing area were captured in order to permit a larger number of frames to be captured in any single run, the amount of computer RAM (4 Mbytes) being the limiting factor.

CONSTANT INJECTION TESTS

The volumetric flow rate of tracer aerosol into the duct, controlled by motor as described above, was ±3150.7cm³/sec (corresponding to a flexi-duct rate of collapse of ±4.13cm/sec). For each data run, the storage/injection device was filled with aerosol 10 minutes before the run to allow the volumetric concentration to stabilize and the optical thickness to reach the single scattering level. Video frames were captured both at varying and constant intervals once the injection had reached steady state. A variety of air flow speeds was used for the data runs. Laser illuminance transmission was measured at the HeNe diagnostic recording a representative value at steady state to determine concentration at the injection port. A sensor mounted in the plane of the laser light sheet (not affecting illumination of the viewing area) was used to measure transmission at the viewing location, and this measure was used to calculate downstream concentration.

PULSED INJECTION DUCT TESTS

Pulsed injection of tracer aerosol was accomplished by weighting the top of the flexi-duct storage/injection device and allowing it to free fall a controlled distance of ±46cm, corresponding to a pulse volume of ±3.35x10⁴cm³. The duration of the fall was ±0.5sec. Laser illuminance transmission was measured at the HeNe diagnostic at the injection port recording a representative value at steady state. Again, the aerosol was injected 10 minutes after generation, and video frames were captured at various constant intervals. The duration of each capture operation was short compared to the interval between frames, even for intervals as low as 0.2sec, and was not added to the interval.

RESULTS/ANALYSIS

CONSTANT INJECTION

Non-uniformity of frames captured during initial constant injection tests indicated that the expected fully-developed conditions were not established, leading to the second configuration (Figure 18). The fan was placed at the downstream end of the duct, eliminating flow structures caused by the motor and mount, and additional dead length was provided between the injection port and observation location to allow the flow to become more fully developed.¹⁴

¹⁴ Fluid dynamics indicates that fully developed turbulent conditions would additionally require significantly greater entrance length unavailable for the present work. Observation of the flow, made possible by the transparency of the duct, revealed that small- to moderate-scale turbulence had been developed.
Tracer concentration at the viewing location relative to concentration at the injection port confirmed theoretical predictions within acceptable error for all tested duct flow velocities, although observation of medium-scale flow structures (relative to the characteristic length of the system, i.e. duct diameter) during the tests indicated that well-mixed conditions had not been fully achieved. These conditions were more prevalent at lower duct velocities, consistent with flow behavior closer to the transition region of Reynolds number.

PULSED INJECTION

Measured relative concentration (pixel values) did not match theoretical predictions for $\text{Re}=3220$, as indicated in Figure 20. At this relatively low Reynolds number, fully developed turbulent conditions may not have been established (transition region), thus the validity of the convection-diffusion theory may be questioned in this regime. Pulse velocity and momentum introduced by the injection process may account for the early arrival of the peak concentration value to the viewing region of the duct (compared with the predicted time). In this regime, specifics of the apparatus may have had significant influence on the test results; specifically, the upstream-downstream orientation of the holes through which tracer aerosol entered the duct indicate that momentum was imparted to the tracer aerosol along the duct, thus influencing the measured time data for the run. The dip in relative concentration at $t=20\text{sec}$ followed by a second, broad peak, may indicate that tracer aerosol was forced out the holes on the upstream side of the injection tube and was subsequently drawn through the duct after the additional diffusion due to path length travelled, turbulence at the mouth of the duct, etc. This explanation is consistent with observed behavior of the system.

The high standard deviation of mean pixel value of captured frames reflects the observed uneven mixing of tracer aerosol, which in turn is an indication of transitional behavior. Other factors, such as spurious video interference (peculiar to the specific test run), may also have contributed.

For progressively higher Reynolds numbers, measured values of pixel value more closely corresponded to theoretical predictions (Figure 21, Figure 22, Figure 23). The transition to unambiguous fully-developed turbulent flow conditions predicts this. In addition, more frequent sampling (5 frames captured per second, Figure 24) at the highest flow rate, $\text{Re}=35400$, provides improved temporal resolution to the test, leading to a statistically better data set for comparison.

In the following series of graphs, measured mean pixel values are shown as large squares; the range of captured pixel values is indicated by vertical lines connecting open diamonds; and standard deviations are shown as dots. Predictions from one-dimensional convection-diffusion theory, plus and minus 10%, are shown as continuous curves.
Figure 22

Figure 23
6 CONCLUSIONS

6.1 VIDEO IMAGE ACQUISITION SYSTEM

The present work has demonstrated that it is possible to rapidly obtain multiple video images of fairly high spatial resolution. The dynamic range of the system used in this work was not high enough to cover a large portion of the range of scattered illuminances produced by the laser light sheet and the aerosol in the regimes examined. In addition, the sensitivity of the system was not high, i.e. the signal to noise ratio was unfavorable at low illuminance (scattering) levels. Laser light sheet illumination can be produced over a small but significant area compared to typical room size environments (on the order of tens of centimeters in both directions) without the difficulties associated with industrial power supply requirements and liquid cooling of the laser tube.

6.2 TRACER CONSIDERATIONS

Tracer aerosols can be used to simulate the behavior of molecular and small particle contaminant dispersal systems within constraints imposed by their characteristics as both particles, i.e. how well they simulate the desired species; and aerosol systems, i.e. their inherent physical behavior vis a vis light scattering and transport/dynamics.

Techniques exist for measuring properties of aerosol systems relevant to the evaluation of contaminant dispersal systems, and these techniques are continually becoming more accurate, and accessible as the computing power required to process large amounts of data (e.g. large numbers of particles, high resolution video data) quickly becomes more advanced.

Some fundamental properties of liquid aerosol systems pose practical difficulties in their use as surrogate tracers for molecular species, namely: The time dependence (and lack of control) of their size distributions and volumetric/mass concentrations, and considerations relating to the generation, storage, transport, and disposal of aerosol substances.

6.3 MEASUREMENT EFFICACY

Quantitative measurement of two dimensional aerosol concentration fields is possible for certain conditions using relatively simple equipment and theory due to Mie. No significant limitations were encountered relevant to the rapidity with which frames could be captured (relative to the time scale of typical indoor air quality flow regimes), or the spatial and brightness resolution of images.

Limitations at low Reynolds number of both the theory to predict and the apparatus to accurately measure concentration fields (indicated by relatively high standard deviations in video data both within and across captured frames) suggest
that the method of research undertaken in this work is more useful for flows of higher $Re$.

Available dynamic range of the method is limited by the dependence on the use of lasers (for single-wavelength illumination), due to power and efficiency (cooling) requirements limiting their portability. These factors influence the maximum area which can be effectively illuminated due to the inherent sensitivity limit of CCD’s.

The present work has revealed two issues that pose difficulties in accomplishing the goal of quantitatively correlating a captured video image to an arbitrary two-dimensional concentration distribution. First, Schmidt number similitude is not preserved between aerosol and molecular disperse contaminant systems (see Table II). That is, aerosol systems do not, in general, accurately model the dispersal of molecular species. Second, the time dependent nature of the aerosol systems prevents an absolute correspondence of concentration to scattered illumination (pixel values) for all flow regimes where theoretically predicted solutions exist.
REFERENCES


10 Friedlander, S. K., Smoke, Dust, and Haze. 1977, John Wiley & Sons, New York


APPENDIX
EQUIPMENT TECHNICAL DATA

Refractometer used to measure refractive index of fog fluid: Abbe-3l Refractometer, prism series 549 (working range 1.30 - 1.71); Milton Roy Co., Rochester, NY

Rosco 1500 fog machine: see information following

Galvanometer/mirror: see information following

Laser: see information following

Fiber optic array: see information following

Photometer/sensor: Li-cor model LI-189 photometer, Li-cor Photometric sensor

Data translations frame grabber board: see information following

Cohu video camera: see information following

Image 1.40 image processing software: Public domain; available by anonymous file transfer protocol (ftp) from alw.nih.gov; Written by Wayne Rasband, Research Services Branch, National Institute of Mental Health; see information following

Sage action bubble generator: see information following

Fiber optic link: see information following
SYSTEM 4700c - A versatile, high performance and easy-to-use system that measures particle size in the range 0.1 to 600 microns.

SERIES 2600c - A versatile, high performance system that measures particle size in the range 0.009 to 1880 microns.

AutoSizer IIIc - A versatile, high performance system that measures particle size in the range 0.1 to 600 microns.

Zetasizer 3 - A versatile, high performance system that measures particle size in the range 0.009 to 1880 microns.

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Keith Brayne, P.A.
Stratopheric Chemistry

IM 100 Issue 3
To make measurements at the appropriate times during sample presentation. The result analysis and printout forms are selected on demand. These commands can be made into lines and programmes to allow long periods of unattended operation at the user's convenience. Additionally an EASY operation mode allows ultra simple procedures to give standard forms of results for those who are unfamiliar or uncomfortable with the use of computers.

All dialogue with the instrument is made using the computer keyboard and all responses are via the screen display. The full description of this dialogue is deferred to later sections.

1.3.4 The Printer
The printer is a separate stand alone product emulating the IBM graphics printer standard. It is provided with an interface cable for connection to the computer. The setting up and use of the printer are covered in a separate Printer User's Guide provided with the order.

This section will have allowed you to identify the parts of the instrument that perform the functions involved in the measurement. You are advised not to use the machine until the full Installation Section has been read.

1.4 MasterSizer Specification

This specification covers the MasterSizer in its most basic form, i.e. without details of the accessories. These are provided in the Accessory Manuals when purchased. The Specification is in several parts, the first giving the basic sizing specification. The others deal with the ancillary information on the measurement unit, computer and software.

### Particle Sizing Specification

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<tr>
<td>45 mm range</td>
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<tr>
<td>100 mm range</td>
<td>0.5 - 180 μm</td>
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<tr>
<td>300 mm range</td>
<td>1.2 - 600 μm</td>
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NOTE: Accessories may have individual size range limits that are more restrictive.

**Dynamic Range**

- 8001 maximum on a single measurement

**Accuracy**

+/- 2% on Volume Median Diameter (measured by an approved technique using a diffraction reference reticule)

**Measurement Data**

- 31 light energy measurements from a custom design semiconductor detector optimised for light scattering measurement. In addition a centre ring reading measures the unscattered light energy for determination of the "obscuration".

**Scattering Angle Range**

- 0.03 - 50 degrees (over the 3 ranges)

**Primary Output**

- Relative volume size distribution
- Laser beam obscuration

**Number of Size Classes**

- 32 or 64 uniformly spaced on logarithmic plot.

**Secondary Output**

- Relative volume concentration
- Volume distribution on sieve size classes (24)
Technical Specifications

Power Requirements
- 240 volts, 30/60Hz, 4.6 amps (Dedicated source recommended)
- 240 volts, 30/60Hz, 4.6 amps
- 240 volts, 30/60Hz, 4.6 amps

Maximum Fluid Consumption
- 1.75 liters per hour
- 5.25 liters per hour
- 1.75 liters per hour (88 ml. per minute)

Fog Output
- 500 cu. ft. per minute
- 4500 cu. ft. per minute
- 500 cu. ft. per minute

Particle Size
- 0.5 - 60 microns
- 0.5 - 60 microns

Warm Up Time
- 10 minutes (approx.)
- 10 minutes (approx.)

Weight
- 18.5 lbs., 8.2 kg.
- 40 lbs., 18.2 kg.

Dimensions
- 15.56" x 6.37" x 6" (39.5 x 16.2 x 15 cm)
- 24.5" x 9.0" x 9.75" (62.2 x 22.9 x 24.8 cm)

Power Cord:
- 7.5 Ft. EAC Type Female Plug
- 7.5 Ft. EAC Type Female Plug

Standard Remote:
- 24V DC System
- 24V DC System

OPTIONAL ACCESSORIES
- Super Remote (Model No. 450060)
- Super Remote (Model No. 450060)

Hose Adapter (Model No. 854197)
- Connects ducting hose to machine
- Connects ducting hose to machine

Ducting Hose (Model No. 821760)
- Weight: 3.5 lbs., 1.6 kg.
- Weight: 3.5 lbs., 1.6 kg.

Rosco Laboratories, Inc., 36 Bush Avenue, Port Chester, NY 10573 (914) 937-1300 FAX: (914) 937-5934 Telex: 234472
Rosco Laboratories, Inc., 135 North Highland Avenue, Hollywood, California 90038 (213) 462-2233 FAX: (213) 462-3338
Rosco Laboratories Ltd., 1071 Devon Street, Mississauga, Ontario, Canada L4B 4P1 (416) 475-4030 FAX: (416) 475-3261
Rosco Labs Ltd., 258 Karlplatz, Street 46a, Munich, Germany (089) 55-50000 Telex: 8953352
Rosco España, S.A., Paseo De Zaragoza 37, Madrid 28, Spain (01) 246-1102 Telex: 23700 Am 42-00802
Rosco Laboratories, Ltd., 79-7900, Alfragide, 28103, Portugal (01) 462-3800 FAX: (01) 462-3800
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Rosco Laboratories, Ltd., 79-7900, Alfragide, 28103, Portugal (01) 462-3800 FAX: (01) 462-3800
Series G Optical Scanners

Features

- Rugged, precision construction
- Lower cost
- Wide range of frequencies and excursions
- Cross-axis motion better than 10 microradians

The Series G Optical Scanners are small, rugged and efficient galvanometers designed to deflect mirrors of various sizes in commercial and scientific optical equipment. They are lower priced than General Scanning’s closed loop models, e.g., G120DT and G325DT, since they do not include a position sensor to provide feedback for precise positioning. As such, they are intended primarily as a lower cost alternative where speed of response or accuracy is not required or where angular position is derived independently. Cross-axis motion is typically below 10 microradians.

Typical applications include facsimile transmissions and optical pointing or tracking.

Scanner selection is dictated primarily by the inertia of the mirror. Mirror inertia should lie between 1/10 and 10 times the armature inertia of the scanner selected. The illustration below shows the resonant frequency in terms of the mirror-to-armature inertia ratio.

In all scanners, the mirror is mounted on a separate mount which is attached to the output shaft of the scanner. Mirror deflection is proportional to drive current. Series G scanners with mounted mirrors can be driven sinusoidally at up to 85% of their resonant frequency and at any amplitude up to the rated mechanical rotation. Using the GSI AX200 amplifier, these scanners can also be driven in sawtooth, triangular or square wave at frequencies up to approximately 5% of the resonant frequency.

The back-emf can be fed back to damp out unwanted oscillations in transient response (see illustration showing Typical Feedback Circuit). With a circuit of this type, oscillations can be damped in approximately two periods of undamped oscillation. For applications requiring faster control of the transient response, units with position feedback, such as General Scanning Models G120DT and G325DT, should be used.

[Diagram showing resonant frequency in terms of mirror-to-armature inertia ratio]
Specifications


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<td>Mounting</td>
<td>On 0.499 inch diameter hub</td>
<td>4 front holes, 1/4 inch deep on 1.400 inch x 0.900 inch centers tapped 6-32 NC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Typical Mirror Sizes
- Series G100: 7 mm diameter
- Series G300: 26 mm diameter

NOTES:
1. All models have shielded bearings and 9 inch cable lengths.
2. No mirror.
3. Coil connection: S = Series, P = Parallel

Specifications subject to change without notice.

GENERAL SCANNING INC.
500 Arsenal Street, P.O. Box 307, Watertown, MA 02272
Telephone 617-926-9951, Fax 617-926-10391

85% OF NATURAL FREQ W/SINE WAVE AS STD. MIRROR
Tunable Argon Ion Lasers
SERIES 543-AP, MAP

Standard Features
- 9 Wavelengths Selectable
- 200mW 488nm or 514nm Multimode
- 130mW 488nm or 514nm TEM\(_{00}\)
- CDRH Certified
- Linear Polarized
- Low Optical Noise
- Forced Air Cooled
- TEM\(_{00}\) or TEM\(_{mn}\) Beam
- Pure Line Selection
- Diagnostic Test Points
- Superior Beam Stability
- Highest Air-Cooled Power
- Most Rugged and Reliable

Optional Features
- Easy Wavelength Selection
- Any Operation Orientation
- Widest Environmental Range
- High Conductivity Resonator
- Digital Operating Time Meter
- Recognized by UL, CSA, and TUV
- Switching Regulator Power Supply
- Over 10,000 Hour Operating Lifetime

### 543-AP and MAP

<table>
<thead>
<tr>
<th>PLASMA TUBE</th>
<th>543-AP TEM(_{00}) LASER OUTPUT POWER (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(AMPS)</td>
<td>454nm</td>
</tr>
<tr>
<td>Output Power vs. Wavelength</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>12*</td>
<td>8</td>
</tr>
<tr>
<td>14*</td>
<td>11</td>
</tr>
</tbody>
</table>

*Intermittent Operation Only
152 MAP Output Powers are (1.5x AP Power)
Power Specifications are typical, not guaranteed.

Omnichrome. Quality Lasers and E/O Systems
COMMON SPECIFICATIONS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Diameter (Ω 1/e²)</td>
<td>0.66 mm (TEM₇₀₀)</td>
</tr>
<tr>
<td>Beam Divergence (Full)</td>
<td>1.1 mrad (TEM₇₀₀)</td>
</tr>
<tr>
<td>RMS Noise (10Hz TO 10MHz)</td>
<td>&lt; 0.5 %</td>
</tr>
<tr>
<td>Oscillation Bandwidth</td>
<td>3 GHz</td>
</tr>
<tr>
<td>Mode Spacing (c/2λ)</td>
<td>349 MHz</td>
</tr>
<tr>
<td>Coherence Length</td>
<td>10 cm</td>
</tr>
<tr>
<td>Linear Polarization</td>
<td>VERTICAL ± 5 DEGREE</td>
</tr>
<tr>
<td>Min Polarization Ratio</td>
<td>250:1</td>
</tr>
<tr>
<td>Warmup Time</td>
<td>45 sec FROM COLD START</td>
</tr>
<tr>
<td>Recovery from Standby</td>
<td>&lt; 1 m/s</td>
</tr>
<tr>
<td>Recoil from Standby</td>
<td>&lt; 0.3 mrad AFTER WARMUP</td>
</tr>
<tr>
<td>Stabilty Over 2 Hours Cooling</td>
<td>0.5%</td>
</tr>
<tr>
<td>Power Supply Required</td>
<td>MODEL 160</td>
</tr>
<tr>
<td>Line Voltage (Specify)</td>
<td>200-254</td>
</tr>
<tr>
<td>Line Frequency</td>
<td>47.63 Hz</td>
</tr>
<tr>
<td>Service Current</td>
<td>20 Amp/ SINGLE PHASE</td>
</tr>
<tr>
<td>LASER HEAD WEIGHT</td>
<td>11.4 kg (25 lb)</td>
</tr>
<tr>
<td>Shipping Weight w Cable</td>
<td>16.0 kg (35 lb)</td>
</tr>
</tbody>
</table>

Warranty Statement
Omnicromie Argon ION Lasers are warranted to be free from defects in workmanship and materials for a period of 18 months from date of shipment. Special OEM warranties will apply.

Omnicromie
13520 Fifth Street
Chino, California 91710
Telephone 714/627-1944
FAX 714/501-8340
For OEM or custom applications — machine vision systems — angled lighting for robotics — metrology — inspection procedures.

All fiber optic products will transmit light generated from any light source (strobes, laser sources, Xenon, etc.) Glass fibers, however, will NOT maintain polarized light.

89xx Fiber Optic Lightline. Black anodized aluminum housing. Randomized fiber guarantees maximum uniformity over the useful length. We usually have 3" and 10" Lightlines in stock but you can get different lengths within 3-4 weeks.

88xx Lens Attachment for STRUCTURED LIGHT with the 8900 Series of Lightlines. NOT designed to increase light intensity, but to project a strip of light.

Unique, built-in aperture system will produce crisp line of light without the usual stray light. Easily attached and adjustable. See price list for part numbers and corresponding Lightline reference.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Approx. Line Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 4&quot;</td>
<td>1/8&quot;</td>
</tr>
<tr>
<td>At 8&quot;</td>
<td>1/4&quot;</td>
</tr>
<tr>
<td>At 12&quot;</td>
<td>3/8&quot;</td>
</tr>
</tbody>
</table>

8580 Dual Lightline. Ideal for round objects such as bottles to fully illuminate the area to be inspected. Adds positioning flexibility not available with Ringlight.

8584 Quaddurcated Lightline. Consists of two dual Lightlines (8580) in one common end.

Color filters and input Opal Diffusers are available for the input ends of all fiber optics to create varied lighting effects.

Custom configurations are available on request. Please call or FAX for quotation.

$15/_foot extra length.
**FOSTMART LIGHT SOURCES**

**PRODUCT BULLETIN 1001**

150 Watt — UL Listed — Factory Guaranteed — American Made — IR Absorbing Filter and efficient cooling system for maximum COLD LIGHT. Lightweight — Compact footprint — Practical. Precisely positioned lamp holder to fully utilize individual lamp focal point and beam pattern.

Heavy duty aluminum housing — Can fully illuminate 60" fiber optic bundle — Easy to read Light Intensity Dial — Thumb screw prevents fiber bundle rotation — Low noise and minimal vibration. 3-prong plug.

Factory installed brackets available for remote mounting — Quartz Halogen lamps — Easily replaced. Private labeling available for quantity orders.

**Solid State Dimmer (Rheostat)**

For workplace illumination — inspection — machine vision — when long life is desired and color temperature is not a prime consideration.

**8100 EJA-R** — Rated 40 to 800 hours. Approximately 100% more intense than EKE (at a .25" diameter spot).

**8150 EKE-R** — Rated 200 to 2500 hours.

**Iris Diaphragm (Adjustable Intensity)**

Our Iris Diaphragm light sources meet Military Standard GOG-2000-1B. The most critical item in this spec is constant color temperature, therefore a Rheostat is not acceptable.

Reduce light intensity without changing color temperature — for color sensitive specimens — photography.

**8200 EJA-1** — Rated 40 hours. 3350°K. Approximately 100% more intense than EKE (at a .25" diameter spot).

**8250 EKE-I** — Rated 200 hours. 3250°K.

---

**Electrical Specs:** 115V, 50/60Hz, 150W, UL. Weight: 7 pounds. CSA listing available. Ask about applicable requirements and cost.

<table>
<thead>
<tr>
<th>SETTING</th>
<th>VOLTAGE</th>
<th>Light Output</th>
<th>Lumen Increase</th>
<th>Color Temp Decrease</th>
<th>IRIS Light Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20</td>
<td>100%</td>
<td>150%</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>9</td>
<td>19</td>
<td>90%</td>
<td>300%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>80%</td>
<td>500%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>70%</td>
<td>200%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>60%</td>
<td>150%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>50%</td>
<td>100%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Light Outputs Measured at 85°F from a 35° Diameter Fiber Bundle.

Rheostat measurements are approximate; therefore, do not recommend using a setting below 15%.

---

**FOSTMART, INC.** 273 GENESSEE STREET - AUBURN, NY 13021  •  (315) 255-2791 • FAX: (315) 255-2695
**FEATURES**

- Frame grabber board and software series for capturing, processing, and displaying video images on the Macintosh II
- 256-gray level model bundled with optional ColorKit software for 24-bit color operation
- Single-board frame grabber boards for easy installation
- 640 x 480 square-pixel resolution
- Continuous or freeze-frame display on Macintosh II monitor
- Shown with software interface for image processing operations
  - Easy, mouse-driven operation, with pull-down menus, dialog boxes, and icons
  - Numerous selections for editing, enhancing, processing, and analyzing images
- Optional QuickCapture Developer's Kit software driver for developing custom applications

**TABLE 1. QuickCapture MODELS**

<table>
<thead>
<tr>
<th>BOARD MODELS</th>
<th>HARDWARE</th>
<th>SOFTWARE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resolution</td>
<td>Frame Grab Speed</td>
</tr>
<tr>
<td>QuickCapture (Model DT2253) &amp; ColorKit</td>
<td>640 x 480 square-pixel; 16.7 million colors or 256 gray levels</td>
<td>Real-time; 1 second (24-bit color)</td>
</tr>
<tr>
<td>QuickCapture (Model DT2253)</td>
<td>640 x 480 square-pixel; 64-gray levels</td>
<td>Real-time</td>
</tr>
</tbody>
</table>
New Models!

SCIENTIFIC REMOTE-HEAD MONOCHROME CCD CAMERA

Precision Control, RS-170 & CCIR Models

The new 6500 Series Scientific Remote-Head Monochrome CCD Camera in RS-170 and CCIR formats. The 6500 Series features a camera control unit (CCU) which allows the user to control manually, set gain levels, and control additional auxiliary connections for machine vision interfaces and remote control. These include Genlock and H or V Drive inputs and Frame Grabber Pulse outputs, plus a microprocessor-controlled exposure time varied between 1/25 or 1/30 second (standard video) and 4 seconds.

The new 6500 Series Scientific Camera also features a high signal-to-noise ratio, improved dynamic range, and Cohu's unique blemish-free image sensor, which eliminates the common problem of dead pixels.

A leading manufacturer of high performance video cameras for over 40 years, Cohu is based in San Diego, California.

INPUT/OUTPUT FEATURES

- Remote Control of integration sensor times from 1/25 to 1/300 second or longer
- Frame Grabber Pulse Outputs
- Pixel Clock Output
- Genlock or H & V Drive Inputs

APPLICATIONS

- Microscopy
- Image Processing
- Medical Imaging
- Machine Vision
- Pattern Recognition
- Non-contact measurement
- Robotics

Designed and manufactured in U.S.A.

CoHu 6500 Series Scientific Remote-Head Monochrome CCD Camera

FRONT PANEL CONTROL FEATURES AND BENEFITS

- Offset: Black level is manually adjustable over a wide range with a calibrated 10-turn pot. The Preset position is used for black level reference.
- Gain: Gain can be controlled manually using a 10-turn calibrated pot; gain can also be controlled automatically. Under varying light conditions, the wide AGC range provides excellent control (10:1 ratio).
- Gamma: Two adjustable ranges are provided. The 0.5 to 1.0 range expands blacks and compresses whites, while the 0.5 to 1.5 range expands whites and compresses blacks.
- Electronic Shutter: Three positions are provided. Off, Low (1/1000 second), and High (1/2000 second). Electronic shutter reduces blurring of fast-moving objects and provides extended light range control.
- Sharpness: High-quality sharpness correction improves image sharpness where better definition is needed.
- Video Polarity: Selects positive or negative video for image enhancement in radiology and negative transparency applications.
- Auto Black: On/Off selectable for contrast enhancement.
- Gray Scale: Provides step gray scale test pattern for monitor alignment.

ADDITIONAL FEATURES AND BENEFITS

- Small, Lightweight Remote Imager ensures maximum application flexibility.
- High Resolution 1/2-inch Image Sensor — 100% blemish-free.
- High Signal-to-Noise Ratio allows for full compatibility with 8-bit digitizers.
- Zero Geometric Distortion ensures precision measurement.

CoHu, Inc.
Electronics Division
### SPECIFICATIONS

#### ELECTRICAL

<table>
<thead>
<tr>
<th>Imager</th>
<th>Sharpness</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPECIFIC ATIO</td>
<td>0.25 dB 60Hz 60Mhz</td>
<td>+5 to +85 IRE units</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Active Picture Elements</th>
<th>Synchronization</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-170 Models: 480-H x 584-V</td>
<td>BIA RS-170 or CCIR crystal.</td>
<td>300 IRE (58-S</td>
</tr>
<tr>
<td>CCIR Models: 699-H x 576-V</td>
<td>13,750 MHz (CCIR clock output)</td>
<td>100 IRE (57-S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell Size</th>
<th>Resolution</th>
<th>Video Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5um(H) x 19.75um(V)</td>
<td>RS-170: 550 horizontal TV lines 350 vertical TV lines</td>
<td>1.0V p-p @ 75 ohms, unbalanced</td>
</tr>
<tr>
<td>CCIR: 525 horizontal TV lines 245 vertical TV lines</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gamma</th>
<th>Gain</th>
<th>Auto Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous variable from 0.5 to 1</td>
<td>Auto/Manual (Multi-Turn)</td>
<td>Maintain set-up level at 7.5±5 IRE units if picture contains at least 10% black</td>
</tr>
<tr>
<td>and from 1 to 1.5</td>
<td>Offset</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Auto Black</th>
<th>Power Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain set-up level at 7.5±5 IRE units if picture contains at least 10% black</td>
<td>RS-170: 115V ac ±10%, 60 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gray Scale</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 - 180 - 180 5-grade gray scale reference signal for set-up</td>
<td>10W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal-to-Noise Ratio</th>
<th>Camera Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 dB (RS-170), 56 dB (CCIR) at 7.5±5 IRE units.</td>
<td>Power On/Off, LED Power indicator</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera Controls</th>
<th>Video Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto/Manual (Multi-Turn)</td>
<td>Continuous variable 0.5 to 1, 1.1 to 1.5, continuous adjustment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sharpness</th>
<th>Shutter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous adjustment</td>
<td>Off</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shutter</th>
<th>Video Post-H-1 Reversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (1/2000 sec.)</td>
<td>Low (1/1000 sec.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ambient Temperature Limits</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating: -30 to 70 °C</td>
<td>Camera Control Unit</td>
</tr>
<tr>
<td>Storage: -40 to 122 °F</td>
<td>Dimensions: Please see Figure 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera Head</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions: See Figure 1</td>
<td>Sea level to equivalent of 10,000 feet/3,000 meters (505mm/20 inches of mercury)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Connectors</th>
<th>AUXILIARY CONNECTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video, external inputs and outputs.</td>
<td>Vertical Trigger Out</td>
</tr>
<tr>
<td>camera head</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical Trigger Out</th>
<th>Horizontal Trigger Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grab Pulse Out (+)</td>
<td>Grab Pulse Out (-)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clock Out</th>
<th>Integrate Period In</th>
</tr>
</thead>
<tbody>
<tr>
<td>(14.318 MHz RS-170, 13.375 MHz CCIR)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1</th>
<th>* Defined at 30% video level, High gain, AGC on</th>
</tr>
</thead>
<tbody>
<tr>
<td>With IR Filter</td>
<td>Without IR Filter</td>
</tr>
<tr>
<td>Full Video, No AGC</td>
<td>0.04 fc (0.4 lux)</td>
</tr>
<tr>
<td>High Gain, AGC On</td>
<td>0.0034 fc (0.034 lux)</td>
</tr>
<tr>
<td>Usable Picture</td>
<td>0.0012 fc (0.012 lux)</td>
</tr>
</tbody>
</table>

#### ENVIRONMENTAL

<table>
<thead>
<tr>
<th>Ambient Temperature Limits</th>
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</tr>
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<tr>
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</tr>
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<td>Usable Picture</td>
<td>0.0012 fc (0.012 lux)</td>
</tr>
</tbody>
</table>
Introduction

Image is a pixel-domain program for the Macintosh for doing digital image processing and analysis. It can acquire, display, edit, enhance, analyze, print, and animate images. It reads and writes TIFF, PICT, and MacPaint files, providing compatibility with many other Macintosh applications, including programs for scanning, processing, editing, publishing, and analyzing images. It supports many standard image processing functions, including histogram equalization, contrast enhancement, density profiling, smoothing, sharpening, edge detection, median filtering, and spatial convolution with user defined kernels up to 63x63. Image also incorporates a Pascal-like macro programming language, providing the ability to automate complex, and frequently repetitive, processing tasks.

Image can be used to measure the area, average density, center of gravity, and angle of orientation of a user defined region of interest. It also performs automated particle analysis and can be used to measure path lengths and angles. Measurement results can be printed, exported to text files, or copied to the Clipboard. Results can be calibrated to provide real world values.

Density calibration can be done against radiation or optical density standards using any user specified units. The user can select from any of eight different curve fitting methods for generating calibration curves.

It provides MacPaint-like editing of color and grayscale images, including the ability to draw lines, rectangles, ovals and text. It can flip, rotate, invert and scale selections. It supports multiple windows and 8 levels of magnification. All editing, filtering, and measurement functions operate at any level of magnification and are undoable. It uses digital halftoning to print images on PostScript printers and Floyd-Steinberg dithering for printing on non-PostScript printers.

It supports the Data Translation QuickCapture card for digitizing images using a TV camera. Acquired images can be shading corrected and frame averaged.

Image is written using Think Pascal from Symanec Corporation, and the source code is available. The program can be easily ported to MPW Pascal.

System Requirements

Image requires a Macintosh with at least 2 megabytes of memory, but 4 megabytes or more are recommended for doing animation, for simultaneously displaying more than a handful of pictures, or for running under MultiFinder. It requires a monitor with the ability to display 256 colors or shades of gray. It also requires a floating-point coprocessor or the PseudoFPU Init, which can emulate a missing coprocessor. Image directly supports, or is compatible with, large monitors, flatbed scanners, film recorders, graphics tablets, PostScript laser printers, phototypesetters, and color printers.

Acknowledgments

The author wishes to thank the following individuals for their help, encouragement, and contributions: Peter Ahrens, Joseph Ayers, Rick Chapman, Dennis Chesters, Ted Collburn, Andras Eke, Chuck Fiori, Garth Fletcher, Tom Ford-Holewinski, Keith Gorlen, Greg Hook, Marshal Housekeeper, Werner Klee, Cary Mariash, Kelly Martin, Reuben Mezrich, Ranney Mize, Steve Pequigney, David Powell, Ira Rampill, Arlo Reeves, Robert Rimmer, Bob Rodieck, Christian Russ, John Russ, Matthew Russeaton, Bruce Smith, Seth Snyder, Roy Standing, Cliff Stoll, Steve Ruzin, and Mark Vivino.
Handpiece

1) To obtain a beam with 10 mrad half angle divergence remove cap containing the lens (L_1) by loosening S_y.

2) For a diverging beam, loosen lock nut (N) and remove lens holder.

3) A separate end cap has been provided for the output end when one or both lenses are removed.

---

**F-LFI Laser Fiber Illuminator**

- S_a: socket head screw: tightening screw will secure head to adapter.
- S_o: socket head screw (3): loosen screw to orient head so that ABC attenuator slide switch is easily accessible.
- S_y: socket head screw (2): allows x-y adjustment of lens.
- ABC: Attenuator (17 dB at 488 nm and 514 nm), BlockClear slide switch: 3-position beam attenuator. Before adjusting the slide switch, loosen the knob by turning it counter-clockwise. Tighten to lock in place.
- S_z: socket head screw: This has been factory adjusted, but should correction be necessary this allows the z-position of the fiber to be adjusted to bring the fiber end face into the focal plane of the lens.
- H: 8-32 mounting hole: to mount head independently of laser.
- P, N, H: Pin fits into notch in adapter so that the head is automatically realigned if head is removed and then replaced.
- L_f: focusing lens (fl: 40 mm): is fixed inside cap: remove for a collimated beam.
- S_c: socket head screw: secure collimating lens.
- L_c: collimating lens (fl: 15 mm): remove for a diverging beam.
- C: end cap
- N: lock nut, loosen to adjust lens holder position
- H_y: lens holder, adjustable

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**Contact Information**

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64
Model F-LFI Laser-Fiber Illuminator

The Model F-LFI Laser-Fiber Illuminator provides a simple method to transport light from a visible wavelength laser to a remote or difficult to access location. The unit consists of a 10 foot long, armor clad fiber connected between a laser coupling head on one end and a handpiece on the other end. The cable, which holds a 200 μm diameter plastic clad silica fiber, is held in both the coupling head and a handpiece by unique, rugged crimp connectors that permit high power handling capability.

To mount the coupling head simply screw the collet into the 1-32 internally threaded bezel at the output of many lasers, or post mount the collet in front of the laser. Then slip the coupling head into the collet, orient it for your convenience, and lock it in place. The laser beam is coupled into the fiber through the AR-coated lens in the coupling head. Fine position adjustments center the focused beam on the fiber, while the outer barrel rotates to position the end face of the fiber in the focal plane of the lens. Just unlock the coupling head and slide it out of the collet when you want direct access to the laser beam. An indexing post automatically re-aligns the coupling head when you replace it in the collet. A 3-position slide bar on the coupling head can be set to block the beam, attenuate it by 17 dB, or pass it unattenuated.

The output end of the fiber is held in a knurled 3.6" long by 0.75" diameter handpiece which emits a beam with a divergence of up to 47° full cone angle. Two optics accessories are included with the illuminator. An AR-coated lens slides on the handpiece to reduce the output divergence to 10 mrad. A second AR-coated lens attachment provides an approximately 0.8mm diameter spot at a focal distance of 40mm. For fixed mounting, the handpiece can be conveniently held by the MH-1 Micro-Series Optics Mount.

The illuminator has power handling capability of several watts with a typical coupling efficiency of 90% at wavelengths from 480 to 700 nm. Optimized performance at other wavelengths is possible with a different fiber and lens coatings on a custom basis.

1) Loosen S₁ and remove collet from coupler.
2) Screw collet into laser accessory bezel (1"-32). If there is no bezel the coupler may be independently post-mounted by means of the size 8-32 mounting hole (H).
3) Insert coupler into collet with pin (P₁) fitted into notch (N₁₁).
4) Secure coupler by tightening screws (S₁). 
5) Loosen screws (S₀) and turn coupler so that the two S₁₁ screws are easily accessible.
6) Tighten S₀ to secure coupler.
7) Make sure that the ABC (Attenuate, Block, Clear) switch is in the Attenuate or Clear position. Before adjusting the slide switch, loosen the knob by turning it counter-clockwise. Tighten to lock in place.
8) Turn laser on and position the output end in front of a power meter.
9) Maximize output intensity by adjusting the x and y positions of the lens using Sₓₓ and the z-position of the fiber using S₁₁, loosens the body so that it may be lengthened by unscrewing. The z-position has been factory adjusted, so correction should not be necessary.

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