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SCHREYER HONORS COLLEGE

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AIRBORNE PARTICLE CHARACTERIZATION FROM OPTICAL SCATTERING: A NEW CONCEPT DESIGN

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Abstract

Determining airborne particle sizes in a simple and efficient manner has many applications to health and atmospheric studies. Through analyzing Mie scattering theory and scattering phase functions, ideas for characterizing airborne particle sizes were investigated. Different locations of the scattering phase functions were analyzed to determine the optimal angles to measure experimentally that would allow the determination of particle size. Utilizing existing polarization ratio theory, a prototype device was designed and fabricated that could be used to measure small concentrations of particles in a laboratory setting. Initially the polarization ratio was determined by using a rotator to change polarizations, but later experiments used two cameras to obtain the two polarizations simultaneously. The methodology of this theory and design steps are described so that this theory could be further investigated.

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I. Introduction

Factors that affect human health are of utmost concern for the scientific community and the society at large. Airborne particulate matter causes problems with breathing and asthma for people susceptible to those problems, as well as those that may develop breathing problems.

Pollen grains, which severely affect 5 to 10 percent of Americans, come from weeds, grasses, and trees range and range in sizes between 10 μm and 100 μm. Other particles such as airborne bacteria and viruses, which are on the range of 0.3 μm to 15 μm, tend to be even more detrimental to humans (Arya, 1999). The larger particles tend to not be carried over long distances because of their weight so it is the smaller particles that are breathed in by humans.

Determining accurately the size of airborne particles will allow proper characterization, which can be important for monitoring and controlling the local environment. A tool that can accurately and remotely detect particle sizes may be useful for detection and classification of particles in this size range.

Remote sensing of particles is done currently by several means. One technique uses an optical sensor device to estimate particle concentrations from scattering intensity. Another technique currently being used extensively to determine the extinction caused by particles uses a device called a nephelometer (Anderson et al, 1996).

Nephelometry has existed for a long time but it has not been until recently that a new method of using backscattering ratio has been investigated (Stevens, 1996). These measurements have all been done in the atmosphere over distances of hundreds of meters to kilometers, but my investigation reanalyzes some of the existing scattering and backscattering ratio theories to propose a methodology for developing a smaller and more efficient device. The final goal is to make a device that is compact and can be used to characterize small concentration of particles in a laboratory setting.

II. Background

A. Nephelometer

The current method of using light scattering to determine particle size is the technique of an integrating nephelometer (Anderson et al, 1996). A nephelometer is a device that sends a light beam through a chamber that holds a sample and then measures the intensity of scattered light using a detector. This measurement is then used to determine the total and back scattering components at one or more wavelengths (Heintzenburg and Charlson, 1996). A nephelometer's main use is to measure this scattering coefficient without any assumptions such as particle size, structure, or physical state (Anderson et al, 1996). A nephelometer is first calibrated with particles with known scattering coefficients. Following the calibration of a nephelometer by measuring the scattering coefficient and extinction of several known particles, the size of unknown distribution of particles can be estimated by an interpolation of the results. This method is cumbersome and requires the availability of a whole range of particles to be on hand for calibration so an alternative to this method is being proposed.

B. Mie Scattering Theory

Mie scattering theory describes the interaction of an electromagnetic plane wave with a sphere. For this theory to be utilized the following factors must be assumed:

particles must be spherical, must have an index of refraction that is known, multiple scattering from particles must be small, and particle distribution is uniform. The complete theory developed by Gustov Mie is highly mathematical and can be found in sources such as Van de Hulst (1957) or Bohren and Huffman (1983).

As seen in Figure 1, by changing the point of observance the scattering intensity of parallel and perpendicular polarization components can be observed.

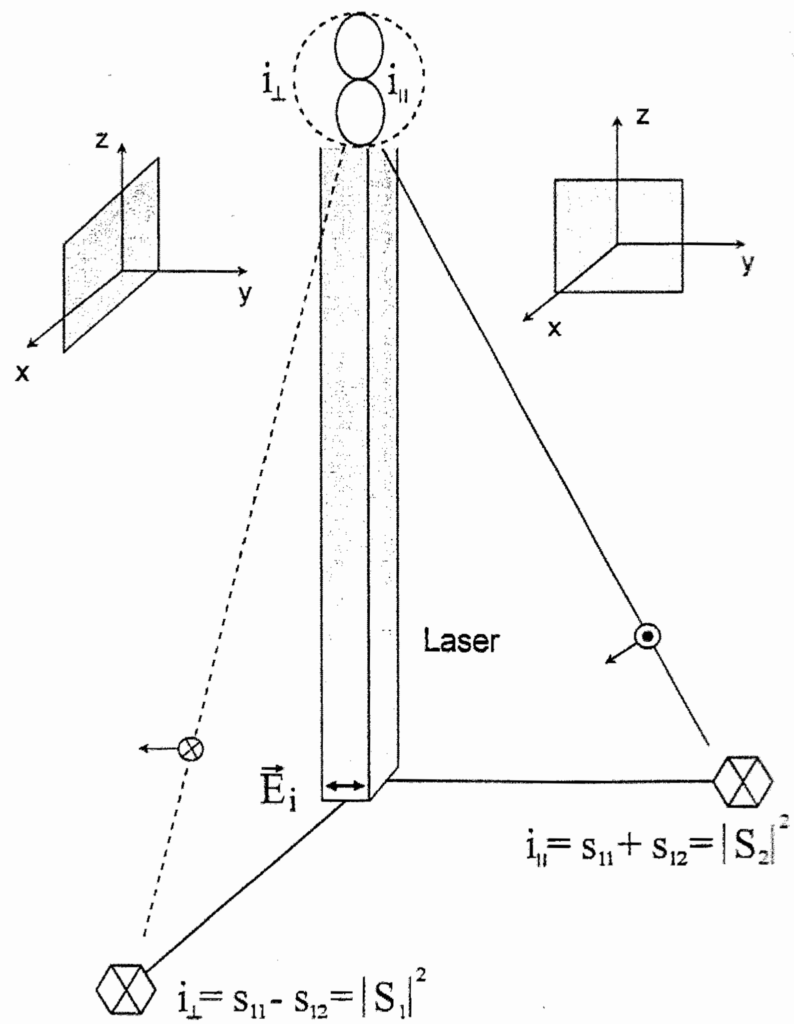

Figure 1: Geometry showing the laser operating vertically, which shows that where the laser beam is observed determines the component of the electrical field that will be measured. (Figure from Stevens, 1996).

$$i_{para} = S_{11} + S_{12} = |S_2|^2 \qquad \textbf{(Eq 1)}$$

$$i_{perp} = S_{11} - S_{12} = |S_1|^2$$

Bohren and Huffman (1983) developed a computer program in FORTRAN called BHMIE, which calculates many parameters, in particular the scattering matrix. From the scattering matrix the parameters S_1 and S_2 are found. Using Eq. 1, the parallel and perpendicular polarized intensities can be determined from the scattering matrix parameters S_2 and S_1 respectively.

The BHMIE program from Bohren and Huffman was translated from FORTRAN into Matlab code by another student, Guangkun Li. This code was modified to generate the polar plots of the parallel and perpendicular intensities found in Appendix A-1.

Mie theory makes use of a parameter that contains the information relating the radius of the particle and the wavelength: the q value. The q value is described as,

$$q = \frac{2r\pi}{\lambda}, \qquad \textbf{(Eq 2)}$$

where r is the radius of the spherical particle and λ is the scattering wavelength.

Note that for a constant wavelength, as the particle radius increases, the q value increases. Therefore the q value directly corresponds to a particle size. This q value is the value that the program BHMIE uses to calculate scattering phase functions.

Using Matlab, the scattering phase plots were generated over the range of q values. Plots generated by hand from advanced theoretical calculation of Blumer (1925) were compared with the plots generated in Matlab for the same q values, as shown in Figure 2 and Figure 3, to determine that the plots generated in Matlab agreed with the earlier work..

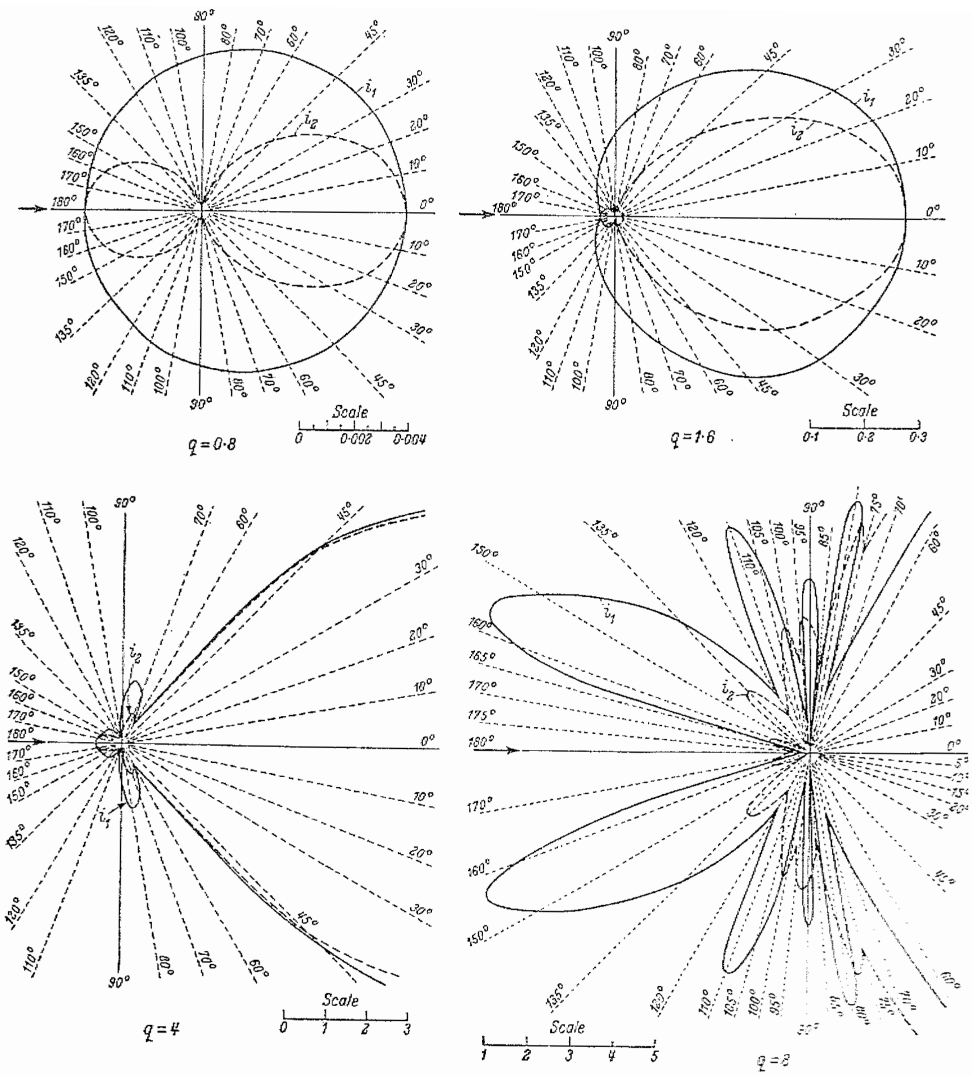

Figure 2: Polar diagrams for the scattering of linearly polarized light from a dielectric sphere of refractive index n = 1.25. (After Blumer, 1925) (Born and Wolf, 1980)

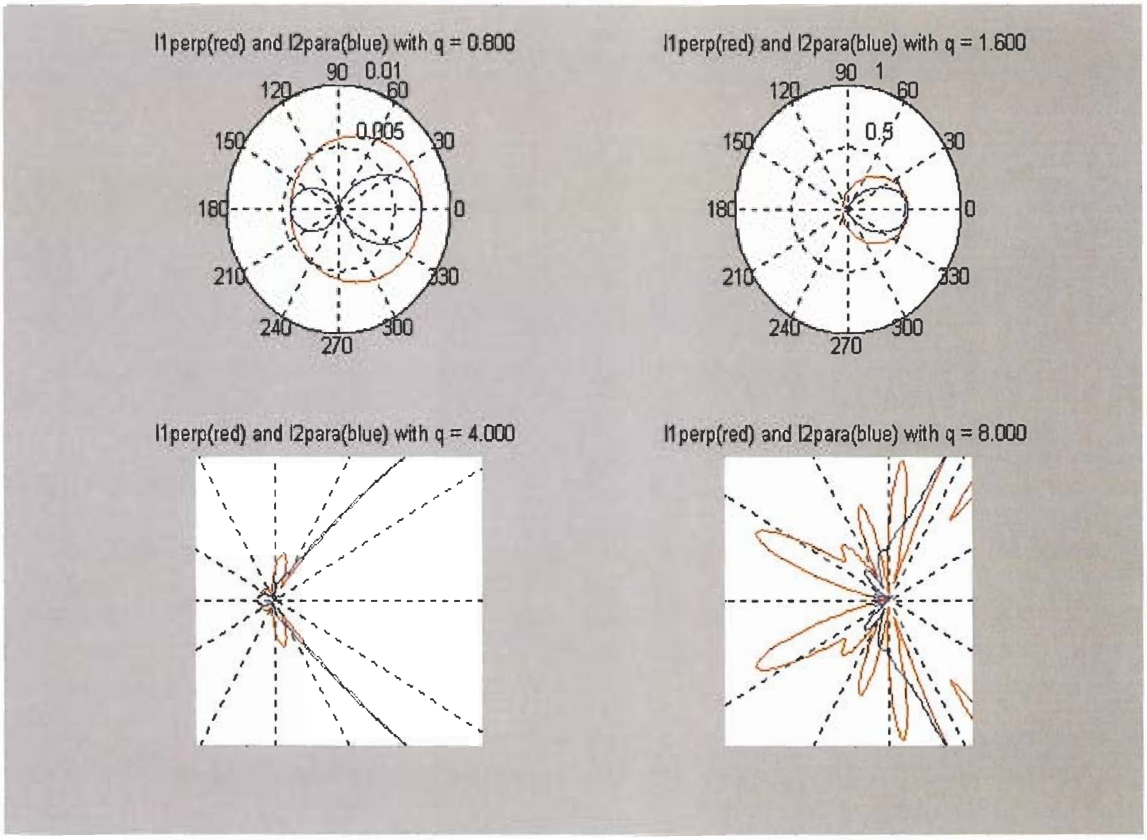

Figure 3: Polar diagrams calculated in Matlab with refractive index n =1.25. This shows that the Matlab code developed matches well with the theoretical analysis of the Mie scattering.

C. Laser Selection

The laser available for this work is an argon ion laser, which operates at several frequencies, with the most prominent being at 488 nm and 514.5 nm (Hecht, 1987).

The prominent line at 514.5 nm is the best choice of wavelength to use because it contains the most power. The range of interesting particles sizes is between 10 nm and 20 μm, and from Eq. 2, the corresponding range of q values is calculated to be from 0.122 to 244.

III. Scattering Plot Analysis

To determine the q value corresponding to a measurement, the information needs to be collected from a certain angular location around the particle. This location needs to be at angles where enough variation in the structure exist to determine the q value from the data collected.

After extensive simulations of the scattering phase functions, three possible regions were found to contain enough data to allow accurate q detection, which would thereby allowing unique particle characterization. The scattering plots of each type can be found in the Appendix B.

Currently the backscattering region is used in nephelometry but my purpose is to analyze the scattering phase plots to determine if another region would be better or more practical as a step in the development for a device.

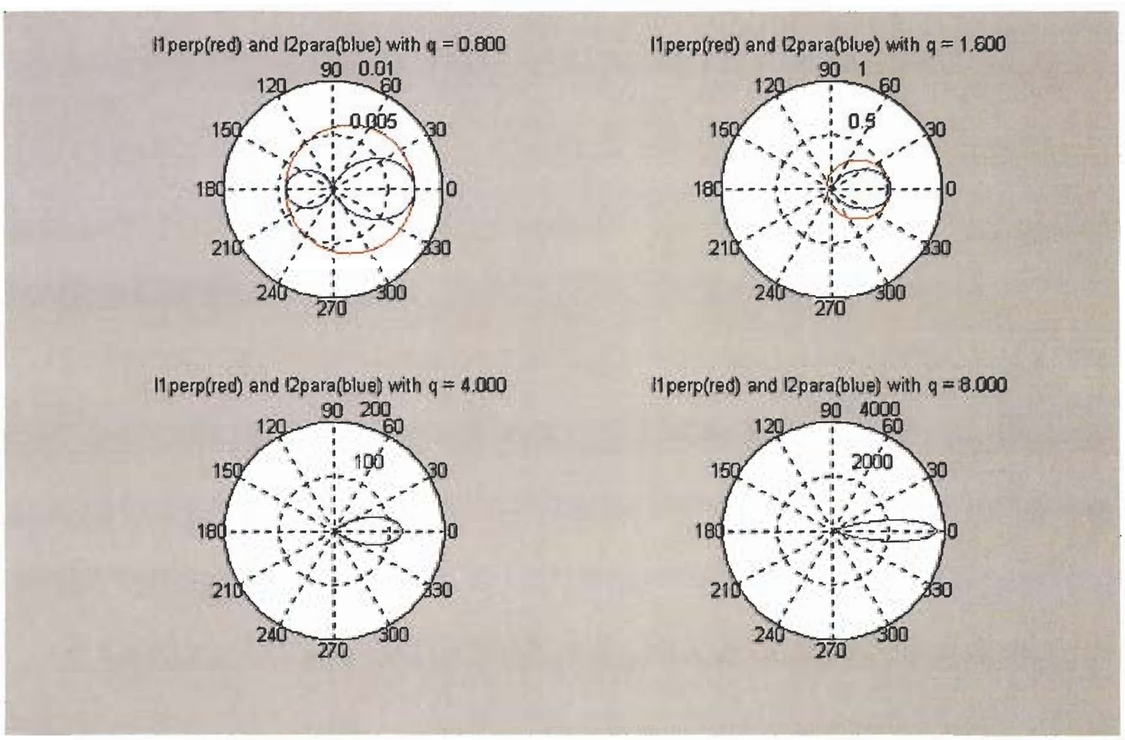

Figure 4: Polar scattering plots showing the explosion of the front beam as the particle size increases.

A. Front Scattering

As the q value increases, the front lobe of the scattering phase plot increases greatly. This area, in the range of 30° to −30°, of the plot constitutes the front lobe. Figure 4 shows the rapid expansion of the front lobe as the q values increase. See Appendix B-1 for more samples of the scattering plots, which zoom in on the front lobe. From this data it can be seen that as the q value increases past q = 4, the difference between the parallel and the perpendicular intensities is practically indistinguishable at distances farther from the origin.

A proposed method would be to measure the front lobe in either the parallel or the perpendicularly polarized intensity. Because this lobe increases rapidly as q increases, there would be enough difference between each measured lobe intensity to provide the accurate determination of q value.

From a practical standpoint measuring the front lobe would be difficult due to the interference of the primary beam that is directed to the front. Devising a method to block out the main beam to then be able to only look at the front-side scatter is a possible method for advancement.

B. Front-Side Scattering

An interesting phenomenon was found in the angles between 30° and 60° of the front lobe of the scattering phase functions. Examples of these angles can be found in Appendix B-2. There exists a dip in intensity for both phase functions at a certain angle that is specific to each size particle. This may be useable as a unique size characteristic that could determine the particle size. This front-side scattering does not become noticeable until about $q > 5$.

Because of this side scattering being in the frontal lobe region the intensities would be quite high in a practical experiment and the difference in intensity between the front lobe and the dip in intensity at the front-side part of the lobe would be small, and possibly undetectable. Realistic particle distributions will contain many particle sizes which could make this distinct feature barely discernable, so theoretical and experimental demonstrations should be explored.

C. Back Scattering

The scattering of the back angles was found to be the most intricate and complex for each particle size. A few plots of backscattering angles are shown the Appendix B-3. The back angles that were analyzed were the angles between 90° and 175°. Because of the back angles unique and complex nature, these angles would be ideal for determining the particle size based on the scattering phase functions. The complexity of the back angles increases greatly as the particle size increases. Backscattering is the method used in many nephelometry techniques, such as Stevens (1996) and Anderson (1996).

D. Polarization Ratio

For every q value there is a unique scattering intensity phase plot for both the parallel and the perpendicular polarized intensity. The ratio of the intensities is also unique for that q value. Using ratios also has the advantage of allowing many mathematical factors to drop out and allow comparison on a case-by-case basis.

Therefore the plot of the ratio of the two scattering phase plots will be used to determine the q value, and thus obtain the particle radius. Examples of some of the ratio plots generated can be found in Appendix B-4.

From these ratio plots it can be seen which angles contain the most information. The angles that have a higher ratio between parallel and perpendicular polarizations create a larger peak on the ratio plot. The angles, which contain these higher peaks in the ratio plot, can be used to determine the distinct size of the particles. Therefore the angles that we wish to use should be ones that contain high peaks in the ratio. For this reason the backscattering angles from 120 to about 175 degrees were chosen as the most promising angles to analyze.

My findings coincide with data collected in Steven's thesis, 1996. He investigated the usage of the ratio of parallel and perpendicular polarization to be used for particle characterization in the atmosphere. Following are his plots, which illustrate the effects of what should happen when particle size increases. As the particle is small the polarization ratio is simple but as the particle size increases so does the complexity of the ratio of the polarizations.

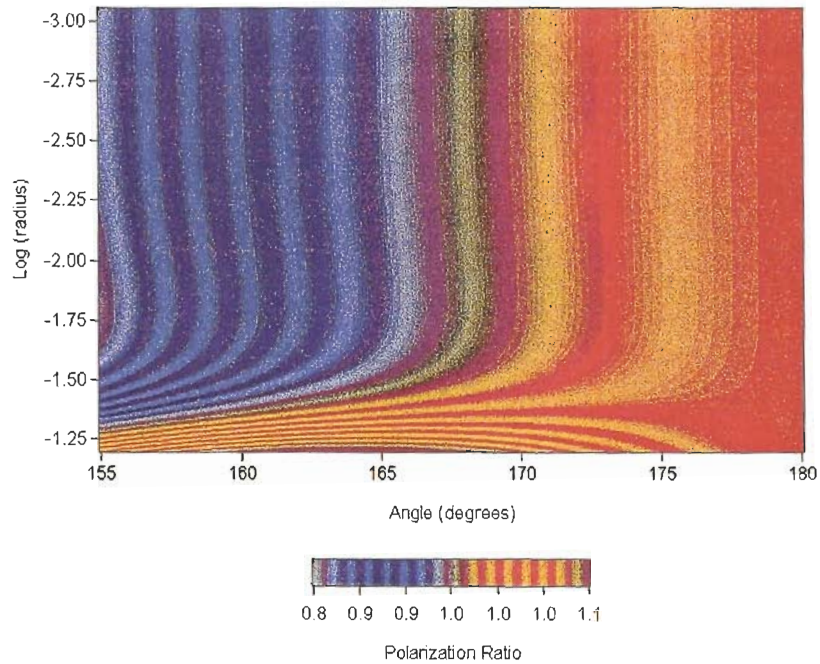

Figure 5: Polarization Ratios for particle radii sizes of 1 nm to 50 nm. (Stevens, 1996)

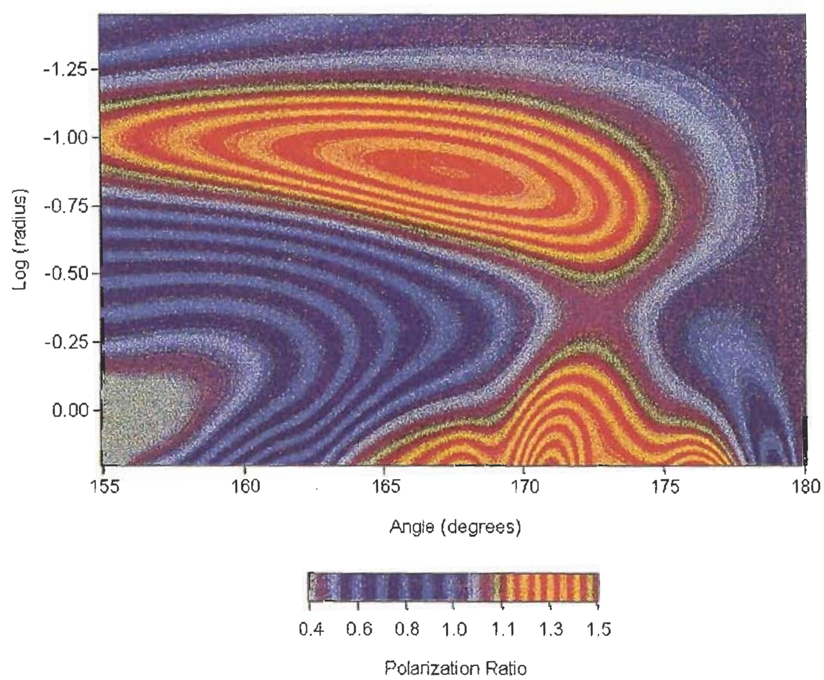

Figure 6: Polarization Ratios for particle radii sizes of 30 nm to 1.8 um. (Stevens, 1996)

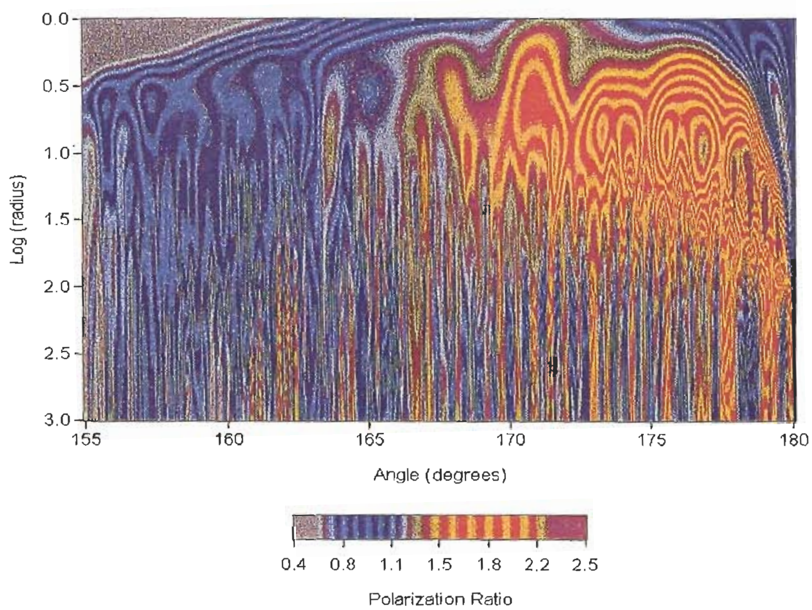

Figure 7: Polarization Ratios for particle radii sizes of 1 um to 1000 um. (Stevens, 1996)

IV. Design Considerations

A. Detector Choice

To capture the reflected light from the backscatter of the laser, a sensitive detector was used. The device also needed to have a field of view of 10 to 30 degrees to be able to capture a range of the backscattered angles. To have a small detector, the focal length of the lens of the detector was needed to be small. Lastly the detector needed to be computer controlled, or be able to have the measured data as output for computer analysis.

Because of availability and fitting all the design criteria above, a Meade Pictor 416XT Charge Coupled Device (CCD) camera was used. A 700 MHz, Windows 98 computer using Pictor View software, controlled the camera. This camera was designed primarily for astronomy observation and because of its high sensitivity to low levels of light and being computer controlled, made it ideal for our purpose.

B. Angles to Analyze

The critical design angles that needed to be defined include the field of view (FOV) angle, the angle of the backscatter, and the angle of the mirror, which is used to align the backscatter with the camera axis.

The FOV angle needed to be large enough to allow data to be measured, but was limited by the lens and camera's capabilities. Also as the FOV increases, the amount of the beam to be viewed increases. As this length is increased, there is a point where it is not possible that the entire beam can be in focus at the same time.

The next design decision was to define what angles would be analyzed. The angles between 120 to 175 degrees were determined from the ratio plots to contain much information. Using a FOV of 15 degrees, the angles of 150 to 165 degrees were chosen.

V. Experiment Design

A. Prototype Design

After the angles, their resolution, and range were chosen, the prototype was ready to be designed. The goal for the prototype was a small, enclosed tabletop unit that could characterize particle sizes from a small sample size.

Because the back angles are the angles of interest, the camera needs to be close to the beam. Due to the distance from the lens to the end of the camera and the need to keep the design as compact as possible, the camera lens could not be positioned close enough to the beam to allow the back angles to be measured because the camera would get in the way of the beam. Therefore a mirror was introduced to allow the camera to be perpendicular to the laser beam and to allow all angles of interest to be measured. To allow fine adjustments after fabrication, the mirror was placed on an adjustable arm so that the scattering could be precisely directed into the lens.

The design calculations and layout were first preformed on paper and then the design was prepared in AutoDesk AutoCAD 2000i. First the design of the laser with the backscattering angles with the camera position was made as seen in Figure 8. Then the unit was drawn in AutoCAD as shown in the drawings found in Appendix D. To fabricate the prototype, the AutoCAD plans were given to the College of Engineering, Department of Engineering Services.

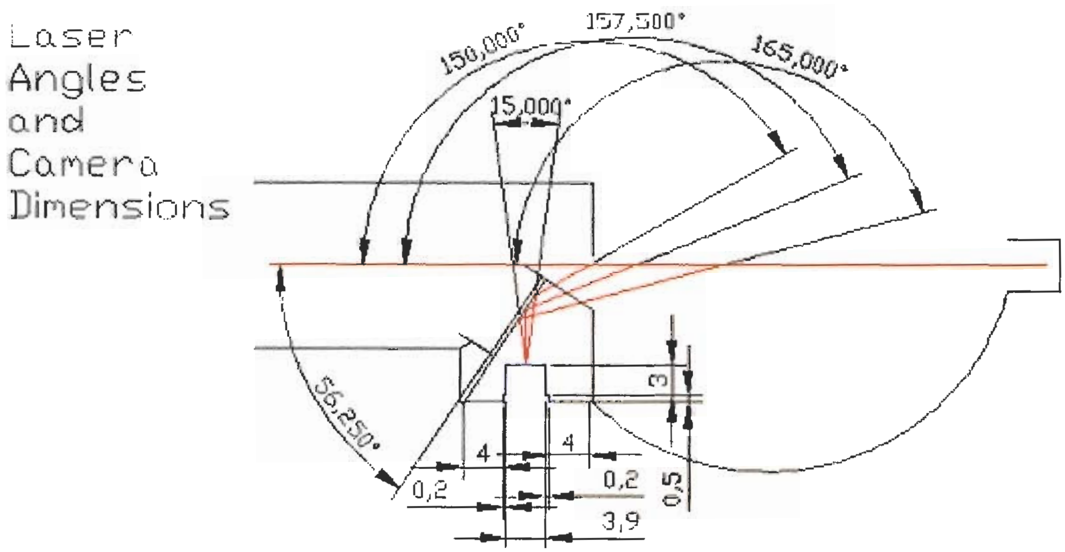

Figure 8: Laser Angles and Camera Dimensions – Shows scattered angles, mirror angle needed, and camera dimensions.

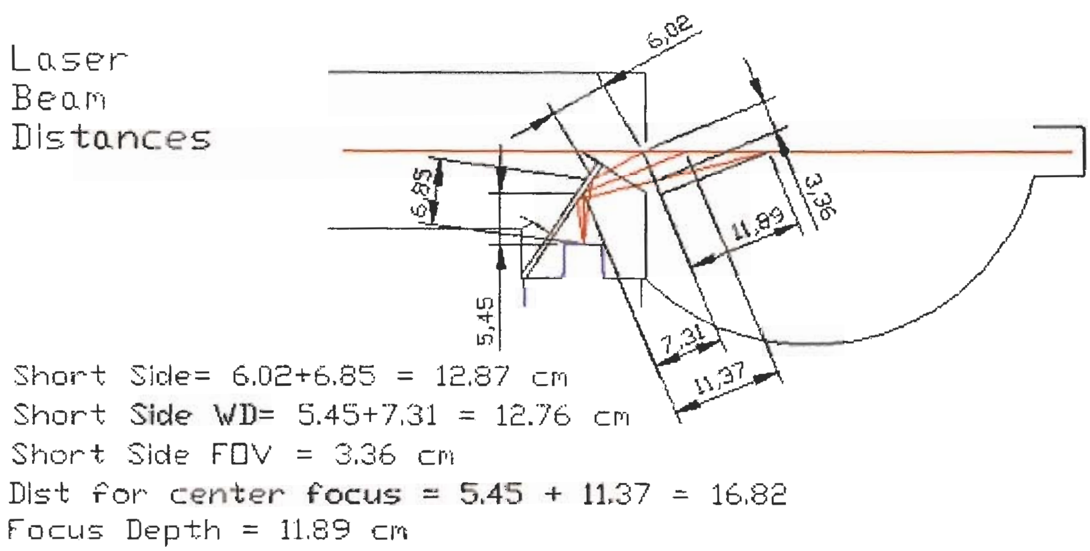

Figure 9: Laser Beam Distances - Drawing shows the distances of lengths of the scattered angles of light, the minimum or short side working distance, the distance to center of angles for focusing purposes, and the focus depth.

Prototype Components Design Considerations:

1. Backscattered Light Mirror Arm – The mirror is mounted on the arm to direct the backscattered light into the camera. This is made adjustable with bolts on the top and bottom.

2. Cylindrical Chamber – The area where the dust was to float in the air was to be an area large enough so that there would be good dispersion to be able to analyze all angles necessary and small enough so that the unit was not too large.

3. Laser Mount – The opening needed to fit around the Argon Ion Laser that was to be used in the experiments.

4. Rotator – During operation a test with a rotator, which changes parallel polarization to perpendicular polarization, will be inserted into the path of the main beam. Then a test will be run without the rotator. This will allow both parallel and perpendicularly polarized angles to be analyzed using the same camera mount.

5. Dispersing the Main Beam – The main beam going through the unit is not needed and needs to be dispersed and not interfere with the measuring of the backscattered laser light.

    a. Main Beam Mirror – This mirror directs the main beam downward so that it is not reflected back to the detector.

    b. TIR Cone – The main beam is directed into the TIR cone (Total Internal Reflection) cone. This cone is designed to have high angles and conical shape to make any light from the laser reflect internally further into the cone and not reflect out of the cone.

6. Camera Mount – A large hole for the lens and two mounting holes were made into the unit for the camera mount.

7. Method to Disperse Particles – A small hole in the top of the unit was made to allow the hose of a pressurized canned air to be inserted. Before an experiment a small sample of the dust is to be placed in a small tray placed on the bottom of the unit. Then though the hole at the top the can of pressurized air is inserted and is shot into to disperse the particles in the small tray.

8. Small Internal Reflections and Other Light Noise – This unit was made enclosed and colored black to block out outside light and that any small amounts of laser light would not be reflected from the walls of the unit.

9. Focus Depth – Camera can only be in focus for certain distance and the less distance between the shortest distance and the longest to be focused on, there exists a better quality focus. Also the in-focus region increases if the camera is positioned further away from the beam. This is because the shortest length and the longest length to be focused become closer to being the same as the center distance increases.

10. Polarization of argon ion laser– The beam of the argon ion laser is already linearly polarized but whether it was oriented in the vertical or horizontal direction was not known. To determine the laser's polarization, a piece of polarized film was used. Using Brewster's

Angle principle a glare from sunlight on the ground was viewed to determine the film's transmission axis. Then the argon ion laser beam was viewed. The argon ion beam was determined to be vertically polarized using this method.

11. Dispersion of Particles – Getting a uniform distribution of particles in the beam proved to be difficult. The sample of particles was placed on the bottom of the unit and then three squirts of Office Depot pressurized air duster was used to spray and disperse the particles.

12. Image Exposure – The image needed exposed long enough so that the light scattered from a particle would be from many particles and not just a few in time. If the exposure was too long the image would saturate to max value of 65536 and there would be no difference from one pixel to the next. Closing the iris of the lens to let less light into the camera and using a lower power of the laser solved this problem. Also by closing the iris, less of the lens is used which gives better depth and reduces the effects of defects of the lens. The power of the laser used was 0.9 W.

13. Camera Lens – The right camera lens was chosen so that the objects from the smallest distance of the scattered light to the longest distance of the scattered light could be in focus using that lens. Figure 9 shows the needed distances and field of view (FOV).

The prototype after fabrication was painted black. The prototype fits around the argon ion laser as seen on the left of the photo and the camera is mounted as shown in Figures 10, 11, and 12. The prototype has all the features as shown in the AutoCAD drawings in the appendix.

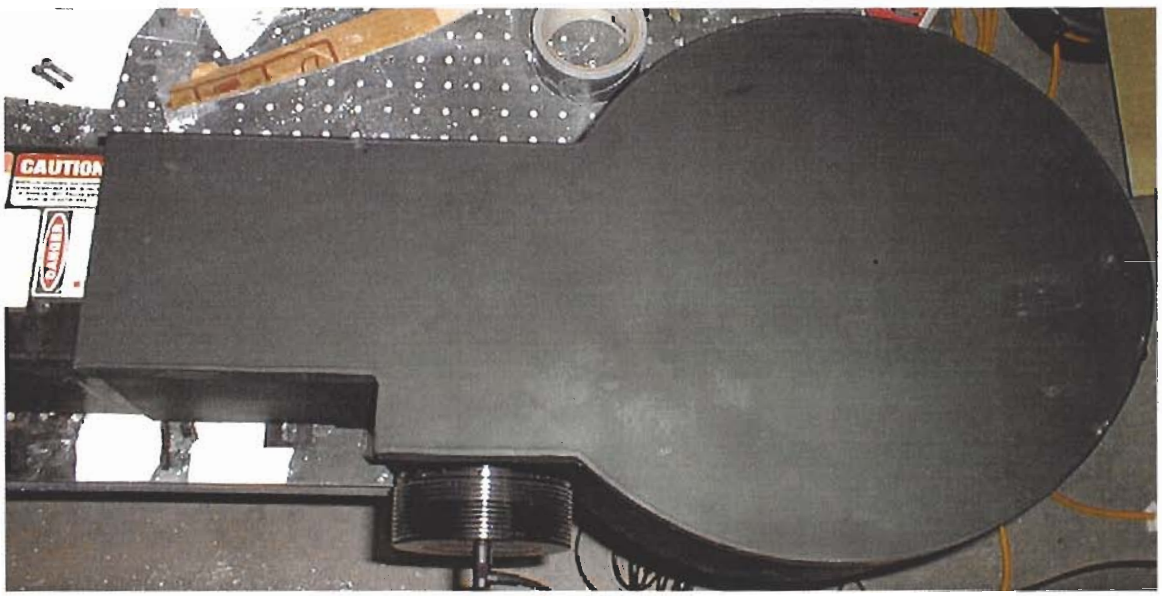

Figure 10: Top view of prototype with cover on.

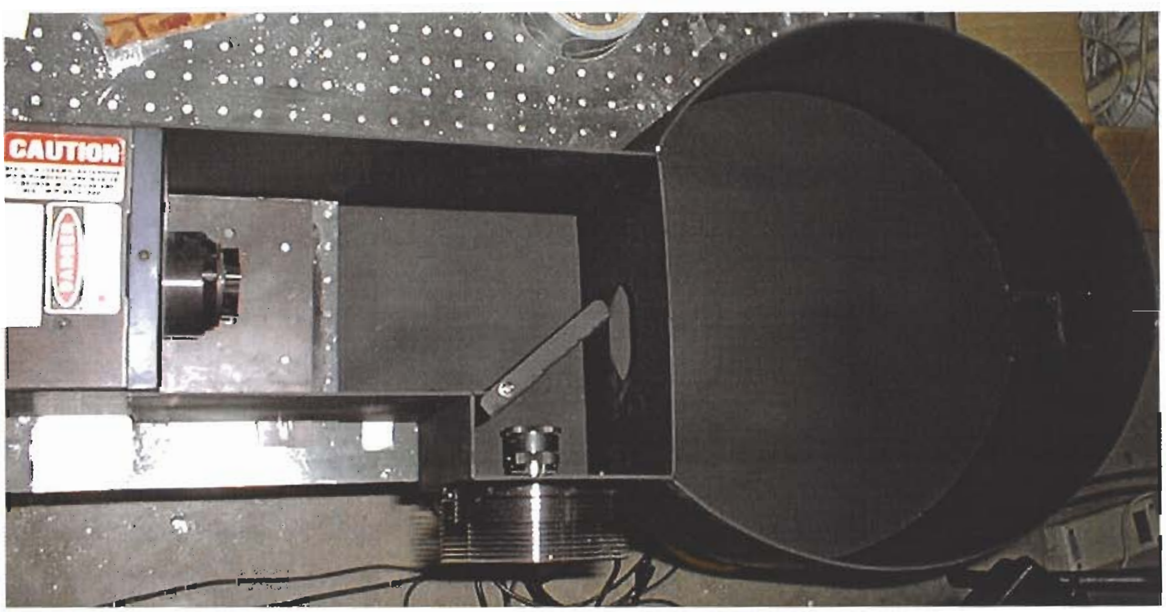

Figure 11: Top view of prototype with cover removed.

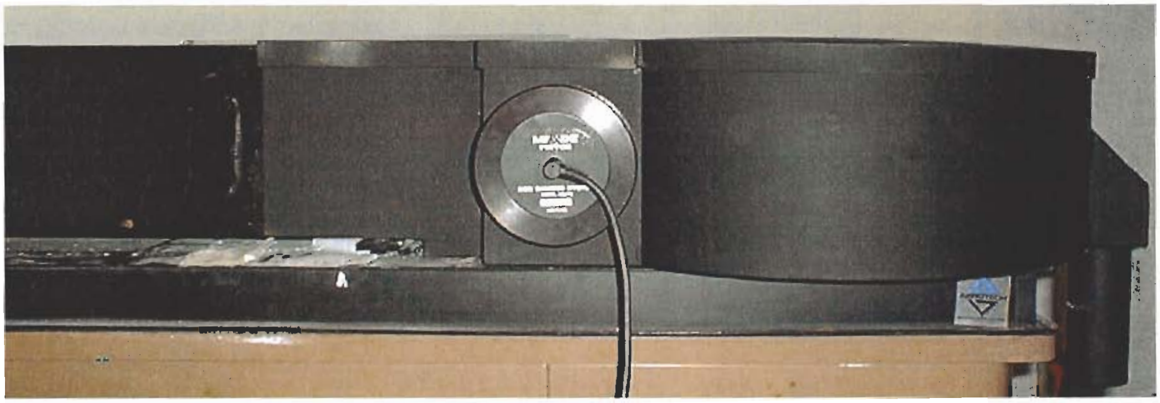

Figure 12: Front view of prototype with argon ion laser on the left and CCD camera mounted.

B. Box Experiment

After design of the prototype was made and preliminary tests showed that it was ready to be fabricated, the prototype was sent out to Engineering Services shop.

As the prototype was being machined, I collected new data and performed new tests. These new tests and data revealed that my prototype had become obsolete because of the difficulty in getting uniform particle distribution to be constant in time in the beam. Polarizations taken at two different times did not coincide because of the particle distribution that changed greatly over time. To be able to get the two polarizations to be accurately depicting the same exact particle distribution, both polarizations were taken simultaneously with two cameras on two computers.

From Figure 1, it is shown that that with the beam polarized vertically, a camera positioned to the side of the laser beam would be observing perpendicular polarization while a camera position on the top of the beam would be observing parallel polarization.

To be able to analyze the angles of 150 degrees to 165 degrees using the new setup using the box and no mirror, the cameras were moved further away from the beam to allow the two cameras to physically fit. The only disadvantage of moving the cameras further back as that it increased the total space needed for all test equipment. Because the compactness of the total setup is only a secondary goal, the cameras were moved back. The geometry used is shown in Figure 13.

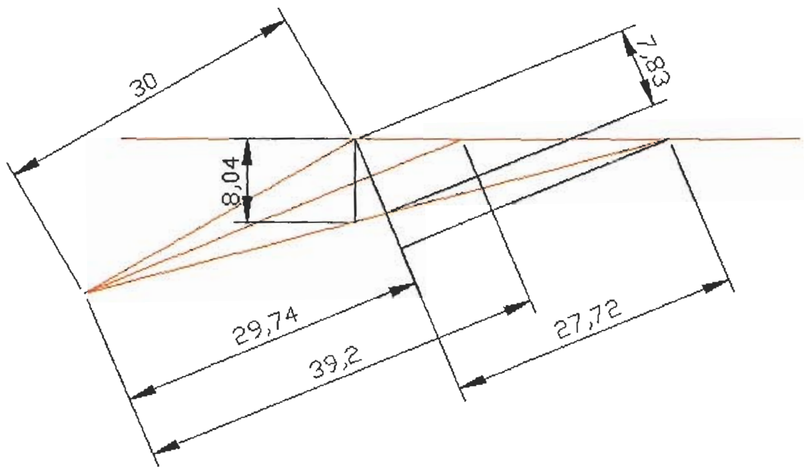

Figure 13: Box Experiment Geometry - The setup for the camera and the laser beam showing the scattering angles that will be measured. This geometry is used both for the camera on the side as well as for the camera positioned on the top of the beam.

VI. Data Analysis

A. Code Test

One test used to see if the code was reading in the images correctly was to use the image shown in Figure 14.

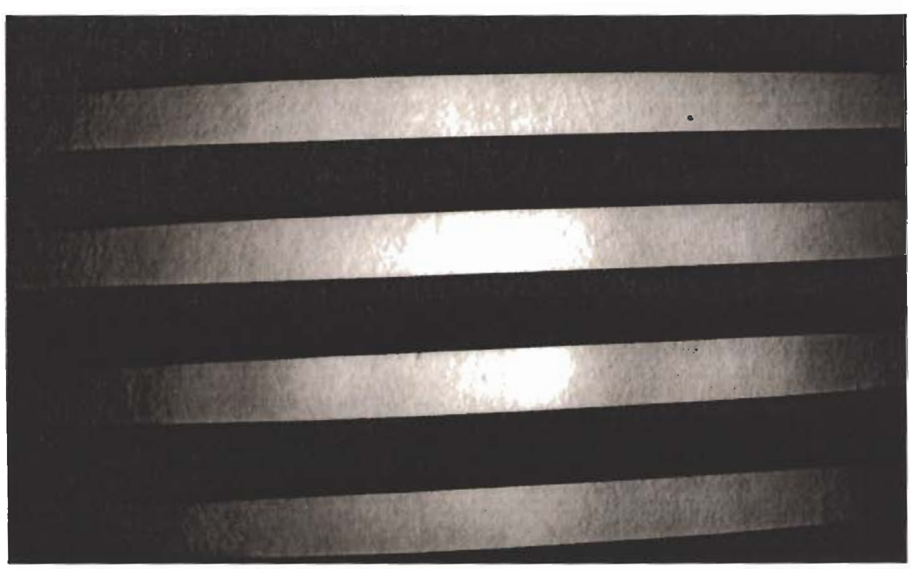

Figure 14: Image of lined paper used for code and image testing.

A piece of the image analyzed vertically should give great variation as the image is analyzed from the light to the dark spaces. Because of the slight unevenness of lighting, when analyzed in the horizontal direction there should be a slight variation in the intensity with the higher intensity in the center and lower on the edges.

The output of scatratio15 Matlab code from analyzing this image can be seen in Figure 15. The output is as expected from the code reading in the image shown in Figure 14.

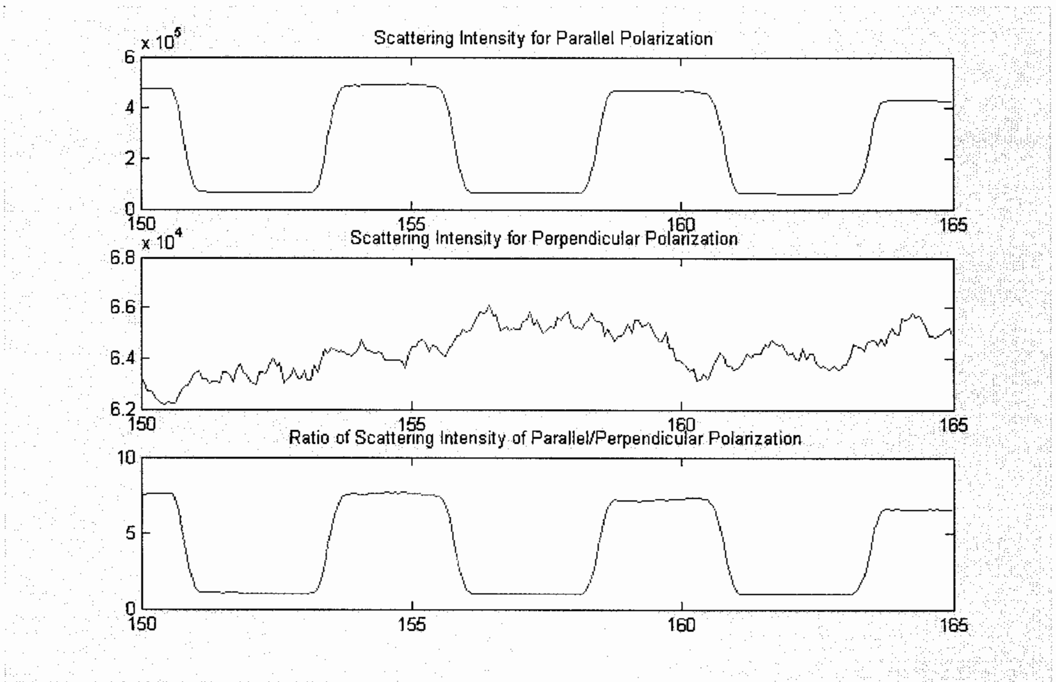

Figure 15: Output data from scatratio15 of image line 85mm 32ms 10cm.fts.

B. Simulated and Measured Data

The box experiment proved to be the most promising so this experiment will be described in detail in the simulated and measured data analysis section.

Previously measured samples of particles that had sizes of 2 μm, 8 μm, and 15 μm were used. Also because uniformity of the particles in the beam proved to be a problem, a fog machine was used to generate airborne particles that were suspended in the air longer than the solid particles.

Theoretical Simulations for Particles of Radius 2 μm, 8 μm, and 15 μm

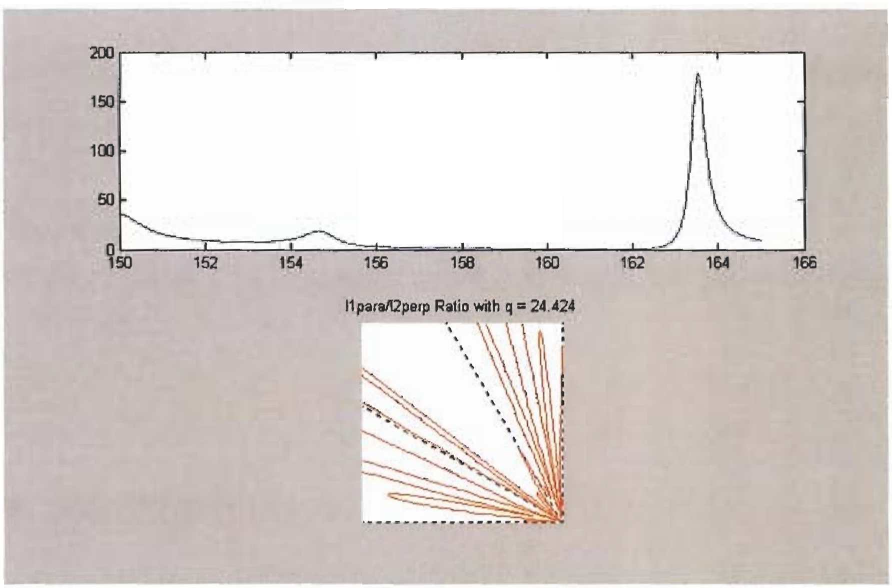

Figure 16: Ipara/Iperp Ratio with r = 2 μm, which is equal to q = 24.424
Top: In rectangular format showing 150° to 165°.
Bottom: In polar format showing 90° to 180°.

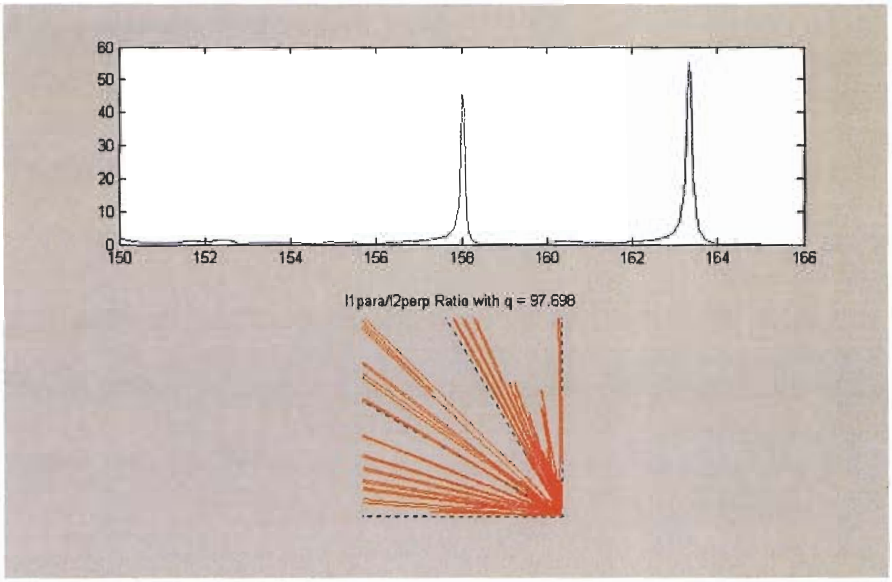

Figure 17: Ipara/Iperp Ratio with r = 8 μm, which is equal to q = 97.698
Top: In rectangular format showing 150˚ to 165˚.
Bottom: In polar format showing 90˚ to 180˚.

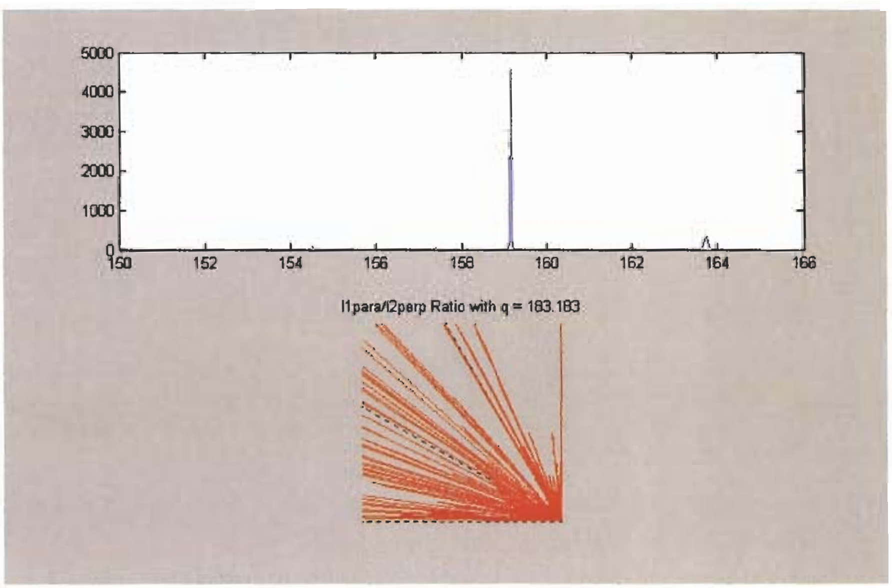

Figure 18: Ipara/Iperp Ratio with r = 15 μm, which is equal to q =183.183.
Top: In rectangular format showing 150˚ to 165˚.
Bottom: In polar format showing 90˚ to 180˚.

The theoretical size of the fog particles is not known and can range from 2 to 15 μm.

Experiment Procedure for Box Experiment:

1. A piece of lined paper was attached to a shaft and positioned at the point at the center of the angles of interest as calculated in the box experiment geometry shown in Figure 13. The cameras were focused on that paper and the paper was centered in the image.
2. A sample of the measured particulates was placed in the box.
3. Then a fan set at slow speed was turned on. This fan provided better uniformity of the particles after they were airborne.
4. The lights were turned off to eliminate excess light noise.
5. The laser was turned on and three squirts from the pressurized air were shot at the particle sample to disperse the particles into the air.
6. Then both computers, which controlled the cameras, were activated simultaneously to give images in the parallel and perpendicularly polarized directions of the exact same particle distribution.

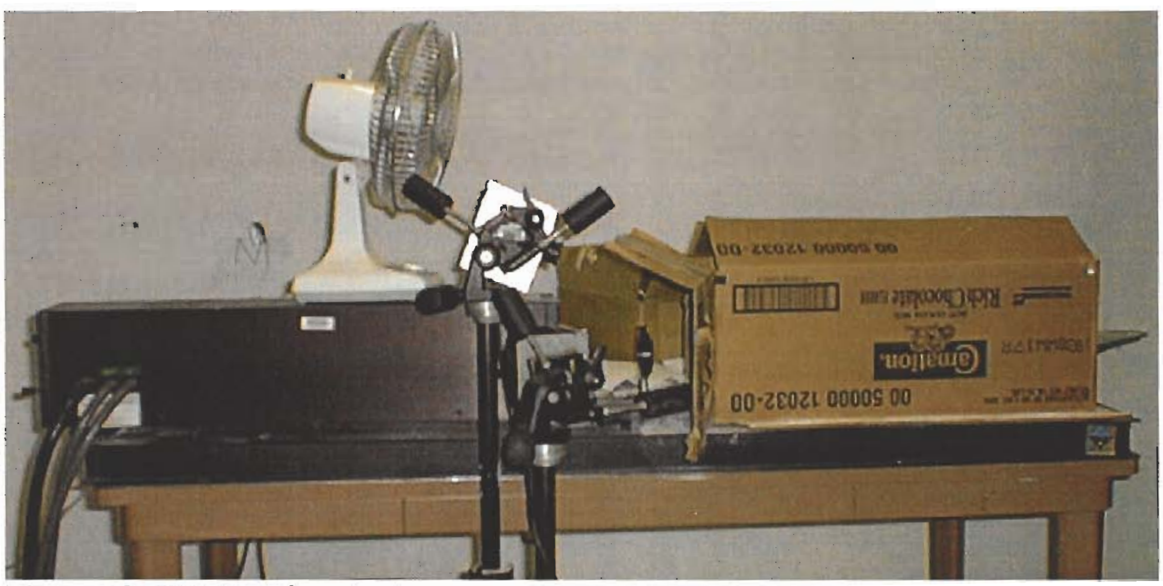

Figure 19: Box experiment setup.

Figure 20: Two cameras, argon ion laser, and fan with cardboard box removed.

Data Analysis:

1. The FITS files from both cameras, which contained the image of the beams, were looked at in the Pictor software and the width of the pixels that were used was determined. A certain width of pixels is calculated because the beam has some width and because of very fine adjustments the beam may not be exactly horizontal or vertical. In this way by adding up for a width, there is no loss of data.
2. The Matlab code was changed accordingly to account for the width.
3. Then twocamread.m was run witch reads in the FITS file and generates the output.

Figure 21 and 22 are examples of the FITS files that were captured by the Pictor camera and PictorView software. The images were then read in by the fitread.m code and then analyzed by the twocamread.m code to generate the output.

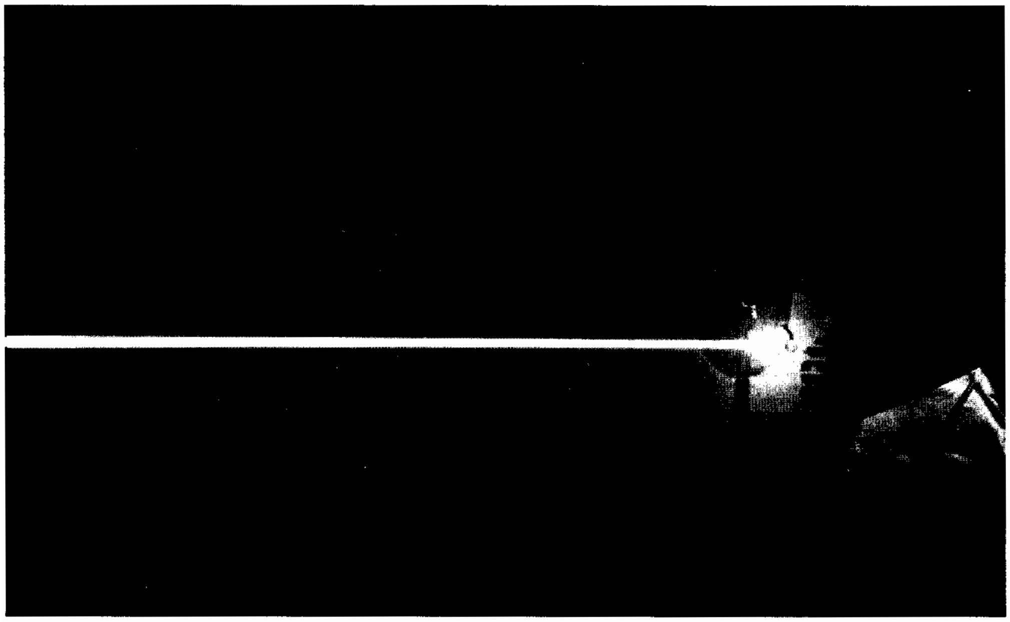

Figure 21: FITS Image from Camera C from Top of Box

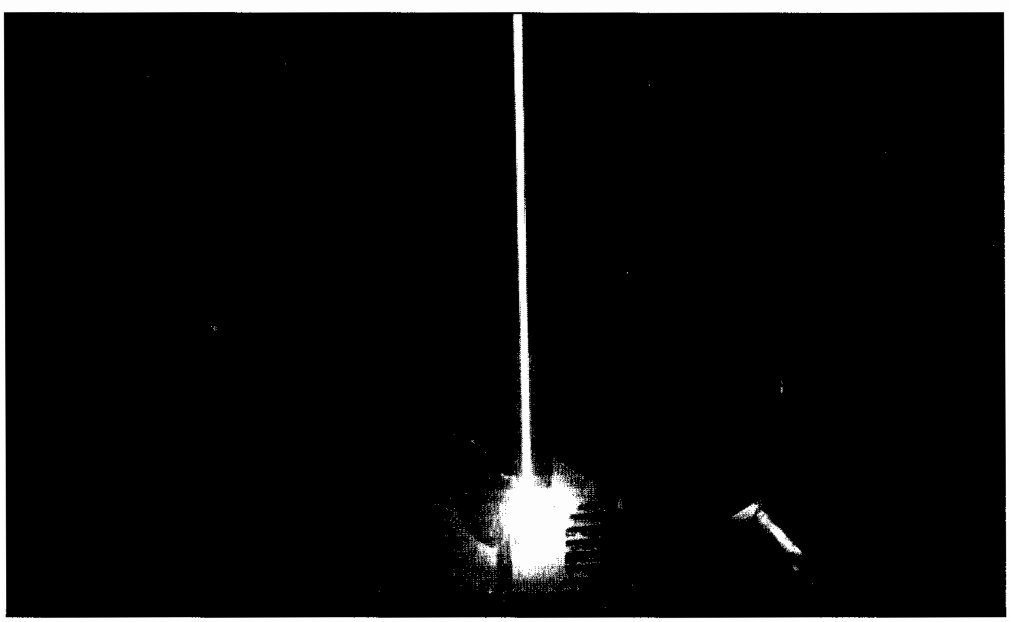

Figure 22: FITS Image from Camera B from Side of Box

Exposure time was 300 ms for fog particles.

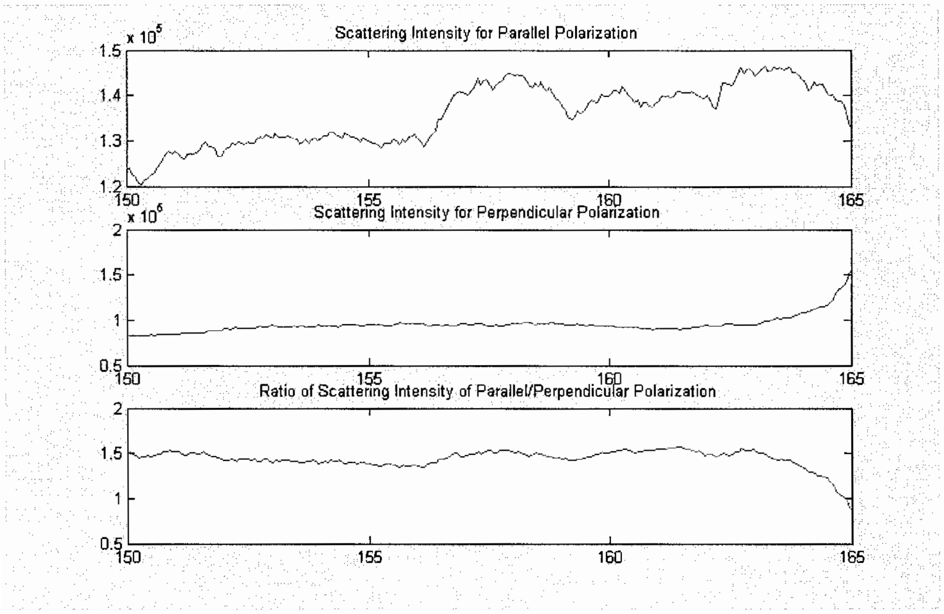

Figure 23: Measured intensities for Parallel, Perpendicular, and Ratio for fog particles.

Exposure time was 500 ms for particles 2 μm, 8 μm, and 15 μm.

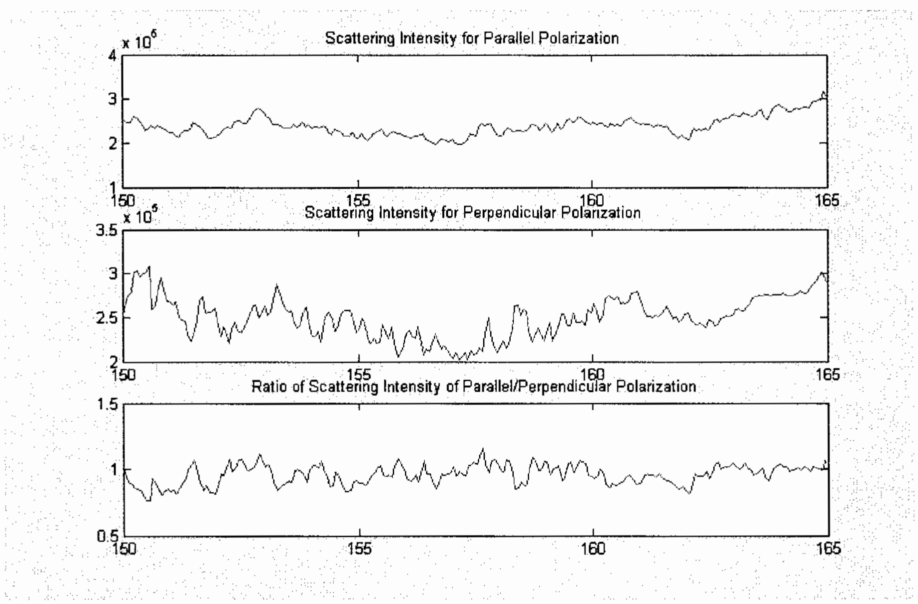

Figure 24: Measured intensities for Parallel, Perpendicular, and Ratio for r = 2 μm

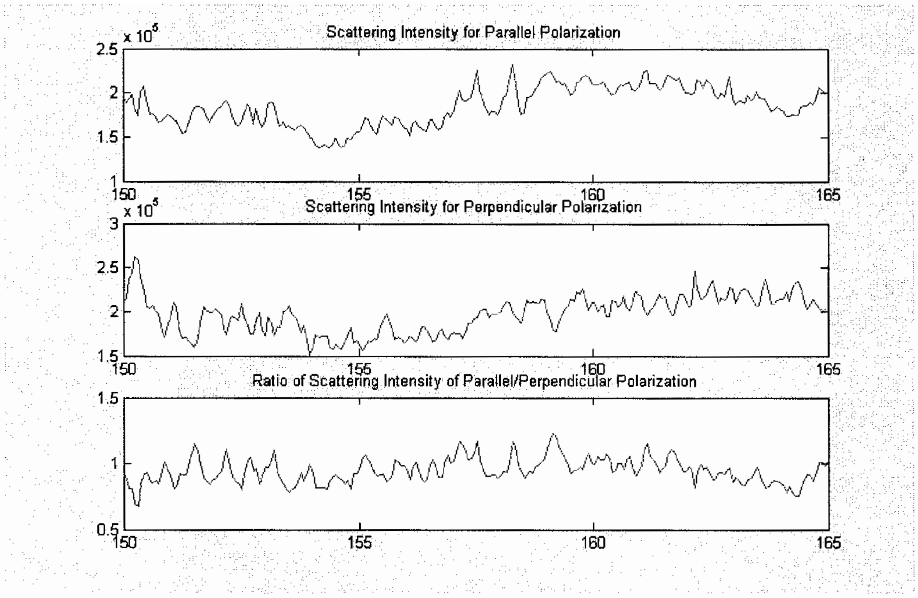

Figure 25: Measured intensities for Parallel, Perpendicular, and Ratio for r = 8 μm

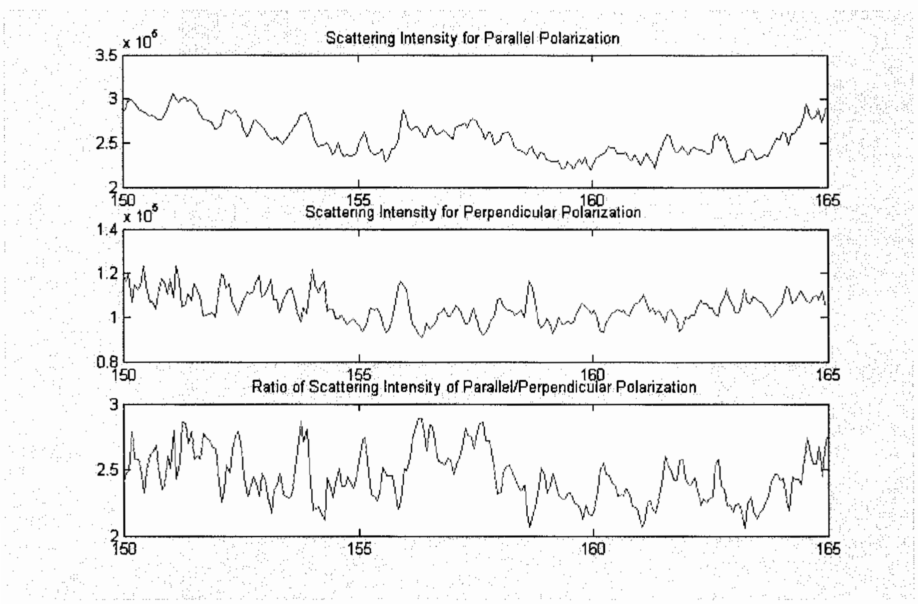

Figure 26: Measured intensities for Parallel, Perpendicular, and Ratio for r = 15 μm

Each trial is slightly different and although this data cannot be compared with the theoretical data to determine particle size conclusively, there is an increase of ratio complexity as the particle size increases, which does indicate an effect of the polarization ratio by particle size.

Even with the new setup the beam still displays two major problems:

1. The particle distribution in the beam is difficult to make uniform. Because the beam is not totally uniform and constant of a period of time, it cannot be determined if the scattered light is due to the scattering of the particles due to their size, or if it is simply due to the number of particles that the light is being scattered.
2. The particle distribution does not stay constant over a period of time. The intensities of the output of each trial are very different than the one before which again makes it difficult to determine if it is the particle size that is changing the scattering, or if it is the amount of particles being viewed at that particular time.

VII. Conclusion

Starting with the analysis of scattering phase plots, the theoretical plots for particles sizes were analyzed. Based on this analysis and design constraints the backscattering angles of 150 to 165 degrees were chosen as the angles of analysis that could be used to determine particle characterization.

As shown by experimentation, the prototype was unable to provide the desired results in the small exposure times of my experiments, but in the future, the prototype can be used for other types of experiments and modified to measure the backscattering in different conditions.

While most design problems could be overcome, the ability to get a uniform beam over several trials was very difficult. Using two cameras in later experiments allowed the data to be more accurate because both polarizations were taken at same time and therefore the measured beam had the same uniformity when both polarizations were taken. However, because the particles in the beam could not be dispersed totally evenly and that several particle sizes innately existed in a sample, the data was not able to fully substantiate the theory of utilizing the polarization ratio technique in a small-scale environment. New methodology and designs were presented that could be used in the future to make an airborne particle characterization instrument.

VIII. Future Research

The purpose of this thesis was to make a new methodology to determine particle sizes from a small sample of airborne particles. Further research would include characterizing many sizes of particles and comparing them with the theoretical values to determine the particle size.

Also work into particle size distribution would be a needed further step. This would need to be done because even though a sample that is measured to be a certain radius and has the majority of particles at the specified size, there are still many particles that are not of that size, which would distort the results.

In my experiments the images were taken over short time exposures. A possible area for advancement would be to analyze relatively clean ambient air from the outside over a long period of time such as hours or days, which would generate a more uniform distribution because the data is measured over such a long time. This method would be used find the average particle size throughout that time frame.

IX. References

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Appendix A:

Matlab Files

```
% File: scattering.m
% Purpose: Given the particle radius, creates polar plots of
%   perpendicular and parallel polarized scattered light.
% Dependence: Calls bhime.m program
% Author: Created 04/00 by Homer Li to calculate extinction value
%        Modified: 09/25/01 through 03/20/02 by Matthew Angert
%           1. To make polar plots in needed form.
%           2. Deleted unneeded portions of code.

function [s1,s2,x,rangm]=scattering(rad,m,n,p);

% Set incident sphere material variables
refmed=1.0;
refre=1.25;
refim=0.0;
refrel=refre+refim*i;

wavel=6.283;    % Wavelength in nm
x=2*pi*rad*refmed/wavel;
% The x (= q value) is input to bhmie and not rad or wavel
% therefore to make calculation of polar scattering plots easier
% to work with, the wavelength value chosen cancels out the 2 pi.

% Number of points between 0 and 180 degrees.
nang=181;

dang=pi/(2*(nang-1));
% Call to bhmie
[s1,s2]=bhmie(x,refrel,nang);

% The 'for' statement is from Homer Li's code to calculate rangm.
nan=nang*2-1;
for j=1:nan
   aj=j;
   ang=dang*(aj-1)*57.2928;
   rang=2*pi/360*ang;
   rangm(j)=rang;
end;

% Calculates perpendicular and parallel intensities.
iperp=abs(s1).^2;
ipara=abs(s2).^2;

% Allows plots to be viewed from 0 to 360 degrees.
nrangm=-rangm;
```

```
% Plots 0 to 180 degrees, then 181 to 360 degrees for perpendicular
%     polarization,
%  then plots 0 to 180 degrees, then 181 to 360 degrees for parallel
%     polarization
subplot(m,n,p), polar(rangm,iperp,'r');
hold on;
subplot(m,n,p), polar(nrangm,iperp,'r');
subplot(m,n,p), polar(rangm,ipara,'b');
subplot(m,n,p), polar(nrangm,ipara,'b');

toptitle = sprintf('I1perp(red) and I2para(blue) with q = %4.3f',x);
title(toptitle);

disp('x=');
disp(x);

return;
```

```
% File: Scatmain.m
% Purpose: Performs multiple scattering plots when input
%    particle radius r.
% Author: Matthew Angert 10/01
% Dependence: Calls scattering.m.
% Notes: This particular set of data reproduces the plots found in
%  Born and Wolf "Principles of Optics" p655.

%rows
m=2;
%columns
n=2;
clf;

% Because of wavelength chosen in scattering.m, rad = q.

rad=0.8;
p=1;
[s1,s2,x,rangm]=scattering(rad,m,n,p);

rad=1.6;
p=2;
[s1,s2,x,rangm]=scattering(rad,m,n,p);

rad=4;
p=3;
[s1,s2,x,rangm]=scattering(rad,m,n,p);
axis([-3 8 -5 5]);

rad=8;
p=4;
[s1,s2,x,rangm]=scattering(rad,m,n,p);
axis([-10 5 -8 8]);
```

```
% Code unchanged from original. -MA

% bhmie.m is a program for calculating extinction and
% scattering coefficients from s1,s2.
% Refer to measure's book. (Attached program)
% *** This is READ ONLY program ***
% Created 04/00 by Homer LI

function
[s1,s2,qext,qsca,qback]=bhmie(x,refrel,nang,s1,s2,qext,qsca,qback)

dx=x;
y=x*refrel;

xstop=x+4*(x^.3333)+2.0;
nstop=xstop;
ymod=abs(y);
nmx=round(max(abs(xstop),abs(ymod))+15);
dang=pi/(2*(nang-1));
%nang
for j=1:nang
   theta(j)=(j-1)*dang;
   amu(j)=cos(theta(j));
end;

d(nmx)=0+0*i;
nn=nmx-1;
for n=1:nn
   rn=nmx-n+1;
   d(nmx-n)=(rn/y)-(1/(d(nmx-n+1)+rn/y));
end;

for j=1:nang %105
   pi0(j)=0.0;
   pi1(j)=1.0;
end;

nn=2*nang-1;

for j=1:nn
   s1(j)=0.0+0.0*i;
   s2(j)=0.0+0.0*i;
end;

psi0=cos(dx);
psi1=sin(dx);
chi0=-sin(x);
chi1=cos(x);
apsi0=psi0;
apsi1=psi1;
xi0=apsi0-i*chi0;
xi1=apsi1-i*chi1;
qsca=0.0;
n=1;

while ((n)<nstop)
dn=n;
```

```
rn=n;
fn=(2*rn+1)/(rn*(rn+1));
psi=(2*dn-1)*psi1/dx-psi0;
apsi=psi;
chi=(2*dn-1)*chi1/x-chi0;
xi=apsi-i*chi;
an=(d(n)/refrel+rn/x)*apsi-apsi1;
an=an/((d(n)/refrel+rn/x)*xi-xi1); %134

bn=(refrel*d(n)+rn/x)*apsi-apsi1;
bn=bn/((refrel*d(n)+rn/x)*xi-xi1);

%abs(an)
qsca=qsca+(2*rn+1)*(abs(an)*abs(an)+abs(bn)*abs(bn));

for j=1:nang
   jj=2*nang-j;
   PI(j)=pi1(j);
   tau(j)=rn*amu(j)*PI(j)-(rn+1)*pi0(j);
   p=(-1)^(n-1);%142

   s1(j)=s1(j)+fn*(an*PI(j)+bn*tau(j));
   t=(-1)^n;
   s2(j)=s2(j)+fn*(an*tau(j)+bn*PI(j));
   if j==jj
   else
      s1(jj)=s1(jj)+fn*(an*PI(j)*p+bn*tau(j)*t);
      s2(jj)=s2(jj)+fn*(an*tau(j)*t+bn*PI(j)*p);
   end;%149
end;
psi0=psi1;
psi1=psi;
apsi1=psi1;
chi0=chi1;
chi1=chi;
xi1=apsi1-i*chi1;
n=n+1;
rn=n;

for j=1:nang
   pi1(j)=((2*rn-1)/(rn-1))*amu(j)*PI(j);
   pi1(j)=pi1(j)-rn*pi0(j)/(rn-1);
   pi0(j)=PI(j);
end;
end;

qsca=(2/(x*x))*qsca;
qext=(4/(x*x))*real(s1(1));
qback=(4/(x*x))*abs(s1(2*nang-1))*abs(s1(2*nang-1));
```

```
% File: Scatratio.m
% Purpose: Given the particle radius, calculates scattering phase
%   functions. Plots the ratio of perpendicular and parallel
%   polarized scattering phase functions.
% Dependence: Need to call bhmie.m program
% Author: Created 04/00 by Homer Li
%        Modified: 09/25/01 through 03/20/02 by Matthew Angert
%           1. To make polar plots in needed form.
%           2. Deleted unneeded portions of code.
%           3. Plots function to plot ratio of polarizations.

function [s1,s2,x,rangm]=scatratio(rad,m,n,p);

% Set incident sphere material variables
refmed=1.0;
refre=1.25;
refim=0.0;
refrel=refre+refim*i;

wavel=6.283;    %Wavelength in nm
x=2*pi*rad*refmed/wavel;
% The x (= q value) is input to bhmie and not rad or wavel
% therefore to make calculation of polar scattering plots easier
% to work with, the wavelength value chosen cancels out the 2 pi.

% Number of points between 0 and 180 degrees.
nang=181;
dang=pi/(2*(nang-1));

% Call to bhmie
[s1,s2]=bhmie(x,refrel,nang);

% The 'for' statement is from Homer Li's code to calculate rangm.
nan=nang*2-1;
for j=1:nan
   aj=j;
   ang=dang*(aj-1)*57.2928;
   rang=2*pi/360*ang;
   rangm(j)=rang;
end;

% Calculates perpendicular and parallel intensities.
iperp=abs(s1).^2;
ipara=abs(s2).^2;

% Calculates ratio of parallel and perpendicular intensities.
ratio=(ipara./iperp);

% Allows plots to be viewed from 0 to 360 degrees.
nrangm=-rangm;

% Creates polar plot of the ratio of the polarizations.
subplot(m,n,p), polar(rangm,ratio,'r');
hold on;
subplot(m,n,p), polar(nrangm,ratio,'r');

toptitle = sprintf('I1para/I2perp Ratio with q = %4.3f',x);
```

```
title(toptitle);

disp('x=');
disp(x);

return;
```

```
% File: scatratiomain.m
% Purpose: Used to call scatratio to perform multiple scattering plots
%  when input particle radius r.
% Author: Matthew Angert 10/01
% Dependence: Calls scatratio.m.
% Note: This file plots ratios for the q values of 6 to 90 in the
%  backscattering region of 180 to 270 degrees.

%rows
m=3;
%columns
n=3;
clf;

% Because of wavelength chosen in scatratio.m, rad = q.
rad=6;
p=1;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=10;
p=2;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=15;
p=3;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=20;
p=4;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=50;
p=5;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=60;
p=6;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=70;
p=7;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=80;
p=8;
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);

rad=90;
p=9;
```

```
[s1,s2,x,rangm]=scatratio(rad,m,n,p);
axis([-5 0 -5 0]);
```

```
% File: Scatratio15.m
% Purpose: Given the particle radius, calculate scattering phase
%        functions. Plots the ratio of parallel and perpendicular
%        polarized scattering phase functions for the 15 degrees
%        of interest of 150 to 165 degrees. Creates theoretical
%        ratio plot.
% Dependence: Need to call bhmie.m program
%
% Author: Created 04/00 by Homer Li
%         Modified: 09/25/01 through 03/20/02 by Matt Angert
%            1. To make polar plots in needed form.
%            2. Deleted unneeded portions of code.
%            3. Plots function to plot ratio of polarizations.


% function [s1,s2,x,rangm]=scatratio15(rad,m,n,p);
clear;
refmed=1.0;
refre=1.25;
refim=0.0;
refrel=refre+refim*i;

clf;
p=1;

rad=0.5;          %Radius of particle in units of um.

% Argon Ion laser wavelength of 514.5 nm is used.
wavel=.5145;    %Wavelength of incident light in um.


x=2*pi*rad*refmed/wavel

% 165 deg = 2.87979327 rad    program: 2.8801
% 150 deg = 2.61799388 rad             2.6188

nang=2676;
dang=pi/(2*(nang-1));
[s1,s2]=bhmie(x,refrel,nang);

nan=nang*2-1;

for j=1:nan
   aj=j;
   ang=dang*(aj-1)*57.2928;
   rang=2*pi/360*ang;
   rangm(j)=rang;
end;

iperp=abs(s1).^2;
ipara=abs(s2).^2;

nrangm=-rangm;
ratio=(ipara./iperp);

% Choose only the 15 degrees from 150 to 165 degrees
for choose=4461:4906
```

```
    comratio(choose-4460)=ratio(choose);
    comrangm(choose-4460)=rangm(choose);
end;

comdeg=comrangm/2/pi*360;
subplot(2,1,1), plot(comdeg,comratio);

% 2.87979327-2.61799388=.26179939/445=5.8831e-4
crangm=2.61799388:5.8831e-4:2.87979327;

% subplot(m,n,p), polar(rangm,ratio,'r');
% hold on;
subplot(2,1,2), polar(rangm,ratio,'r');

toptitle = sprintf('I1para/I2perp Ratio with q = %4.3f',x);
title(toptitle);
axis([-5 0 0 5]);

% return;
```

```
% File: twocamread.m
% Purpose:  Reads in parallel and perpendicular polarized FITS
%           files and outputs parallel, perpendicular, and
%           ratio plots for 150 to 165 degrees.
% Dependence: Need to call fitsread program
%
% Author: Created April 2002 by Matthew Angert
%

clf;
clear;
% Puts output "ans" of "fitsread" into "para" and "perp" matrices
% Size of matrix = 512 x 768

% %Code Test
% fitsread ..\camera\line85mm32ms15cm.fts;
% para = ans;
%
% fitsread ..\camera\line85mm32ms15cm.fts;
% perp = ans;
%
fitsread ..\Data040702\laC-023.fts;
para = ans;

fitsread ..\Data040702\laB-023.fts;
perp = ans;

%This makes matrices now in Matlab look like the coordinates in Pictor.
fpara = flipud(para);
tfpara = transpose(fpara);
fperp = flipud(perp);
tfperp = transpose(fperp);


% Top => beam runs horizontal => Parallel
% Calculates 240 pixels;
% Start at pixel 265 and go to pixel 504 = 240 pixels
for pix=1:240;
    sumwidth=0;

% Adds values for 11 pixels wide and puts in 1x446 matrix
% Pixel 248 to 258
% tfpara in form of (x+1,y+1) of Pictor coordinates
%   (0,0)Pictor = (1,1)Matlab
%   so tfpara has one more than pictor coordinates
%  matrix read (row, col)
for width=1:11;
        sumwidth=tfpara(265+pix,248+width) + sumwidth;
        testpara(width,pix)=tfpara(265+pix,248+width);
        respara(pix)= sumwidth;
    end
end

% Side => beam runs vertical => Perpendicular
% Calculates 240 pixels;
% Start at pixel 137 and go to pixel 376 = 240 pixels
for pix=1:240;
```

```
    sumwidth=0;

% Adds values for 11 pixels wide and puts in 1x406 matrix
% Pixel 380 to 390
%  matrix read (row, col)
      for width=1:11;
        sumwidth=tfperp(380+width,137+pix) + sumwidth;
        testperp(width,pix)=tfperp(380+width,137+pix);
        resperp(pix)= sumwidth;
    end
end

% 15 deg /239 pixel=0.062761506
degmat=150:0.062761506:165;

% With rotator Polarizations switch
resparatemp=resperp;
resperp=respara;
respara=resparatemp;

resratio=respara./resperp;

subplot(3,1,1), plot(degmat,respara);
title('Scattering Intensity for Parallel Polarization');

subplot(3,1,2), plot(degmat,resperp);
title('Scattering Intensity for Perpendicular Polarization');

subplot(3,1,3), plot(degmat,resratio);
title('Ratio of Scattering Intensity of Parallel/Perpendicular
Polarization');
```

```
% Code unchanged from original- MA

function [output_image, bzero, bscale] = fitsread(filename,n_hdu)
%FITSREAD reads a FITS image into a Matlab variable.
%
%  [data, bzero, bscale]=fitsread(filename)
%  [data, bzero, bscale]=fitsread(filename,h_hdu)
%
% The variable 'n_hdu' explicity tells FITSREAD how many
% sets of 36 header 'cards' precede the data. One normally
% lets the function figure this out on its own.
%
% Final data values are to be computed by data*bscale+bzero
%
% Known problems
%     Will only deal with 2D fits files.
%
% Version 2.0
% R. Abraham, Institute of Astronomy, Cambridge University
%
% Modified R.G.Lane 18 November 1997 to use strcmp
%                                to return bzero, bscale
% EEE University of Canterbury

%The first few cards of the first set of 36 cards must give information
%in a pre-defined order (eg. the data format, number of axes,
%size etc) but after that the header keywords can come in any
%order. The end of the last card giving information is flagged by
%the keyword END, after which blank lines are added to pad the
%last set of cards so it also contains 36 cards. After the last card
%the data begins, in a format specified by the BITPIX keyword.
%The dimensions of the data are specified by the NAXIS1 and
%NAXIS2 keywords.
%
%Reference:   NASA/Science Office of Standards and Technology
%           "Definition of the Flexible Image Transport System"
%                             NOST 100-1.0
%
%           This and other FITS documents are available on-line at:
%           <A
HREF="http://www.gsfc.nasa.gov/astro/fits/basics_info.html">http://www.
gsfc.nasa.gov/astro/fits/basics_info.html</A>

%Set flag indicating unknown number of HDUs
if nargin<2
      n_hdu='unknown';
end;

if isstr(n_hdu)
      n_hdu=upper(n_hdu);
end;

%Allow user to specify a few keywords to indicate number of card sets
if strcmp(n_hdu,'HST') | strcmp(n_hdu,'STSCI') | strcmp(n_hdu,'MDS')
   n_hdu=6;
end
if strcmp(n_hdu,'FREI')
```

```
   n_hdu=2;
end

%Open the file
fid=-1;
if ~isstr(filename)
      filename=setstr(filename);
end;
if (isempty(findstr(filename,'.'))==1)
      filename=[filename,'.fits'];
end
[file,message] = fopen(filename,'r','l');
if file == -1
      error(message);
end


%First five cards must contain specific information
[d,simple,d]=parse_card(setstr(fread(file,80,'uchar')'));
[d,bitpix,d]=parse_card(setstr(fread(file,80,'uchar')'));
[d,naxis,d]=parse_card(setstr(fread(file,80,'uchar')'));
[d,naxis1,d]=parse_card(setstr(fread(file,80,'uchar')'));
[d,naxis2,d]=parse_card(setstr(fread(file,80,'uchar')'));


if n_hdu=='UNKNOWN'
      %Keep reading cards until one turns up with the keyword 'END'.
      n_card=5;
      keyword=' ';
      while(~strcmp(upper(deblank(keyword)),'END'))
                  n_card=n_card+1;
            card=setstr(fread(file,80,'uchar')');
                keyword=parse_card(card);
            if (strcmp(upper(deblank(keyword)),'BZERO'))
                  [keyword,bzero,comment]=parse_card(card);
                  end
            if (strcmp(upper(deblank(keyword)),'BSCALE'))
                    [keyword,bscale,comment]=parse_card(card);
                  end
      end;
      %Go past the blank lines of padding before the start of the data
      n_blanks = 36 - rem(n_card,36);
      dummy=fread(file,n_blanks*80,'uchar');
else
      dummy=fread(file,((n_hdu*36)-5)*80,'uchar');
end;

%Read the data. Note big-endian switch is used (Mac and UNIX!
if bitpix==-64
   X=fread(file,naxis1*naxis2,'float32','b');
elseif bitpix==-32
   X=fread(file,naxis1*naxis2,'float','b');
elseif bitpix==8
   X=fread(file,naxis1*naxis2,'uint8','b');
elseif bitpix==16
   X=fread(file,naxis1*naxis2,'short','b');
elseif bitpix==32
```

```
   X=fread(file,naxis1*naxis2,'long','b');
else
   error('data type specified by BITPIX keyword is not -64, -32, 8, 16,
or 32');
end;

%Clean up and output data
fclose(file);
output_image=rot90(reshape(X,naxis1,naxis2));
```

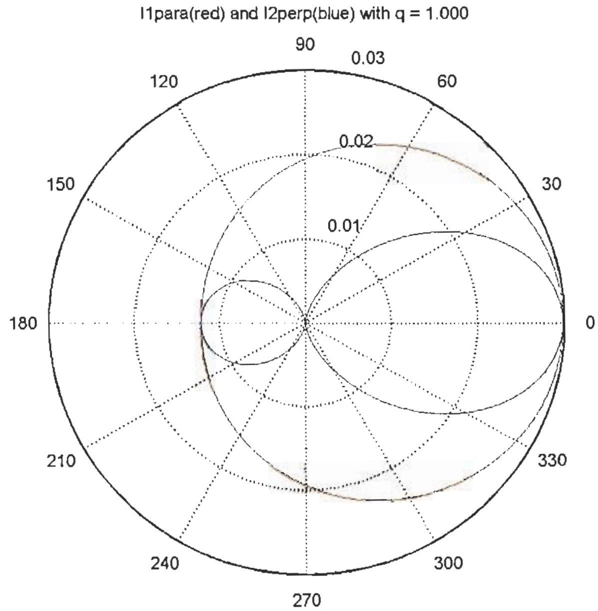
```
% Code unchanged from original- MA
% Needed for use with fitsread.m

function [keyword,value,comment] = parse_card(s)
%PARSE_CARD Parses a FITS header card.
%Reference:
%                NASA/Science Office of Standards and Technology
%           "Definition of the Flexible Image Transport System (FITS)"
%                        NOST 100-1.0    June 19, 1993

%Set defaults
s
keyword=[];value=[];comment=[];

%Get keyword in bytes 1 - 8
keyword=s(1:(min(max(size(s)),8)));
%keyword=s(1:8);
if nargout==1
   return;
end

%If keyword is blank then the line is a comment
if strcmp(keyword,'       ')
    keyword=[];
      value=[];
      comment=deblank(s(11:80));
      return;
end;


%Keyword is non-blank. Check if there is a corresponding value/comment.
%If not then the only possibilities are that bytes 11:80 are a comment
%or that they are blank
if ~strcmp(s(9:10),'= ')
    keyword=deblank(keyword);
      value=[];
      comment=deblank(s(11:80));
      return;
end;

%Card is a standard keyword/value/comment structure. Break the
value/comment
%string (bytes 11 - 80) into separate strings by tokenizing on "/"
character.
%Remove the leading and trailing blanks on the value and the trailing
blanks
%on the comment.

keyword=deblank(keyword);
[value,comment]=strtok(s(11:80),'/');
comment=deblank(comment);
value=fliplr(deblank(fliplr(deblank(value))));

%Now figure out whether to output the value as a string or as a number.
%The FITS standard requires all values that are strings to be in single
%quotes like this: 'foo bar', so I can simply look for occurences of a
%single quote to flag a string. However, logical variables can take the
```

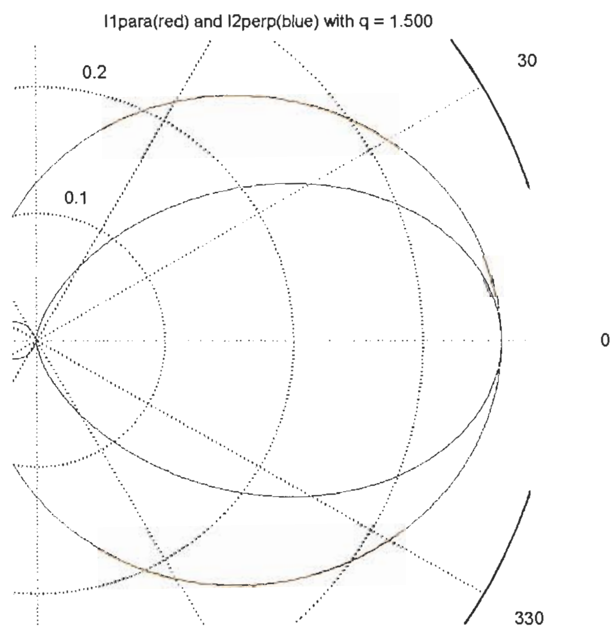
```
%values T or F without having any single quotes, so I'll have to look
%out for those also.

%Test for logical. Return logical as a string.
if strcmp(upper(value),'T') | strcmp(upper(value),'F')
      return;
end;

%Test for string. Return string unconverted.
if length(findstr('''',value)) ~= 0
      return;
end;

%Only thing left is a number. Convert string to number.
value=str2num(value);
```

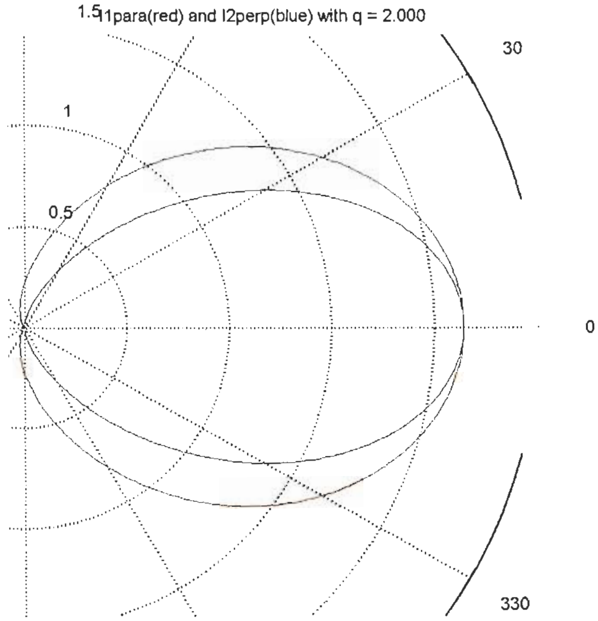
Appendix B:

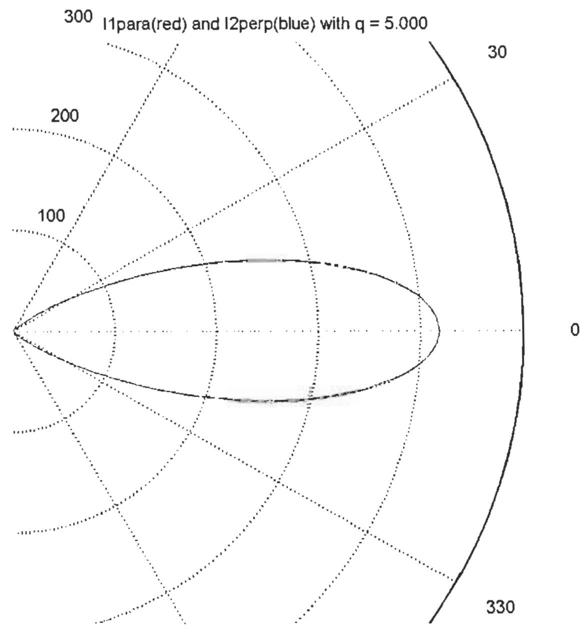
Scattering Plots

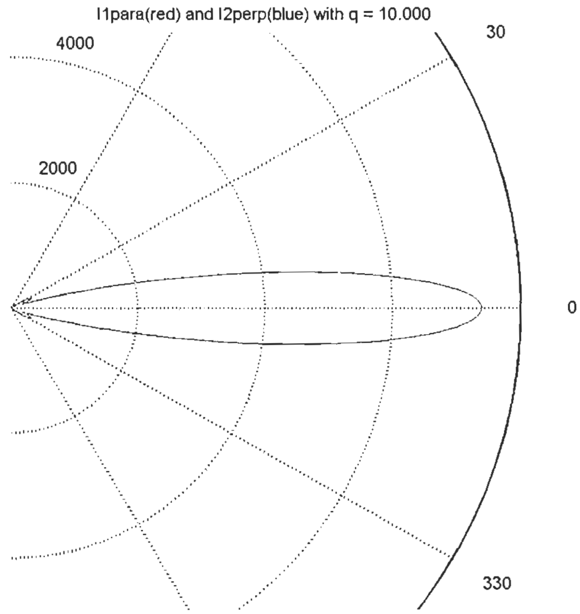
Front Scattering Plots:

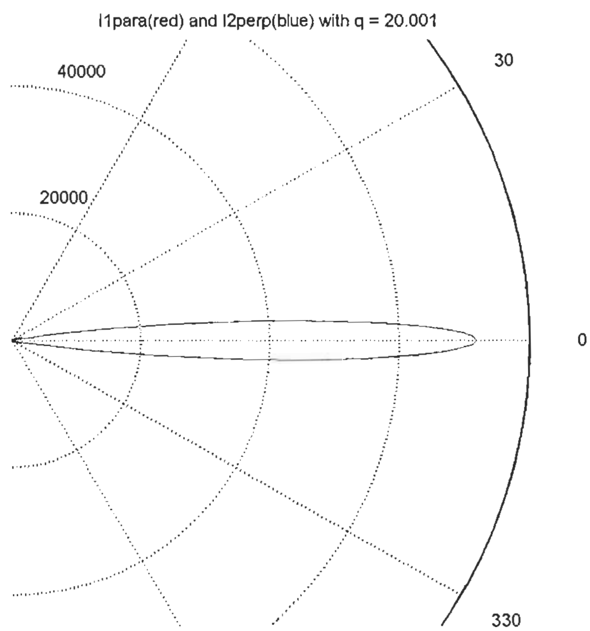





1.5
I1para(red) and I2perp(blue) with q = 2.000
30
1
0.5
0
330

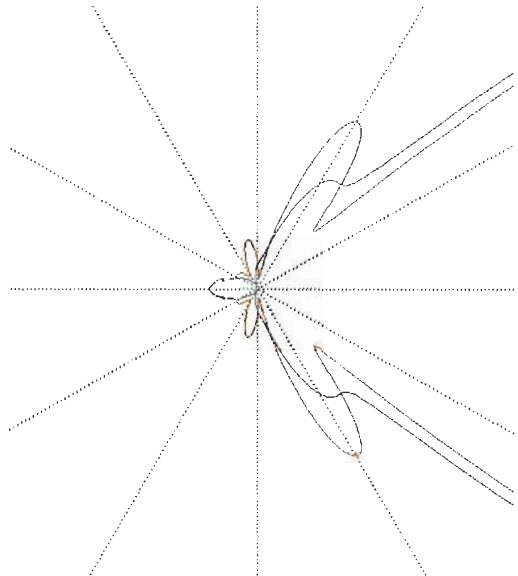

300
I1para(red) and I2perp(blue) with q = 5.000
30
200
100
0
330


I1para(red) and I2perp(blue) with q = 10.000
4000
2000
30
0
330

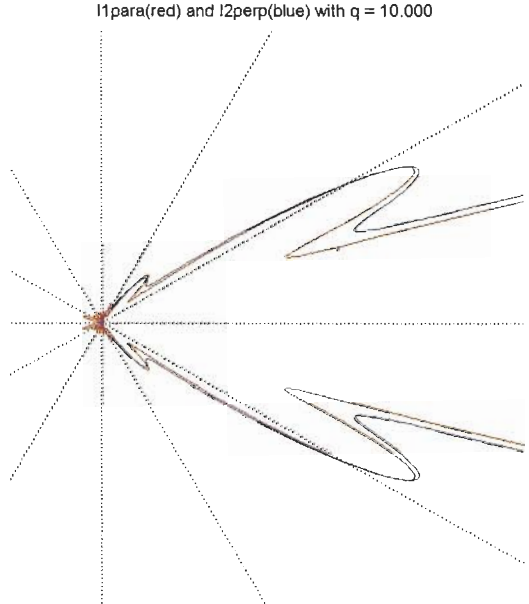

I1para(red) and I2perp(blue) with q = 20.001
40000
20000
30
0
330

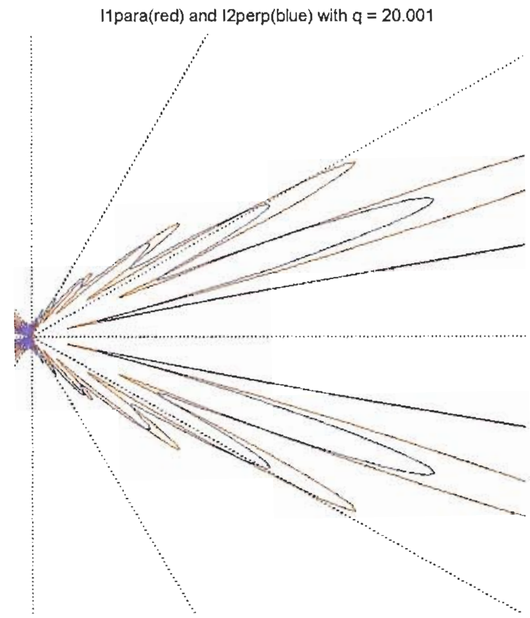
Front Side Scattering Plots:

I1para(red) and I2perp(blue) with q = 5.000

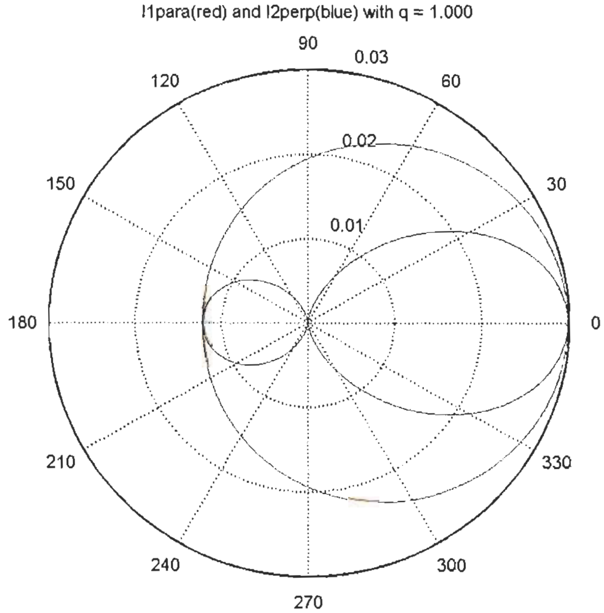


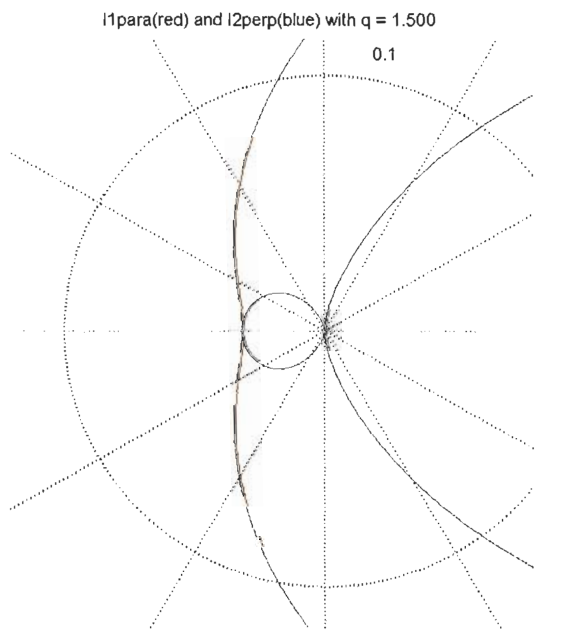
I1para(red) and I2perp(blue) with q = 10.000



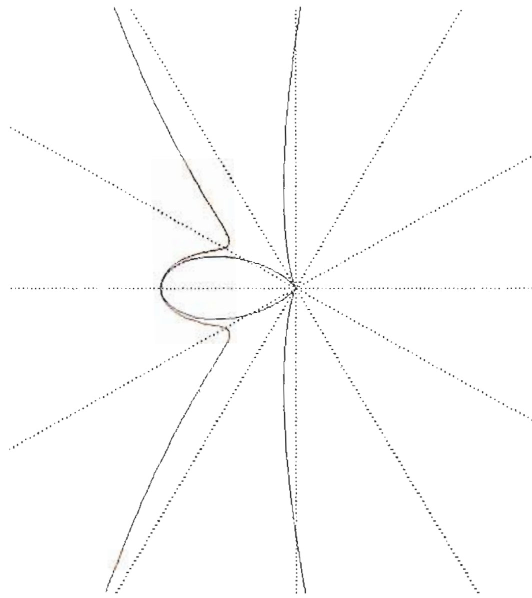

I1para(red) and I2perp(blue) with q = 20.001

Back Scattering Plots:

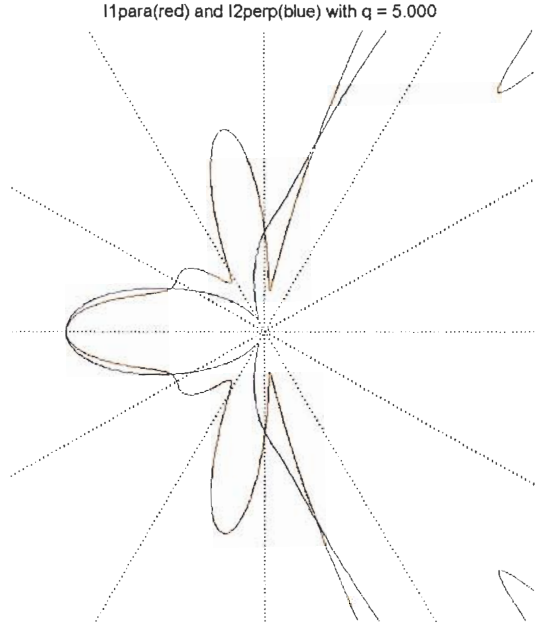




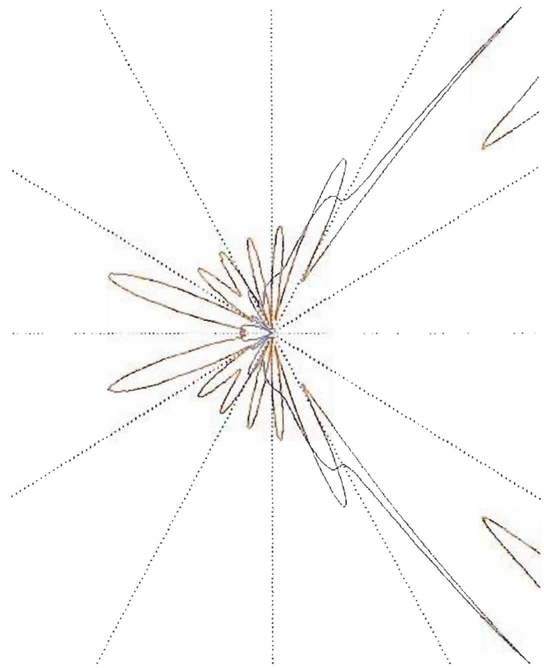
I1para(red) and I2perp(blue) with q = 2.000



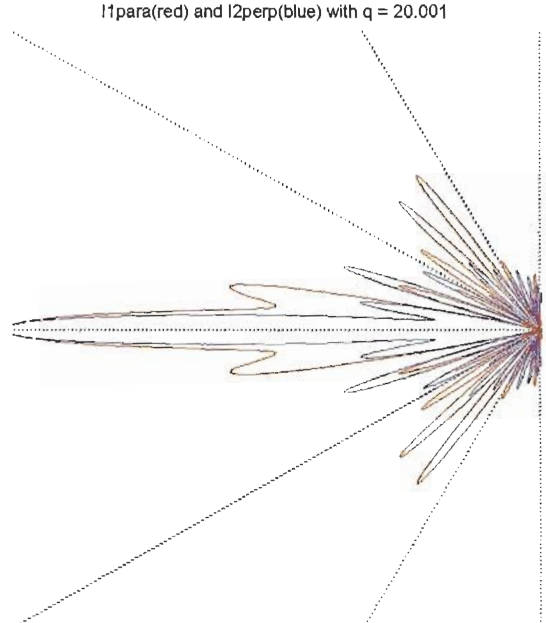
I1para(red) and I2perp(blue) with q = 5.000



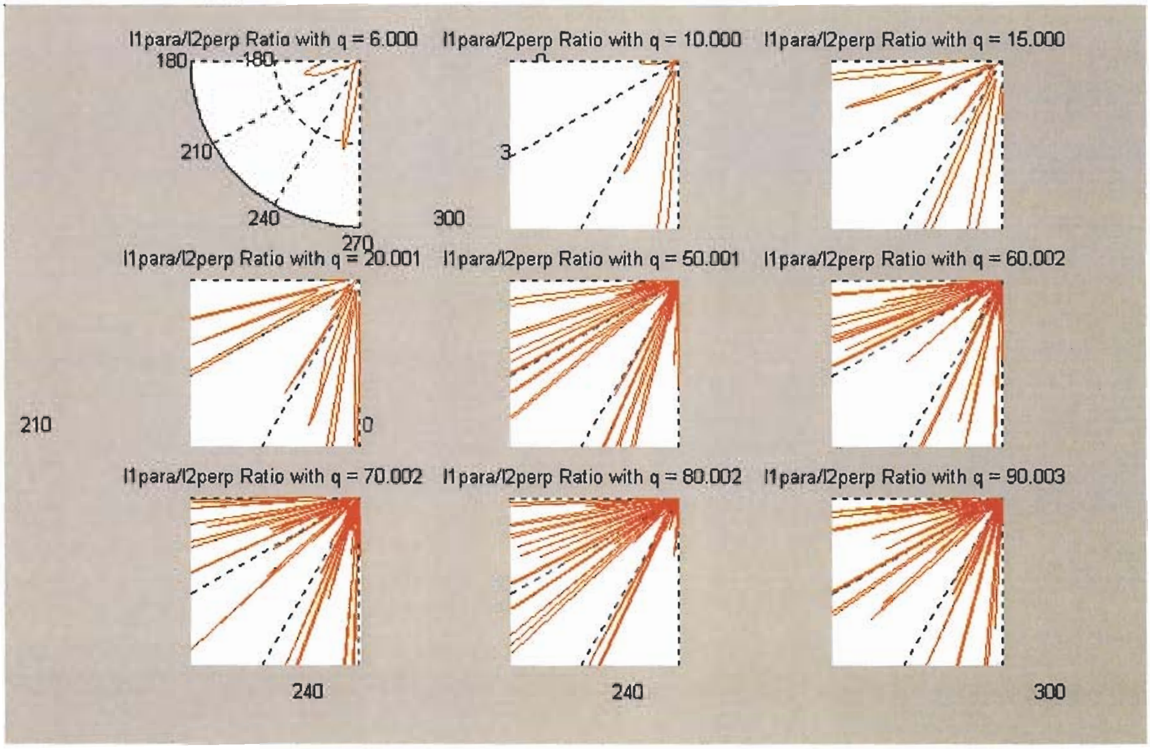
I1para(red) and I2perp(blue) with q = 10.000



I1para(red) and I2perp(blue) with q = 20.001



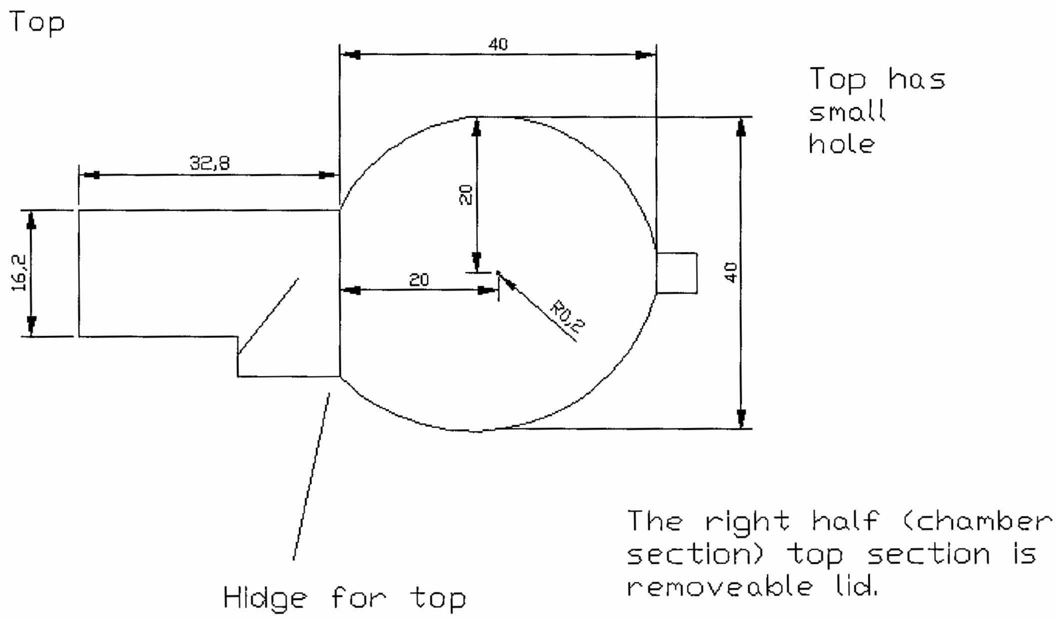
Polarization Ratio:

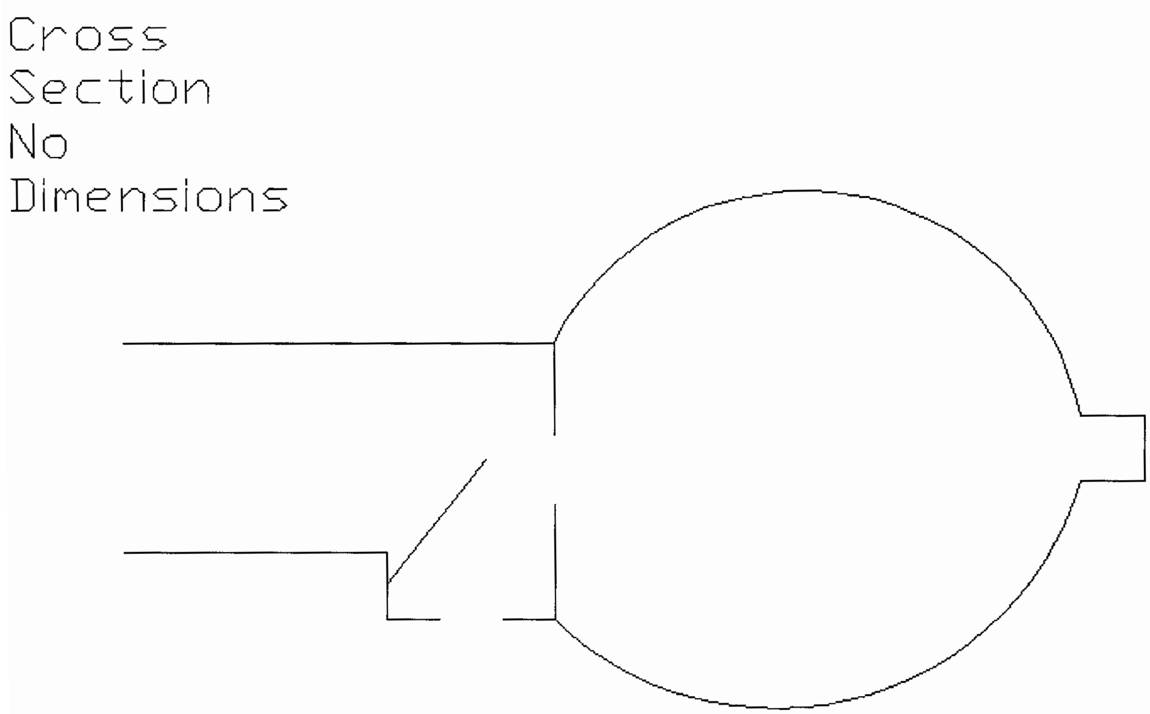


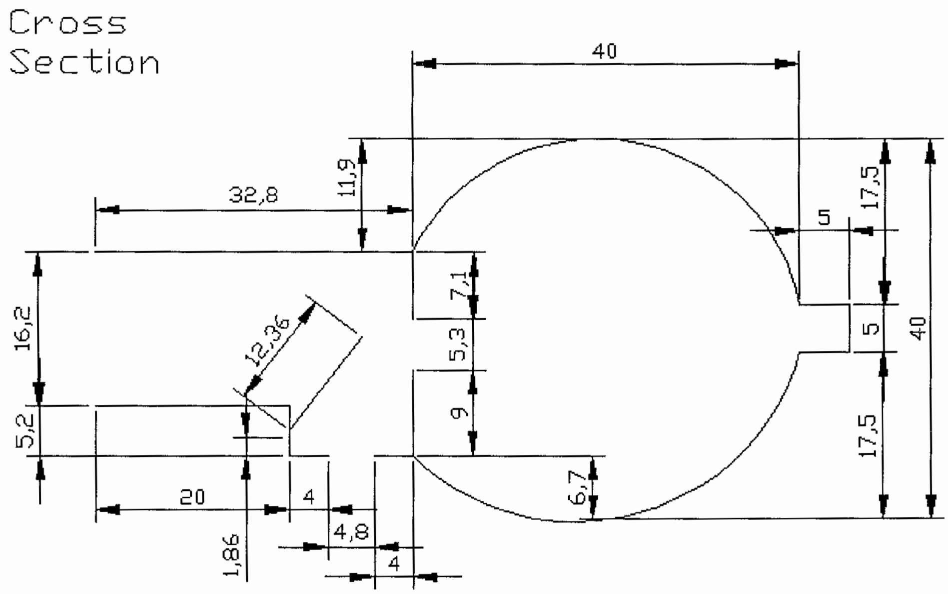
Appendix C:

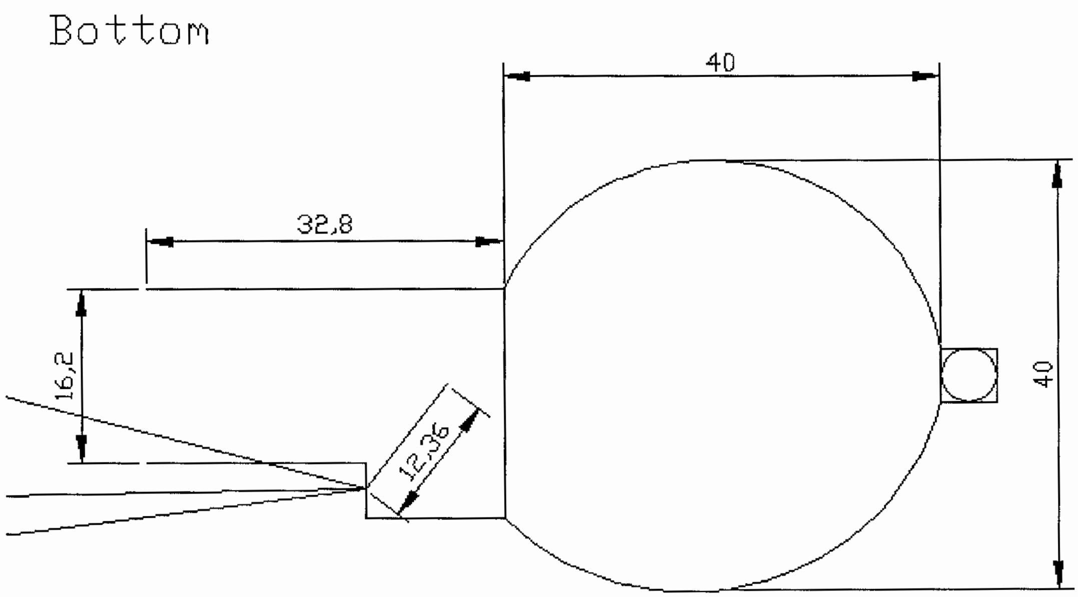
Prototype AutoCAD drawings

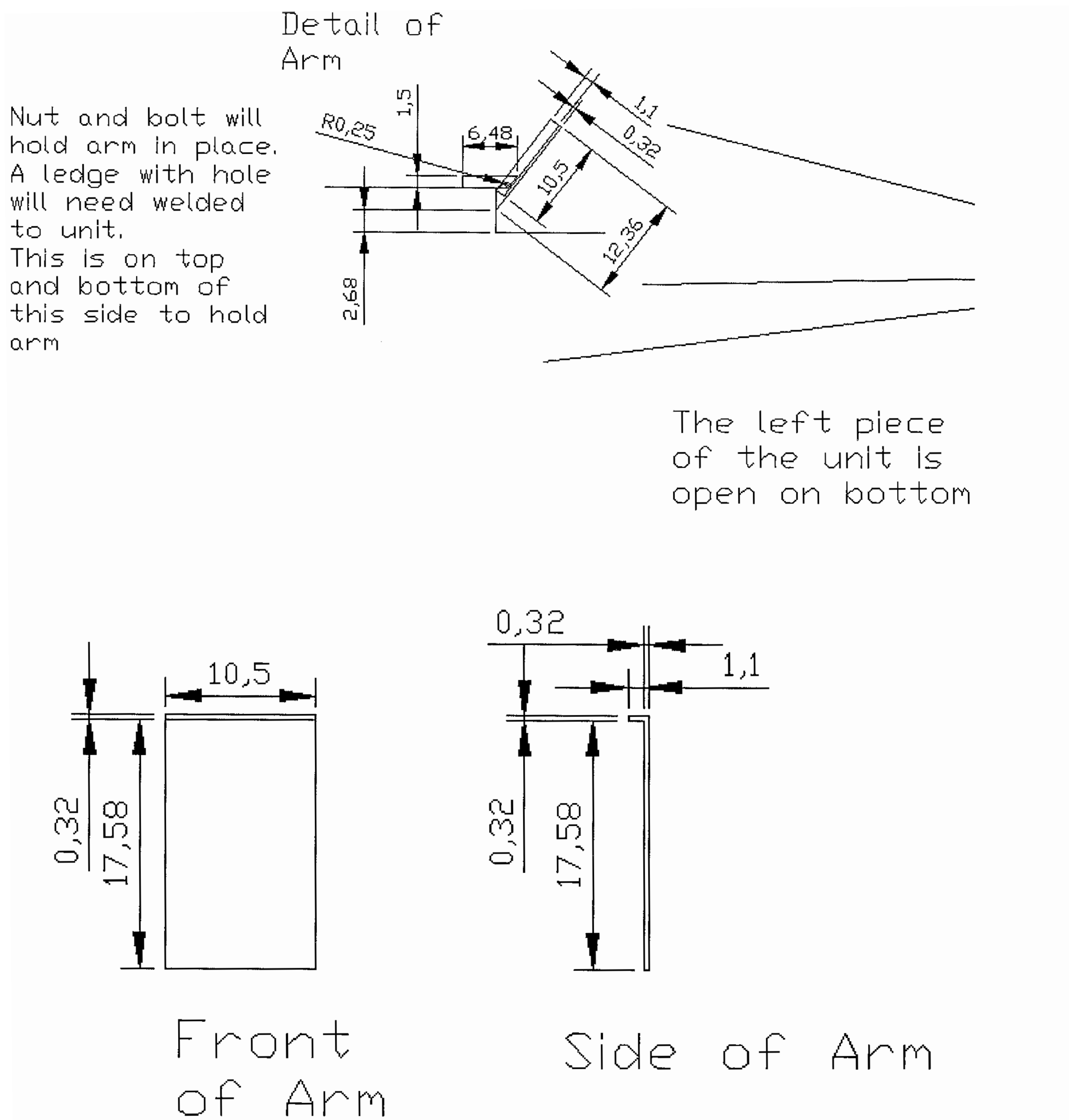
Prototype Design:



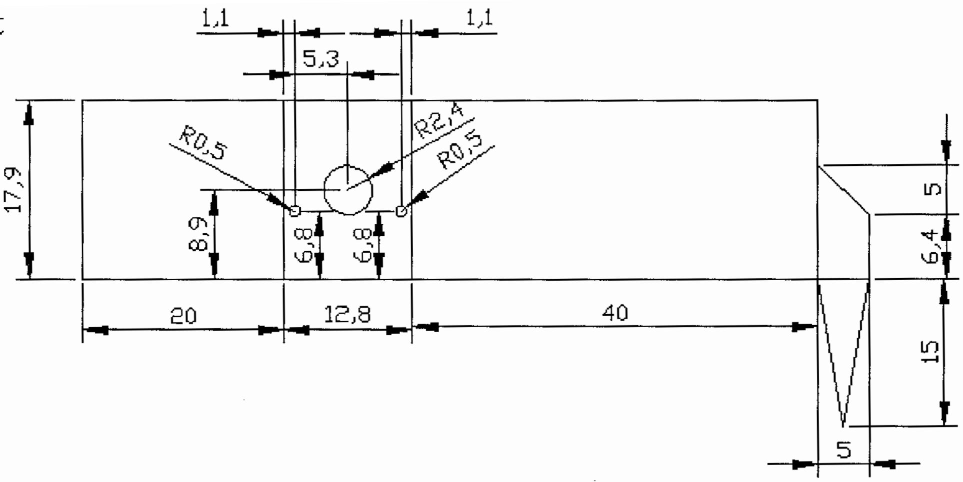



Cross
Section
40
32,8
11,9
17,5
5
16,2
7,1
12,36
5,3
5
40
9
5,2
17,5
6,7
20
4
4,8
1,86
4


Bottom
40
32,8
16,2
40
12,36


Detail of Arm
Nut and bolt will hold arm in place. A ledge with hole will need welded to unit. This is on top and bottom of this side to hold arm
R0,25
1,5
6,48
1,1
0,32
10,5
12,36
2,68
The left piece of the unit is open on bottom
10,5
0,32
17,58
Front of Arm
0,32
1,1
0,32
17,58
Side of Arm

Front



The circle and two vertical lines are hidden lines

Right Side