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I am submitting herewith a thesis written by Howard Bruce Barnes entitled "Design of a Two Color Two Spot Laser Velocimeter." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Physics.

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DESIGN OF A TWO COLOR TWO SPOT
LASER VELOCIMETER

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Howard Bruce Barnes

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ABSTRACT

The design of a two color two spot laser velocimeter based on an argon ion laser and using backscattered light is presented. The equations necessary for determining the parameters of the transmitting optics for optimum focusing of the laser beam are developed. A prism assembly that is used for splitting the laser beam into a 514.5 nm beam and a 488.0 nm beam, rotating the 2 beams, and varying the separation of the beams at the target, is shown. The equations used to determine the signal power collected by a bistatic receiver from a particle crossing the beams is presented. Finally, the results from an experimental system are used to verify the theoretical calculations for particles that are 50 and 100 meters from the transmitter.

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CHAPTER I

INTRODUCTION

The main purpose of this study was to design and develop a backscatter laser velocimeter system capable of measuring the velocity of an aerosol at distances of approximately 100 meters from the transmitter and receiver. This aerosol was assumed to be composed of particles ranging in size from 10 to 100 microns. An argon ion laser capable of delivering up to 15 watts and a 14-inch reflecting telescope were used in the velocimeter system. Operational convenience (location of the transmitter and receiver together) dictated that backscattered radiation be used for the measurements.

The distance from the receiver to the probe volume and the use of the backscattered radiation necessitate that the amount of light scattered by a particle in the probe volume be as great as possible. In order to achieve the highest possible power density at the probe volume, the two spot system was chosen over a fringe system. The two spot system allows all of the laser power to be concentrated into two highly focused spots. To obtain an optimum spot size for a specified optical geometry, equations are developed in Chapter II to maximize the power density at the probe volume and to specify the transmitting

optics so that the optimum spot size at the probe volume is produced.

In many two spot systems the beams have different polarizations so the direction of travel of the particle between the two beams can be determined and beam interference can be eliminated in the probe volume. Since the argon laser produces approximately equal power at 514.5 nm and 488.0 nm wavelengths, the 2 colors are used to produce the 2 spots used in the system. Hence color identification can be used to distinguish which beam the particle passed through, making different polarizations unnecessary. As Chapter IV shows, the use of 2 colors also allows the spots to be rotated about a common center without rotating the receiver, since a simple dichroic mirror is used in the receiver to split the backscattered light into a 514.5 nm and a 488.0 nm beam. Thus two components of particle velocity can be measured. The use of two wavelengths also allows increased utilization of the total power available from the laser. The primary difficulty encountered in this approach was found to be the wavelength dependence of most optical elements. However, as is demonstrated in Chapter V, this difficulty has been overcome.

In order to calculate a particle's velocity in a two spot system the time of flight for the particle between the two spots is measured. This time of flight is simply the time delay between the signals from the two PM tubes.

The velocity of the particle is then equal to the separation of the spots divided by the time delay. Since a particle may also pass through the edge of the spots or through only one spot, the velocity of the flow is taken to be the statistical average of a large number of particle velocities. As shown in Chapter V, the averaging process is accomplished by using a correlator to measure the time delay for particles passing through the spots. The correlator measures a very large number of time delays and uses them to construct a histogram whose mode is the time delay used in calculating the average flow velocity.

In order to test the theoretical calculations an experimental system for measuring the flow rate of atmospheric dust particles at distances of 50 and 100 meters was built. The system was tested using a fan to create a flow at the probe volume and with just background wind moving dust through the probe volume. The results of that experiment are given in Chapter V.

The final stage of this study, the construction of a mobile self-contained velocimeter system, has not been accomplished since a smaller argon laser needed for a mobile system was not available. However, a brief description of a possible mobile system is presented.

CHAPTER II

FOCUSING OF THE LASER BEAMS

As stated in the preceding chapter, a very important benefit of using a two spot system is that for a given transmitting lens size it provides the highest power density at the probe volume and, consequently, the highest amplitude signals from the particles crossing the probe volume.

In order to achieve this high power density the two spots must be as well focused as possible. The output of a laser operating in the fundamental mode is a gaussian beam, therefore the laser beam's propagation and focusing cannot be treated by using geometric optics. Therefore, in this chapter the necessary equations are developed to describe both the general and optimum focusing of a gaussian beam. The use of optimum focusing as described in the second section describes the minimum spot size attainable at the probe volume, while at the same time maximizing the irradiance.

Since this discussion has been adapted from that of Reference [1]¹, special note should be taken of the fact that the beam-width parameter b_1 is larger by a factor of $\pi^{1/2}$ than the beam-width parameter that is used when the

¹Numbers in brackets refer to similarly numbered references in the list of references.

radius of the beam is measured to the $1/e$ amplitude point.

1. General Focusing of a Gaussian Beam

Before the effect of a lens on the propagation of a gaussian beam can be described, the equations necessary for describing the normal propagation of the beam must be developed. The gaussian beam is described in the plane $z = z_1$ by the complex amplitude distribution

$$u_1(r) = A_1 \text{Gaus}\left(\frac{r}{b_1}\right) q(r : 1/\lambda R_1) , \quad (1)$$

with the gaussian function Gaus defined as

$$\text{Gaus}\left(\frac{r}{b_1}\right) = \exp\left[-\pi\left(\frac{r}{b_1}\right)^2\right] \quad (2)$$

and the quadratic-phase signal q defined as

$$q(r : 1/\lambda R_1) = \exp\left[\frac{j\pi r^2}{\lambda R_1}\right] , \quad (3)$$

where A_1 is a constant, j is the square root of -1 , b_1 is the beam-width parameter, R_1 is the radius of curvature of the beam, and r is the distance measured from the z axis, as shown in Figure 1. The radius of curvature R_1 is positive if the beam is diverging and negative if the beam is converging. The irradiance of the beam is given by

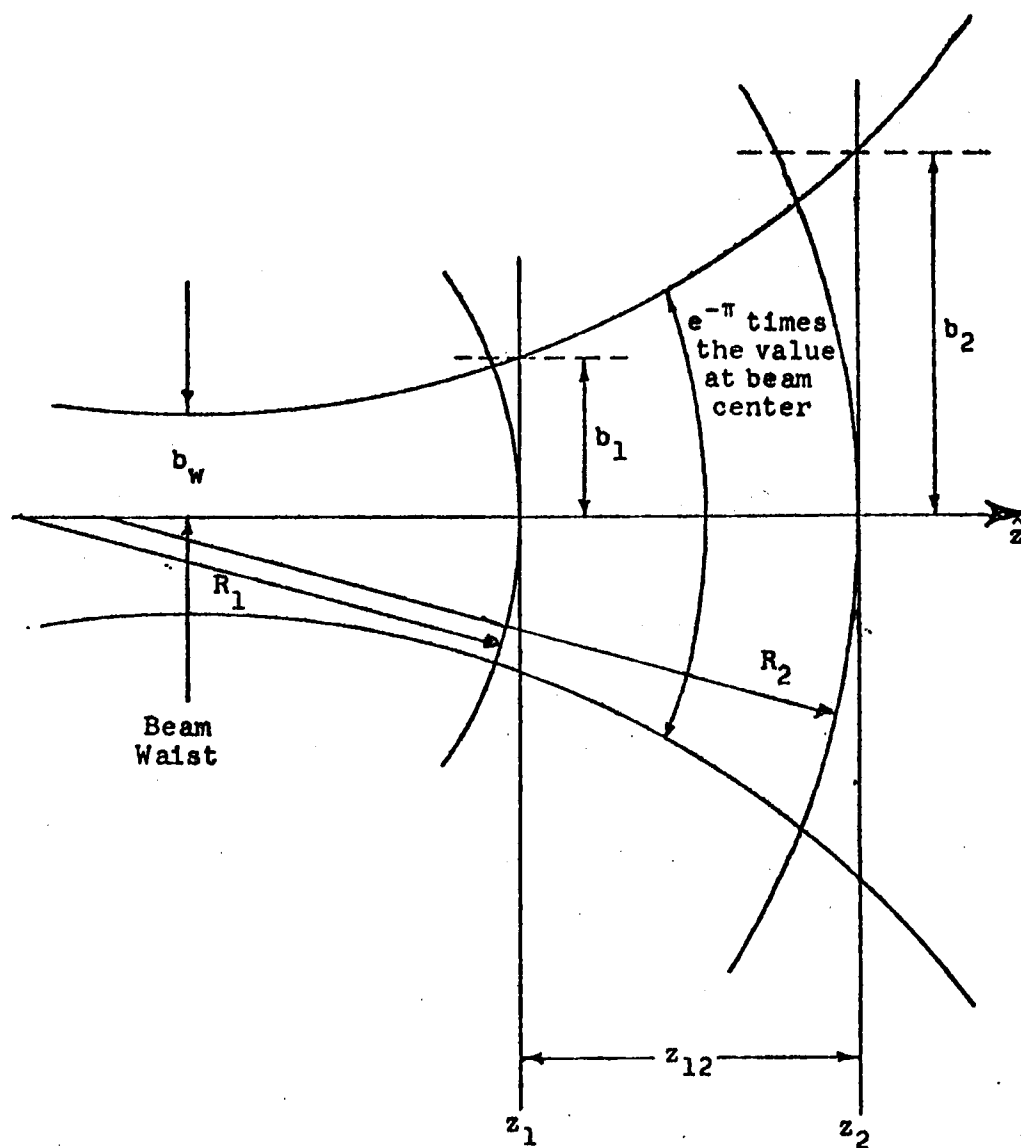


Figure 1. Propagation of a Gaussian Beam.

$$I(r) = |u_1(r)|^2 = |A_1|^2 \text{Gaus} \left(\frac{\sqrt{2} r}{b_1} \right) . \quad (4)$$

The propagation of the gaussian beam shown in Figure 1 is described by

$$b_2 = b_1 \left[(\delta_1 + 1) \left(\frac{z_{12}}{R_1} \right)^2 + 2 \left(\frac{z_{12}}{R_1} \right) + 1 \right]^{1/2} , \quad (5)$$

$$R_2 = R_1 \left[\frac{(\delta_1 + 1) \left(\frac{z_{12}}{R_1} \right)^2 + 2 \left(\frac{z_{12}}{R_1} \right) + 1}{(\delta_1 + 1) \left(\frac{z_{12}}{R_1} \right) + 1} \right] , \quad (6)$$

where the symbol δ_1 is a dimensionless quantity given by

$$\delta_1 = \left[\frac{\lambda R_1}{b_1^2} \right]^2 . \quad (7)$$

Now by use of Equations (5) and (6) the radius of curvature and the radius of the beam can be found at any point, if they are known at 1 point.

The effect of a lens on the propagation of a gaussian beam will now be examined. In this section it is assumed that the lens is large enough not to truncate the beam. This condition is satisfied if the radius of the physical aperture, the lens, is equal to or greater than the radius of the beam b_2 , shown in Figure 2, at

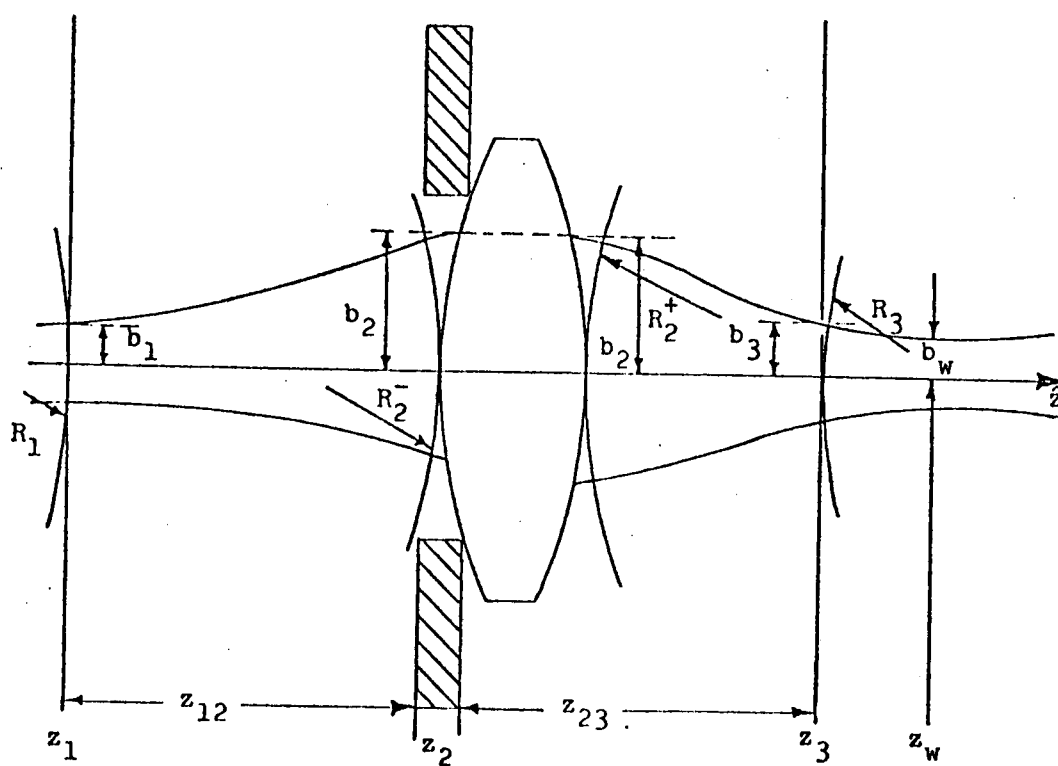


Figure 2. Effect of a Lens on a Gaussian Beam.

the aperture. If this condition is satisfied, then the truncation effects on the transmitted beam that are described in Reference [2] can be neglected.

The configuration shown in Figure 2 is used to determine the effects of a lens on a gaussian beam. The complex amplitude incident on the lens is given by

$$u_2^-(r) = A_2 \text{Gaus} \left(\frac{r}{b_2} \right) q(r : 1/\lambda R_2^-) , \quad (8)$$

where R_2^- is the radius of curvature of the beam that is incident on the lens. The complex amplitude that is transmitted by the lens is given by

$$u_2^+(r) = A_2 B_L \text{Gaus} \left(\frac{r}{b_2} \right) q(r : 1/\lambda R_2^+) \rho_L(r) , \quad (9)$$

where R_2^+ is the radius of curvature of the beam that is transmitted by the lens. The quantity B_L is a constant that accounts for the optical thickness at the center of the lens and any losses due to reflection or absorption by the lens and $\rho_L(r)$ is the aperture function. In order to find the beam radius b_3 and the radius of curvature R_3 it is convenient to make 2 definitions. First, the dimensionless quantity

$$\delta_2^+ = \left[\frac{\lambda R_2^+}{b_2^2} \right]^2 \quad (10)$$

is defined in analogy with δ_1 in Equation (7). Then in

a form analogous to the lens-makers formula from geometric optics,

$$\frac{1}{R_2^-} - \frac{1}{R_2^+} = \frac{1}{f} , \quad (11)$$

where f is the focal length of the lens and R_2^- and R_2^+ are shown in Figure 2. Using these definitions, the quantities b_3 and R_3 are written as

$$b_3 = b_2 \left[(\delta_2^+ + 1) \left(\frac{z_{23}}{R_2^+} \right)^2 + 2 \left(\frac{z_{23}}{R_2^+} \right) + 1 \right]^{1/2} , \quad (12)$$

$$R_3 = R_2^+ \frac{\left[(\delta_2^+ + 1) \left(\frac{z_{23}}{R_2^+} \right)^2 + 2 \left(\frac{z_{23}}{R_2^+} \right) + 1 \right]}{\left(\delta_2^+ + 1 \right) \left(\frac{z_{23}}{R_2^+} \right) + 1} . \quad (13)$$

In geometric optics the beam is assumed to be focused to a point, but a gaussian beam is focused to a minimum radius, which is always greater than zero, called the beam waist. The beam waist designated by b_w and its location z_{2w} are given by

$$b_w = \left| \frac{\lambda R_2^+}{b_2} \right| \frac{1}{\left(\delta_2^+ + 1 \right)^{1/2}} , \quad (14)$$

$$z_{2w} = \frac{-R_2^+}{\delta_2^+ + 1} . \quad (15)$$

The expression for the beam radius b_3 can be simplified if the initial beam waist, b_{w1} , is located at the plane $z = z_1$, so the value b_{w1} replaces b_1 shown in Figure 2. Then, as shown in the Appendix, b_3 becomes

$$b_3 = b_{w1} \left(\frac{z_{12}}{z_{R1}} \right) \left[\left(1 - \frac{z_{23}}{z_{12}} - \frac{z_{23}}{f} \right)^2 + \left(\frac{z_{R1}}{z_{12}} \right)^2 \left(1 - \frac{z_{23}}{f} \right)^2 \right]^{1/2} \quad (16)$$

where

$$z_{R1} = b_{w1}^2 / \lambda \quad (17)$$

A special case of Equation (16) that we will make use of in the next section occurs when $z_{23} = f$, which yields

$$b_3 = \frac{\lambda f}{b_{w1}} \quad (18)$$

Equations (14) through (18) show how to compute the radius and location of the focused beam spot for the general case provided the initial beam waist and the focal length of the lens are known.

2. Optimum Focusing of a Gaussian Beam

The equations used to find the size of the beam spot at focus are now used to determine the minimum spot size attainable at a target a fixed distance from the lens. The configuration for obtaining this minimum

spot size designated $(b_3)_{\min}$ is shown in Figure 3. In order to obtain the optimum radius of curvature R_2^+ , differentiate Equation (12) with respect to R_2^+ and set the expression equal to zero. This yields a value of

$$R_2^+ = -z, \quad (19)$$

which yields a minimum spot size

$$(b_3)_{\min} = \left| \frac{z\lambda}{b_2} \right| \quad (20)$$

at the target which is a distance z from the lens. Therefore, $(b_3)_{\min}$ increases linearly as the distance to the target increases. This is shown in Figure 4. Then by examining Equations (14) and (15), this value of R_2^+ is found to produce a beam waist where z is greater than z_w and b_w is less than $(b_3)_{\min}$.

The lens system shown in Figure 5 was used to not only minimize the beam spot at the target, but also to maximize the irradiance. Using $R_2^+ = -z$ and the fact that the target is on the z axis maximizing the amplitude $|u_3(0)|$ will maximize the irradiance at the target. As shown in Reference [1], the quantity $|u_3(0)|$ is a maximum when

$$b_2 = 0.791 d_L, \quad (21)$$

where d_L is the diameter of the final transmitting lens. Even though this value of b_2 truncates the beam and

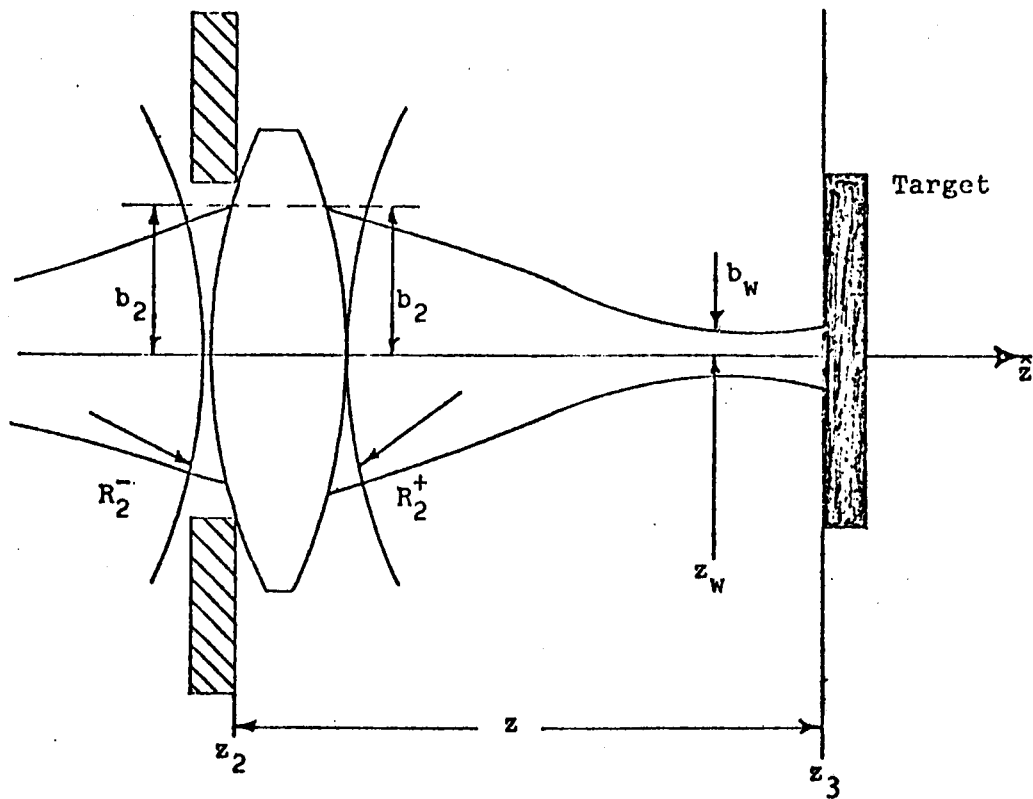


Figure 3. Optimum Focusing of the Beam on a Target.

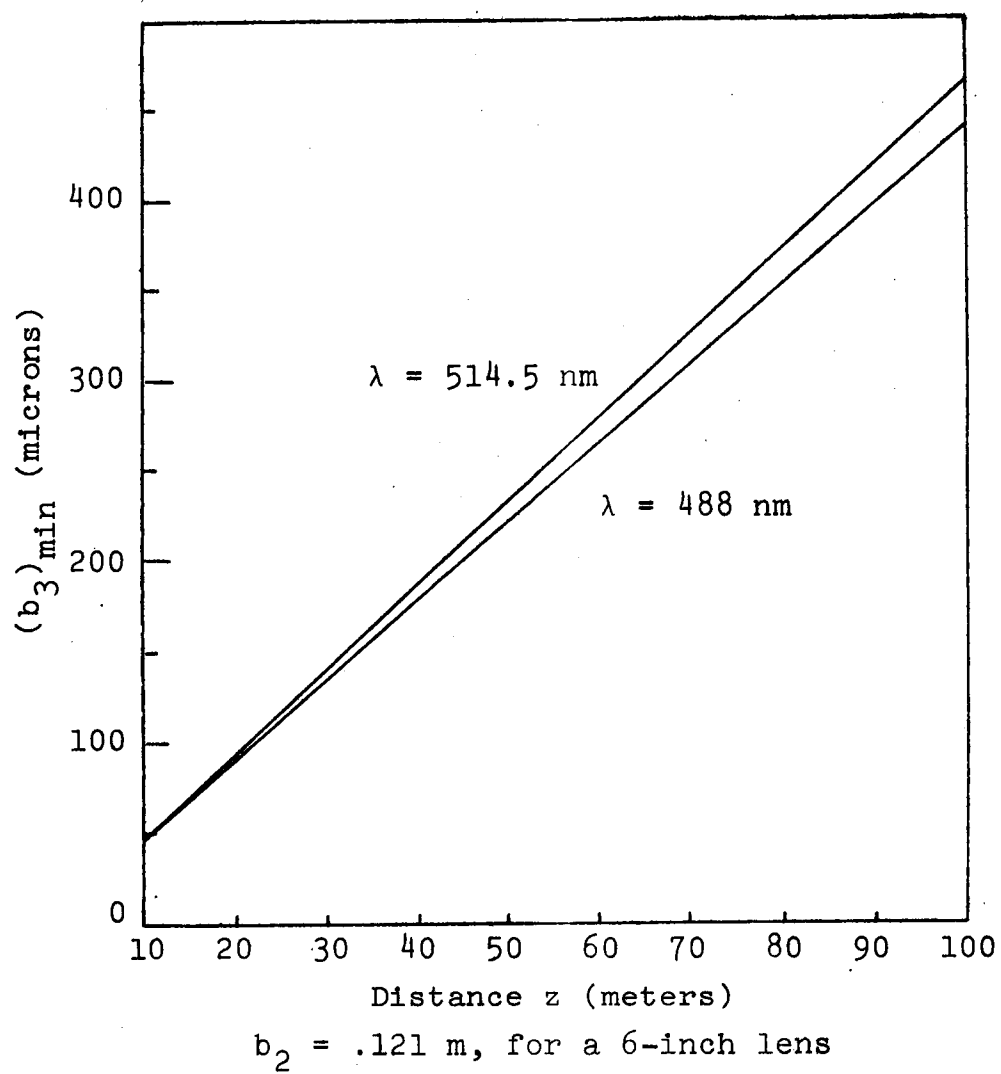


Figure 4. Minimum Spot Size Versus Distance to the Target.

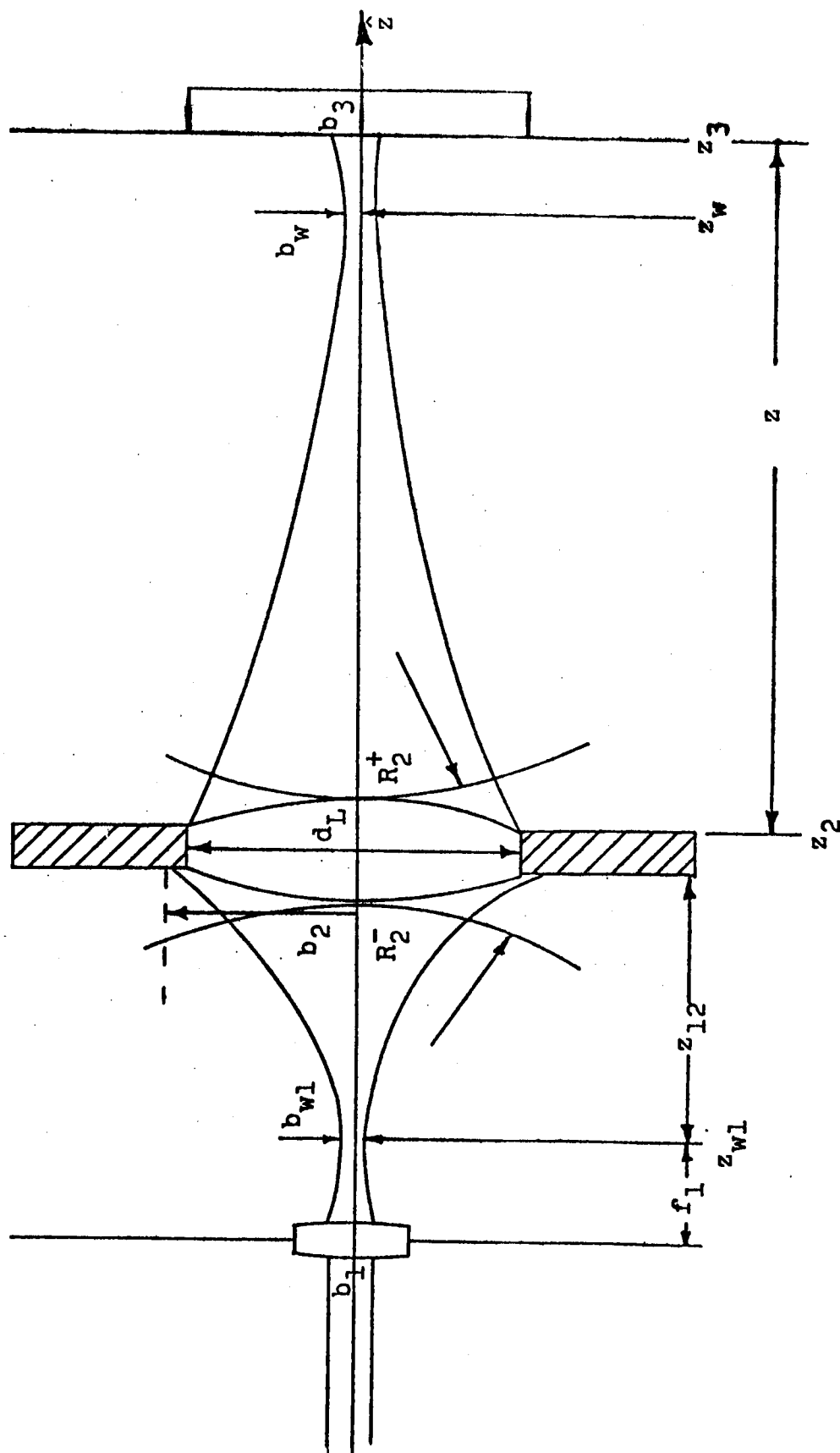


Figure 5. Transmitter System for Optimum Focusing.

therefore allows only 91.9% of the incident power to be transmitted, it is shown in Reference [1] that there is a 40% increase in the peak irradiance at the target as opposed to the case of a nontruncated beam with $b_2 = .5d_L$, which allows 99.8% of the power to be transmitted.

The necessary parameters of the 2-lens system shown in Figure 5 are determined in the following way. Using the fact that at the second lens, $R_2^+ = -z$ and $b_2 = 0.791 d_L$, and using Equation (11), R_2^- is found. Then referring to Equations (5) and (6), the correct values for b_{w1} and z_{12} are determined. In this case z_1 is at the waist and $R = \infty$ at the waist. This yields the two equations

$$b_{w1} = \left[\frac{\lambda^2 (R_2^-)^2 b_2^2}{b_2^4 + \lambda^2 (R_2^-)^2} \right]^{1/2} \quad (22)$$

$$z_{12} = \frac{b_{w1}}{\lambda} (b_2^2 - b_{w1}^2)^{1/2} \quad (23)$$

which can be easily solved to find b_{w1} and z_{12} .

Now assuming that the beam incident on the first lens is collimated, which is shown in the next section to be approximately true, and the radius b_1 is at the first lens, the necessary focal length of the first lens is found by using Equation (18) in the form

$$f_1 = \frac{b_{w1} b_1}{\lambda} . \quad (24)$$

A system of two lenses that provides optimum focusing of the beam at the target is then completely described.

Note that the quantity $\lambda^2 \left(R_2^- \right)^2$ that appears in Equation (22) is much less than b_2^4 in most cases, and Equation (22) then simplifies to

$$b_{w1} = \frac{R_2^- \lambda}{b_2} . \quad (25)$$

By use of these equations the necessary lenses can be selected to provide optimum focusing of the laser beams at the target. In the next chapter the method used for splitting the laser beam into its constituent colors and rotating the two beams produced will be examined.

CHAPTER III

GENERATION AND SEPARATION OF THE 514.5 NANOMETER AND 488.0 NANOMETER BEAMS

The argon ion laser's output is spread over several lines when it is operated in the broad band mode. Of these lines, the 514.5 nm and 488.0 nm lines were chosen for use as the 2 colors that would produce the 2 spots since approximately 40% of the total power is contained in each line. In order to use these two colors as the two spots, the laser's output beam must be split into its constituent colors. In the first section, the use of a prism to separate out those two colors is examined in detail. In the second section, a prism assembly that separates the two colors and allows the two spots to be rotated is shown. This same prism assembly can also be used to vary the separation of the two spots and the necessary equations for determining that separation are presented.

1. Chromatic Dispersion by a Prism

A 60 degree dispersing prism was used to separate the laser beam into its constituent colors. In Figure 6, the deviation of a monochromatic ray as it passes through the prism is shown. The total deviation of the ray, δ , is shown in Reference [3] to be

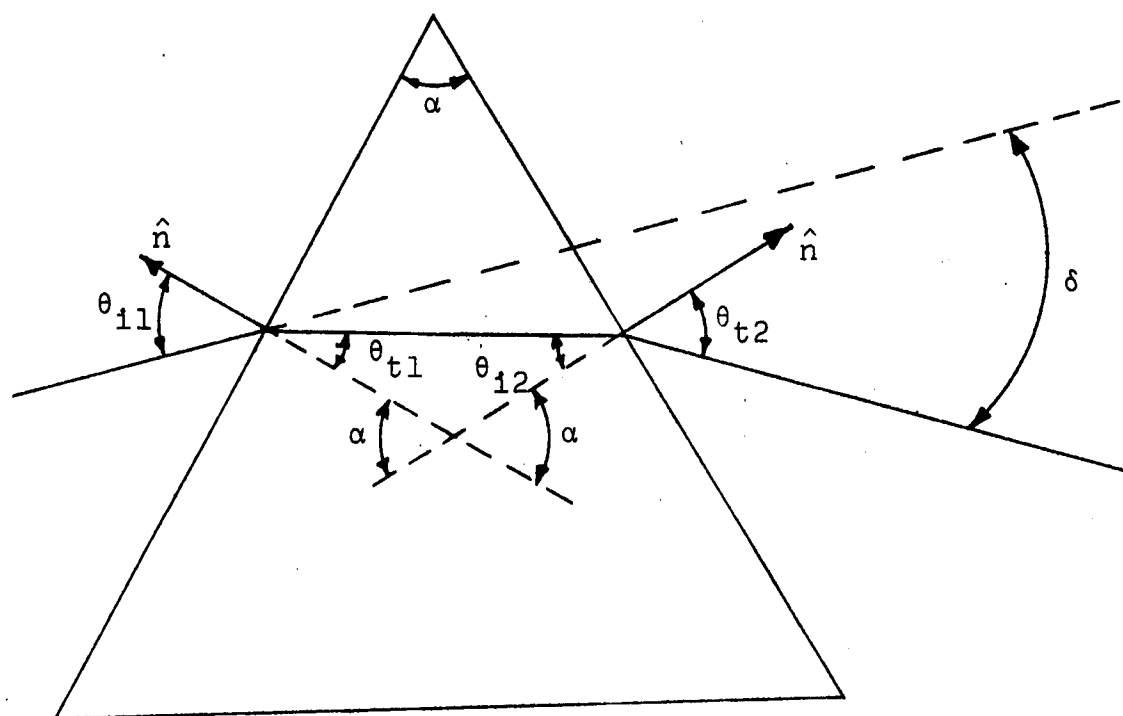


Figure 6. Bending of a Monochromatic Ray by a Prism.

$$\delta = \theta_{11} + \sin^{-1} \left[(\sin \alpha) \left(n^2 - \sin^2 \theta_{11} \right)^{1/2} - \sin \theta_{11} \cos \alpha \right] - \alpha. \quad (26)$$

The angles θ_{11} and α are constant for the laser beam that is split by the prism. Therefore, the angle between the 488.0 nm and 514.5 nm beams is only a function of the index of refraction which is wavelength dependent.

2. Determination of the Separation of the Spots at the Target

In order to determine the orientation of the mean velocity vector of the particles that pass through the beams, it is necessary to rotate the spots about a common center. An easy way to rotate the spots is to rotate the dispersing prism used to separate the two beams. However, to rotate the prism without realigning the lenses of the transmitter, the incident and transmitted beams at the prism must be coaxial. This is not the case when a single prism is used; therefore, a prism combination such as that shown in Figure 7 has been developed to separate the 2 wavelengths of interest and to rotate the 2 beams about an axis. Figure 7 shows the incident beam striking the first prism at Brewster's angle, which is given by

$$\theta_B = \tan^{-1}(n) , \quad (27)$$

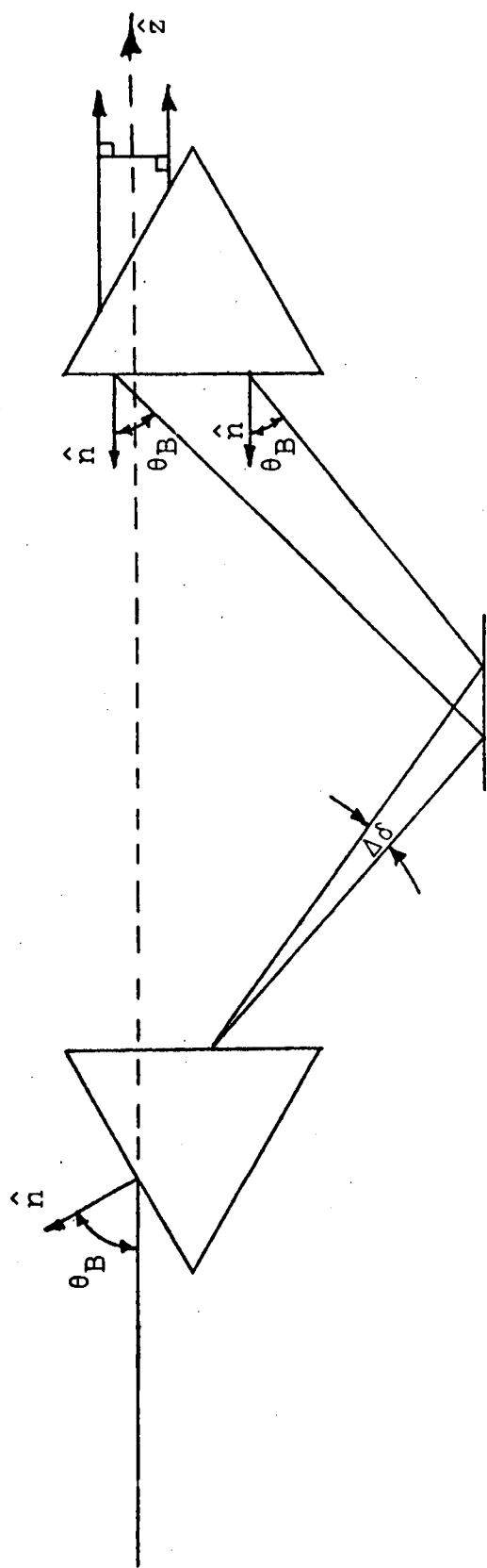


Figure 7. Prism Assembly for Splitting the Laser Beam.

where n is the index of refraction of the prism. In this way incident reflection losses are minimized. After reflection from the mirror, the 2 beams then strike the second prism near θ_B and emerge with the central rays nearly parallel to each other, as can be shown by using Equation (26). If the entire prism assembly is now rotated about an axis formed by the incident beam, the two spots at the target will rotate as desired without any adjustments to the rest of the transmitting optics. In order to keep the incident beam, which is initially vertically polarized at Brewster's angle with respect to the first prism as the prism assembly rotates, a polarization rotator was used at the output of the laser. This polarization rotator is made up of a pair of Fresnel rhombs. This polarization rotator is therefore not wavelength dependent, thus compensating for polarization orientation in both beams.

Since the two beams emerging from the prism assembly are parallel, the separation distance between the two prisms is used to change the separation of the spots at the target. As shown in Figure 8, the central rays of the 2 beams will cross at 1 focal length from the transmitting lens system. This fact is then used to determine the angle between the two rays, which will be called $\Delta\delta$, by use of the focal length of the lens

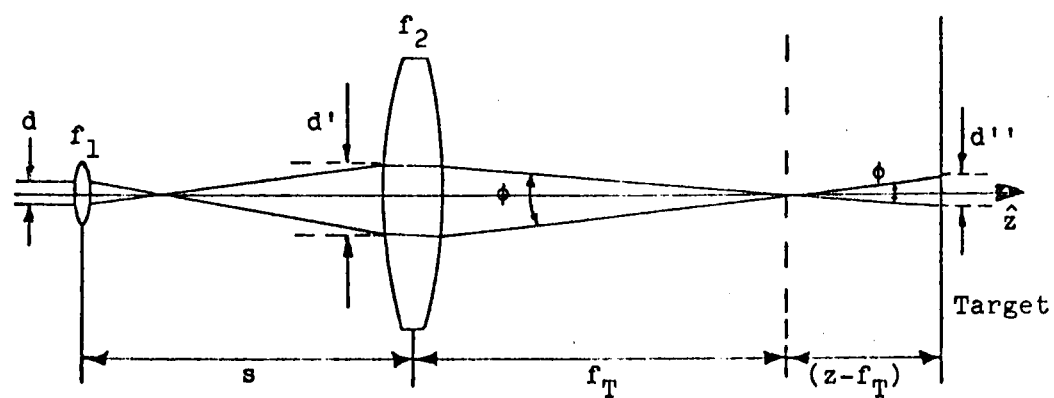


Figure 8. Separation of the Beam Centers at the Target.

system and the separation of the central rays at the second lens. The lenses used in the system were diffraction limited and can therefore be treated as thin lenses. For this case, the back focal length of the lens system is given by

$$f_T = \frac{f_2 (s - f_1)}{s - (f_1 + f_2)} , \quad (28)$$

as shown in Reference [4]. Where f_1 and f_2 are the focal lengths of the first and second lenses, respectively, and s is the distance between the 2 lenses. The separation of the central rays of the two beams at the second lens is

$$d' = d \cdot M = d \cdot \frac{f_2}{f_1} , \quad (29)$$

where d is the separation of the 2 rays as they enter the system. The magnification of the system, M , is approximately equal to the ratio of focal lengths, since the distance s is just slightly greater than the sum of the two focal lengths.

The angle ϕ is then

$$\phi = 2 \tan^{-1} \left(\frac{d'}{2f_T} \right) . \quad (30)$$

The target is located a distance z from the second lens where z is greater than f_T . The separation of the centers of the two spots at the target is given by

$$d'' = 2(z - f_T) \tan \frac{\phi}{2} . \quad (31)$$

Therefore, the separation at the target can be written in terms of the initial separation by substituting the angle into Equation (31), which yields

$$d'' = (z - f_T) \left(\frac{df_2}{f_1 f_T} \right) . \quad (32)$$

Now if the angle $\Delta\delta$ shown in Figure 7 is known, the separation of the centers of the 2 spots at the target can be calculated from the separation of the 2 prisms. Due to the approximations that were used to obtain d'' , a check of the actual separation should be made before a test is run by sending particles traveling at a known velocity through the probe volume and timing their time of flight between the centers of the spots. Now that the transmitting optics for the system can be selected, in order to produce the necessary two spots at the target, the signal power that can be expected from a particle crossing those spots will be estimated.

CHAPTER IV

SIGNAL RECEPTION AND ANALYSIS

The preceding two chapters can be used to determine the radius of each beam and the beam separation at the target for a given lens system. In order to determine what method and equipment are needed for a complete velocimeter system, for receiving and analyzing the signals from particles in the flow, two other factors must be considered. First, signal power that can be expected from particles of a given size and type as they cross a beam should be estimated. Second, the variation in the signal power in relation to particle position in the beam must be considered in order to determine which particles in the probe volume contribute a measurable signal magnitude.

1. Backscattered Power from a Particle in the Beam

The power backscattered by a particle in the beam that is collected by a receiver is shown in Reference [5] to be

$$P_s = I_0 T \sigma \Omega \quad , \quad (33)$$

where I_0 is the illuminating irradiance at the probe volume, T is the transmittance of the atmosphere, σ is the backscatter cross section, and Ω is the solid angle subtended by the receiver.

The irradiance I_0 is given by

$$I_0 = \frac{T P_0}{A_B} , \quad (34)$$

where P_0 is the laser power measured at the final lens of the transmitter system, and A_B is the cross-sectional area of one of the beams at the target. It is assumed that the beam radius is measured to the $e^{-\pi}$ intensity points. The cross-sectional area is also a function of the beam F number and hence the distance, z , from the final lens to the probe volume as shown in Equation (20).

The transmittance of the atmosphere is given by [6]

$$T = \exp(-\gamma z) , \quad (35)$$

where γ is the attenuation coefficient. Over the range that the velocimeter is designed to operate, the transmittance will be approximately unity.

The backscatter cross section is given by

$$\sigma = \frac{\lambda^2}{\pi} i(180^0) , \quad (36)$$

where $i(180^0)$ is the backscatter intensity function for the particle and is itself a function of the relative refractive index and the size of the particle.

Since the backscattered light can be treated as coming from a point source, the solid angle is

$$\Omega = \frac{A_R}{z^2} , \quad (37)$$

where A_R is the collection area of the receiver.

By combining the preceding equations, the backscattered power collected by the receiver becomes

$$P_s = P_0 A_R i(180) \frac{T^2 b_2^2}{\pi^2 z^4} , \quad (38)$$

where the distance z is always measured to the beam radius, $(b_3)_{\min}$. In Equation (38) all of the terms except $i(180)$ and z can be taken as constant for a system.

In order to make an estimate of the minimum size particle that can be detected, the backscattered power is written in terms of the energy in the scattered photons as

$$P_s = \frac{n h \left(\frac{c}{\lambda} \right)}{t} , \quad (39)$$

where n is the number of scattered photons, h is Planck's constant, and t is the time the particle is in the beam. The time t is then approximately equal to the diameter of the beam divided by the particle velocity v . By use of Equation (20), the power P_s becomes

$$P_s = \frac{n b_2 v}{\lambda^2 z} 10^{-25} \text{ watts} . \quad (40)$$

In order to make an estimate of n , the typical values of the constants in Equations (38) and (40) were chosen. For the velocimeter system used in Chapter V, $b_2 = .121 \text{ m}$ and $A_R = .1 \text{ m}^2$. Then equating Equations (38) and (40) and using $P_0 = 1 \text{ watt}$ and $T = .95$, the number of photons n is equal to

$$n = (1.106 \times 10^{22}) \frac{\lambda^2 i(180)}{v z^3} . \quad (41)$$

If all the backscattered light is due only to fresnel reflection from the particle, Reference [7] shows that the backscattered intensity is given by

$$i(180^0) = \frac{\pi^2 a^2}{\lambda^2} \left| \frac{m-1}{m+1} \right|^2 , \quad (42)$$

where a is the radius of the particle and m is its relative index of refraction. For a water particle, $m = 1.33$, and at a range of 100 m , Equation (41) becomes

$$n = (2.19 \times 10^{15}) \frac{a^2}{v} . \quad (43)$$

If, for example, approximately 1000 photons must be scattered and collected in order to provide a good signal, a 10 micron particle could be detected if

it were moving at 50 m/sec or less. The minimum detectable size increases to 45 microns for water particles moving at 1000 m/sec.

2. Data Collection

Equation (38) gives the signal power that can be expected from a particle crossing the beam at the point where the beam radius is $(b_3)_{\min}$. The change in signal power when a particle crosses the beam at another point along the beam will now be examined.

There existed the possibility that an error in the results occurs, due to the fact that the beam waist, b_w , is not at the same point as $(b_3)_{\min}$ and the beam centers are not the same distance apart at the 2 points. Also, since b_w is smaller than $(b_3)_{\min}$, the signal power from a particle passing through the waist is greater than the signal power from a particle in the probe volume. In the velocimeter system that has been constructed, the final lens that is used in the transmitter has a diameter of .152 m and f equal to .762 m. Then at a range of 100 m, Equations (15) and (20) show that the beam waist is never located a distance greater than 1.5 mm from $(b_3)_{\min}$. This means that virtually no errors are introduced in the results when it is assumed that $(b_3)_{\min}$ and b_w are coincident. The intensity I_0 decreases on either side of $(b_3)_{\min}$, since the radius of the beam is increasing, as shown in the view of the probe volume in Figure 9.

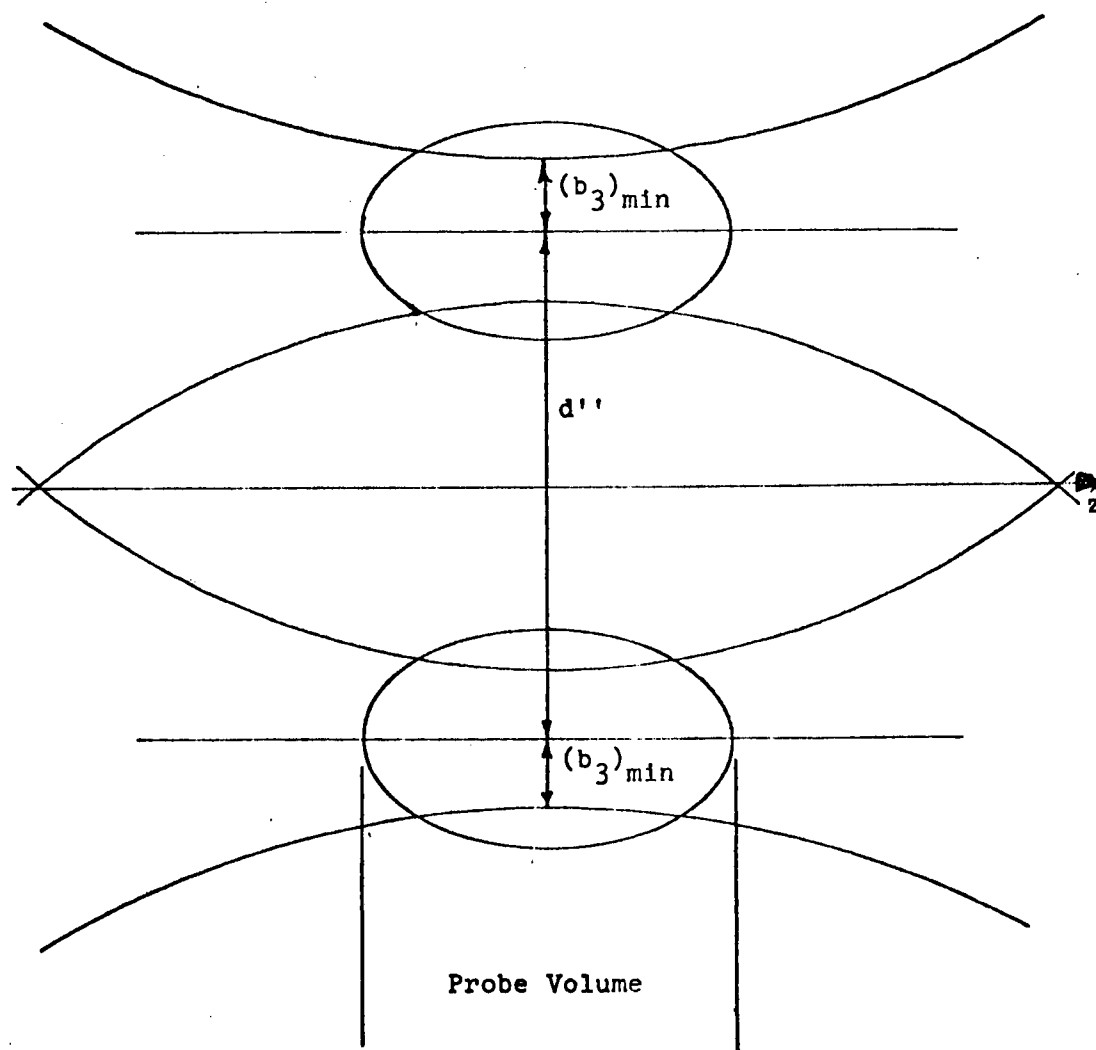


Figure 9. View of the Probe Volume.

The probe volume for the two spot system is defined by use of the depth of focus of the transmitter and the depth of field of the receiver. As shown in Reference [8], the depth of focus for a gaussian beam is given by

$$L_G = \frac{2}{\lambda} (\rho^2 - 1)^{1/2} b_w^2, \quad (44)$$

where ρ is the tolerance factor; if within a distance $L_G/2$ the radius of the beam increases by 50%, then ρ is 1.50. Since b_w is approximately equal to $(b_3)_{\min}$, Equation (44) can be written as

$$L_G = \frac{2 \lambda z^2}{b_2^2} (\rho^2 - 1)^{1/2}. \quad (45)$$

Reference [9] shows that the depth of the field for the receiver is given by

$$L_R = \frac{\lambda z^2}{D^2}, \quad (46)$$

where D is the diameter of the receiver aperture and z is the effective focal length of the receiver, which is assumed to be the distance to the beam waist.

The length of the probe volume is then a function of Equations (45) and (46). It is apparent from these two equations that the depth of field of the receiver is the more important limiting factor on the length of the probe volume. As can be seen in

an example where z is 100 m , λ is 514.5 nm , and the receiver is a 356 mm telescope. Using these values in Equation (46) yields a depth of field of only .04 m , but since some light scattered outside of this region would be collected, the length of the probe volume is estimated to be approximately .1 m in order to provide a margin for error, as shown in Figure 10.

A large particle that crosses the beams outside of the probe volume could yield an equal amplitude signal as a smaller particle passing through the probe volume. There is also the possibility that a particle could pass through only one beam or that two succeeding signals could be produced by two different particles. But, in all of these cases, the time delay between the signals would be different from the average time delay between the signals for particles that pass through the probe volume, which is $\Delta\tau$. These time delays would then be randomly distributed while $\Delta\tau$ would be constant and additive.

The receiver that is used in the velocimeter system is shown in Figure 11. The telescope is focused so that light scattered at the probe volume is nearly collimated at the image plane. The collimated beam is then split by the dichroic mirror into a 488 nm and 514.5 nm beam. The scattered light that is not incident from within the probe volume does not yield a good signal as seen from the definition of the probe volume. The 2 PM tubes also

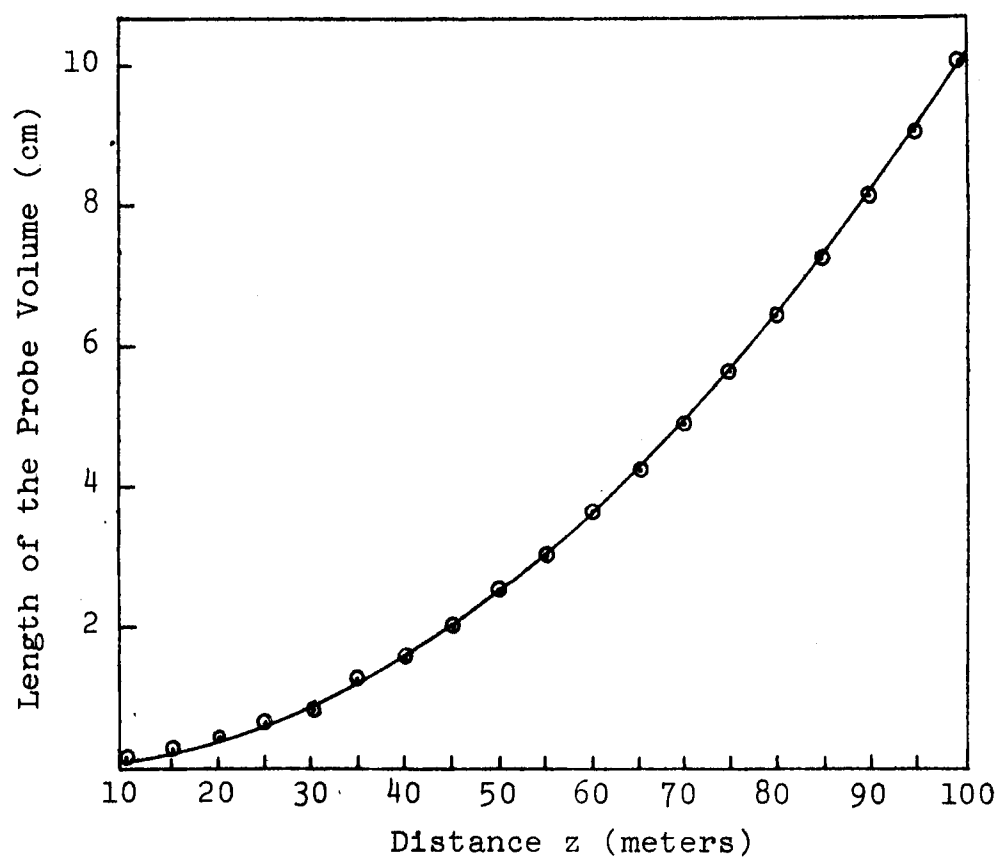


Figure 10. Length of the Probe Volume Versus the Distance z .

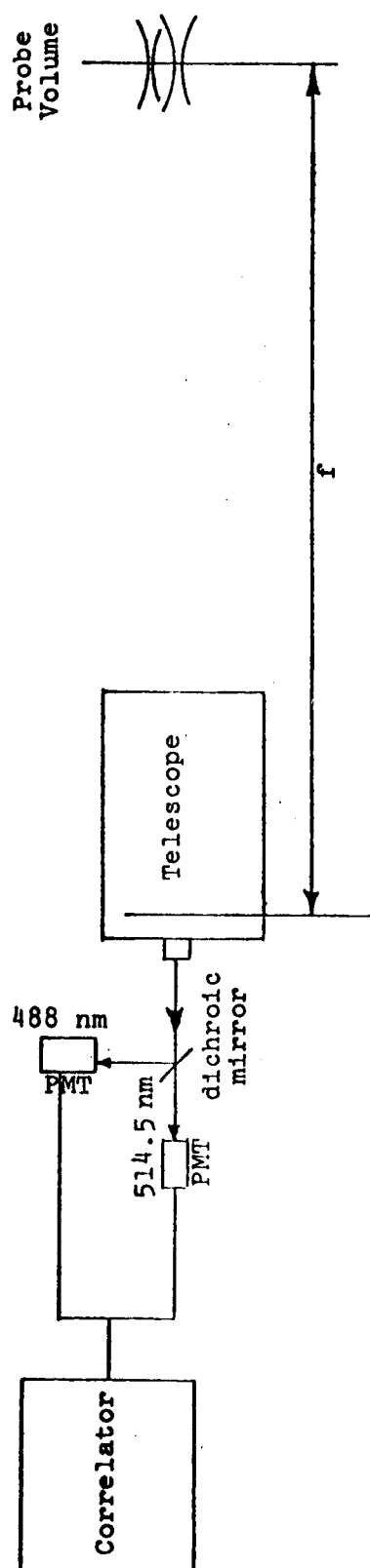


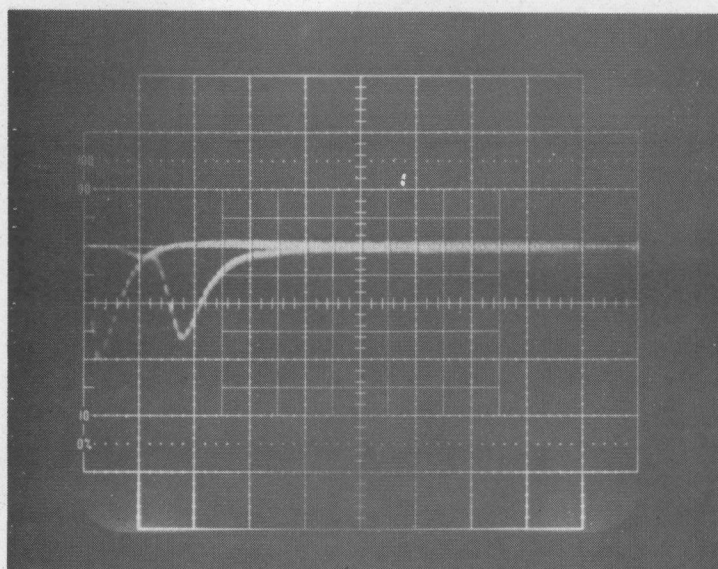
Figure 11. Receiver System.

contain $10\text{\AA}$ filters centered about $5145\text{\AA}$ and $4880\text{\AA}$ respectively to filter out background light.

Since two PM tubes are used, the direction the particles are traveling can be found by determining which tube triggers first. Furthermore, by having one PM tube trigger only after the other tube has triggered, the number of time delays caused by two particles can be reduced. In order to find the flow velocity, the signal correlation is measured. A correlator measures the time delay between two successive signals from the PM tubes and then builds up a histogram of the time delays for a large number of particles crossing the beams. Figure 12 shows a representative histogram and the input into the correlator produced by rotating a filamentary wire through the probe volume. Since the time delays caused by particles passing through the probe volume are additive, the peak of the histogram is at $\Delta\tau$. Since this is the peak-to-peak time delay for two signals, the velocity of the particles is given by

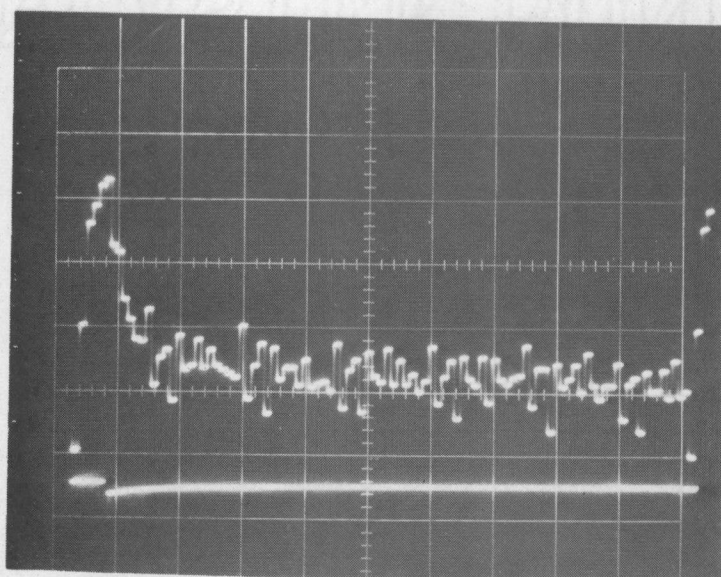
$$v_P = \frac{d''}{\Delta\tau} \quad . \quad (47)$$

The correlator records either a positive or a negative time delay depending on which channel triggered first. In doing so, the correlator distinguishes between which of the two signals come first, yielding the direction of the particle velocity vector. By rotating the two beams



Input into the correlator

50 msec/div



Sample increment: 20 msec

peak bin: #5

Figure 12. Representative Histogram for Signals from 5 Meters from the Transmitter.

until the minimum standard deviation in the histogram is found, the primary flow direction and velocity of the flow can be found, as is shown in the next chapter.

CHAPTER V

DESIGN OF AN EXPERIMENT TO TEST THE SYSTEM

1. Experimental Setup

In order to test the velocimeter system, an experiment was conducted to measure the velocity of atmospheric dust at 50 and 100 meters from the velocimeter system. The flows that were measured were set up by a fan that pushed the dust through the probe volume and the natural flows caused by the wind. The experimental arrangement is shown in Figure 13. The transmitting optics consist of a positive lens with a focal length of 25 mm and a 152 mm diameter 762 mm focal length transmitting lens. Both of the lenses that were used were achromats in order to focus the beams at nearly the same point. Figure 7 (page 21) shows the prism assembly which was used. It was enclosed in a box that could be rotated through 360 degrees.

The receiver was a 356 mm diameter schmidt-cassegrain telescope. Two EMI 9781R PM tubes were used as photodetectors. The signals from each PMT were amplified and low pass filtered. The low pass filter had a 10 kHz cutoff. A Honeywell SAI-42A correlator and probability analyzer was used to produce a correlogram of the time delays between the incoming signals. Table I gives a summary of all of the system parameters. In order to

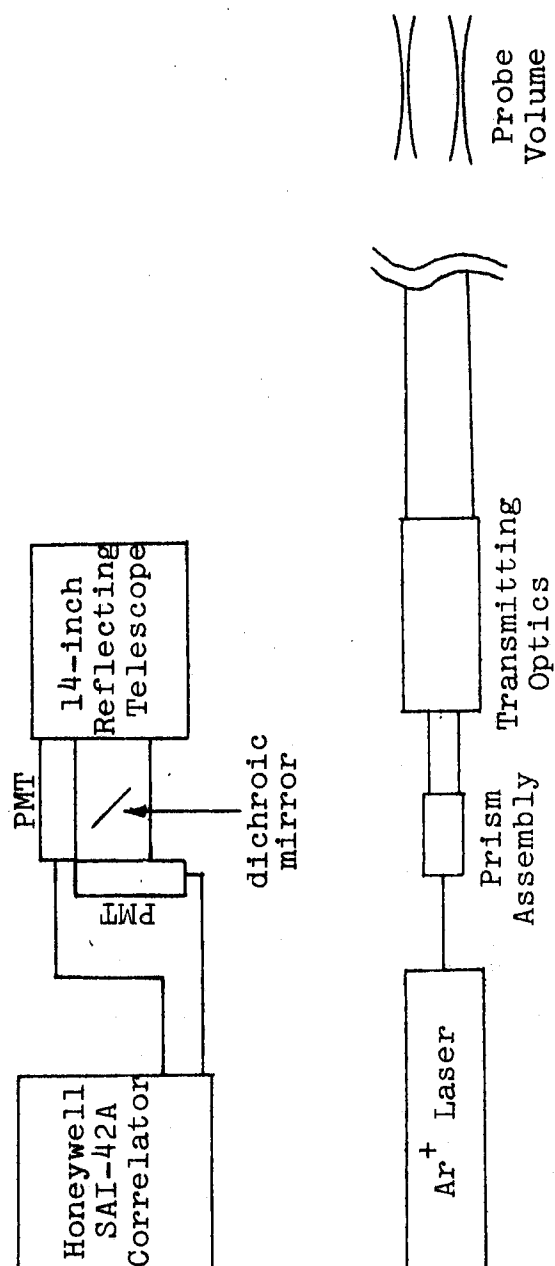


Figure 13. Experimental Setup for Flows at 50 and 100 Meters.

TABLE I
SUMMARY OF SYSTEM PARAMETERS

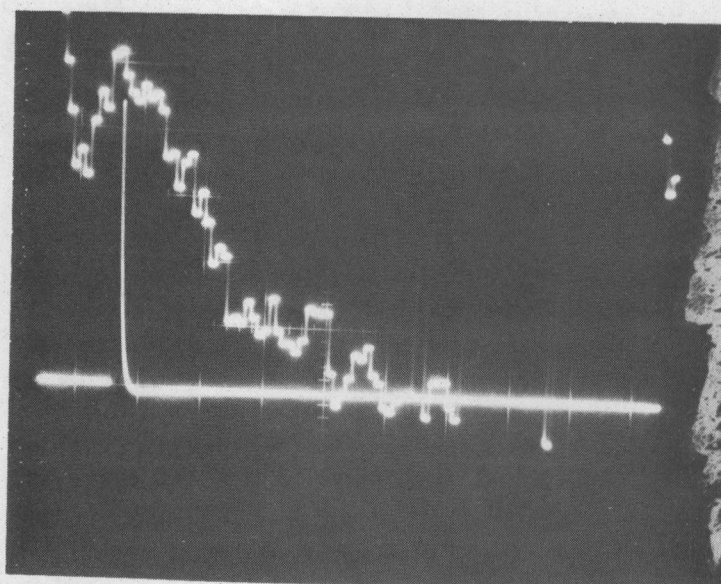
Parameters	Flow at 50 Meters	Flow at 100 Meters
z	50.0 m	100.0 m
R_2^+	-50.0 m	-100.0 m
f_1	.025 m	.025 m
f_2	.762 m	.762 m
d_L	.152 m	.152 m
b_2	.121 m	.121 m
R_2^-	.774 m	.768 m
b_{w1}		
514.5 nm	8.2 μm	8.2 μm
488.0 nm	7.8 μm	7.8 μm
z_{12}	.774 m	.768 m
f_T	49.2 m	97.5 m
d''	1.9 mm	3.9 mm
$(b_3)_{\min}$		
514.5 nm	430 μm	850 μm
488.0 nm	400 μm	800 μm

measure the exact separation of the 2 spots at the flow, a filamentary wire was spun through the spots at a constant speed of 20.618 m/s. The time delay measured for the signals from the wire was then used to determine the distance d'' given in Table I. It should be noted that if a focal length, f_1 , of 10 mm had been used instead of 25 mm, the spot diameters would have been approximately $1/2$ the diameters given in Table I.

2. Experimental Results

In the first part of the experiment a fan was used to create a flow of atmospheric dust at 50 and 100 meters from the system. The velocity of the flow was checked with an LDV system and found to be 16.33 m/s at the center of the flow. The fan was then used to set up a flow at 50 m and the velocity of the flow was measured with the 2 spot system. The correlogram shown in Figure 14 was obtained with 700 volts on the PM tubes and 2 watts of total laser power. The peak gives a $\Delta\tau$ of 120 μsec for a velocity of 15.8 m/s. This gives 4% uncertainty between the known and measured velocity of the flow.

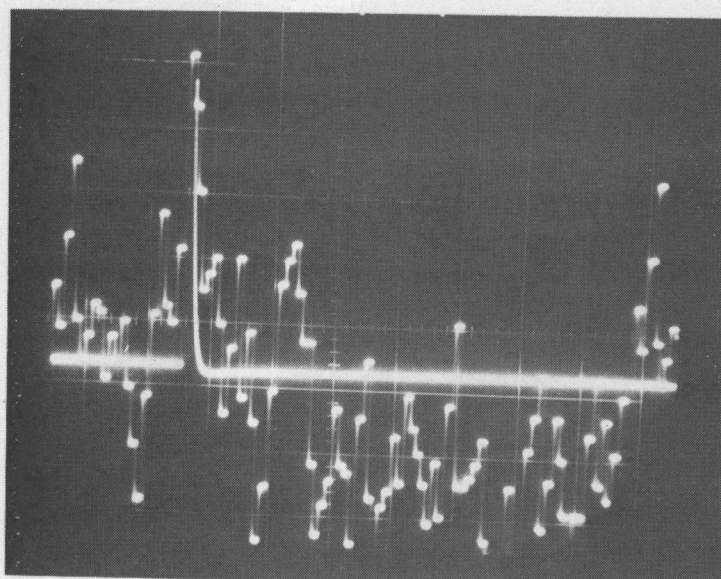
The fan was then moved out to 100 m and the correlogram shown in Figure 15 was obtained. The total laser power was 3 watts and there was 800 volts on the PM tubes. The peak gives $\Delta\tau$ as 220 μsec for a flow velocity of 17.7 m/s or 8% uncertainty. For both correlograms, the correlator was allowed to accumulate signals until the



10 μ sec per bin

peak bin #12

Figure 14. Correlagram for Dust at 50m.



10 μ sec per bin

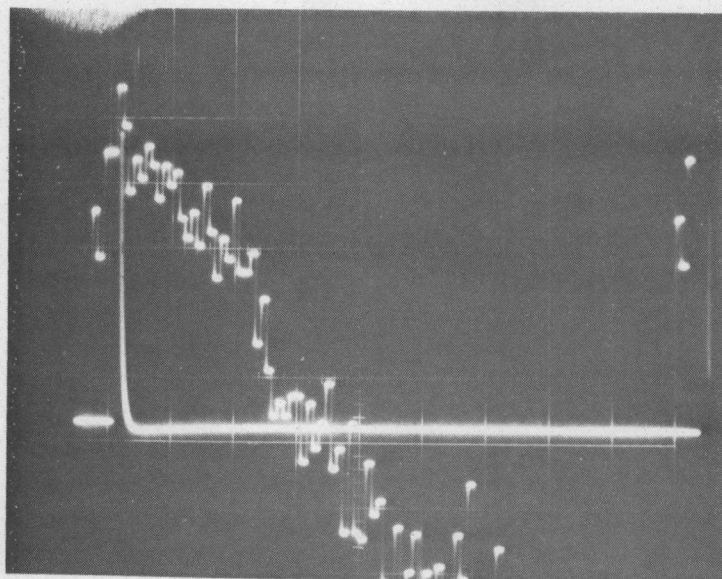
peak bin #22

Figure 15. Correlagram for Dust at 100m.

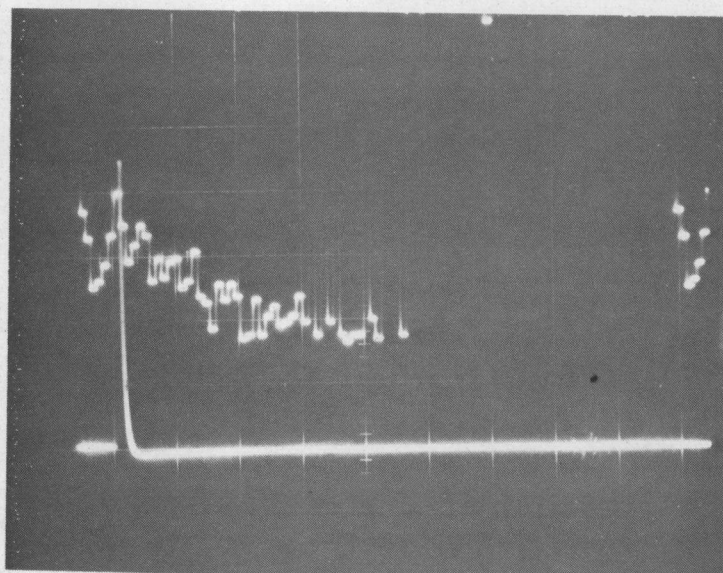
memory was full. By reducing the spot size and improving the electronic processing of the signals, improvements in the accuracy of the velocity measurements should be obtained.

The second part of the experiment was designed to test the limits of the system and was performed with the system set up for flows at 50 meters. When the results in Figure 14 were obtained, the flow was set up parallel to the ground. In order to show that accurate results are obtained when the spots are rotated, the flow was set up perpendicular to the ground and the spots rotated 90 degrees. Then the results in Figure 16 were obtained with the laser power high enough to yield a very good peak for the upper correlagram, and then with the laser power turned down to the minimum power necessary to generate a discernable peak for the lower correlagram. In both cases, the PM tube voltage was held constant at 700 volts on each tube. The measured velocity was then 15.8 m/s as compared to the known velocity of 16.33 m/s.

As a final test of the system, the spots were rotated 90 degrees so they would be parallel to the ground and the background wind velocity was measured. The correlagram in Figure 17 was obtained with 700 volts on the PM tubes and a total laser power of 2 watts. The resulting peak yields a $\Delta\tau$ of 2.0 msec for a wind velocity of 0.95 m/s. The 2 correlagrams in Figure 18 were taken the

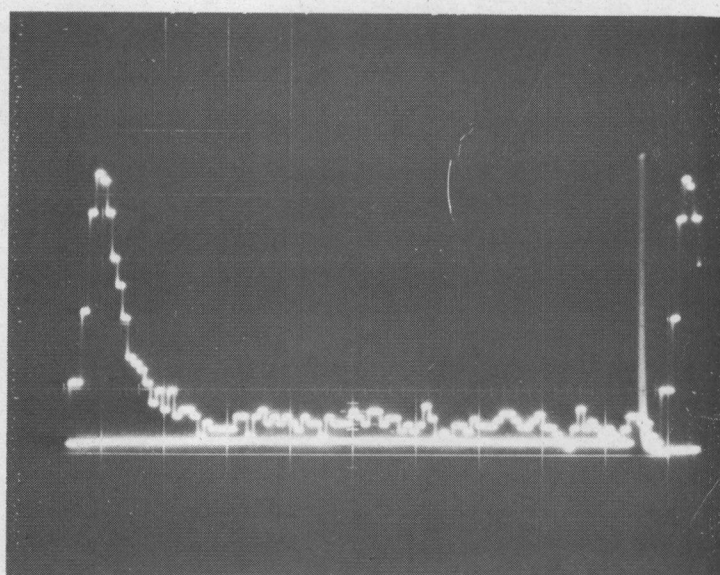


2 watts total power



.6 watts total power

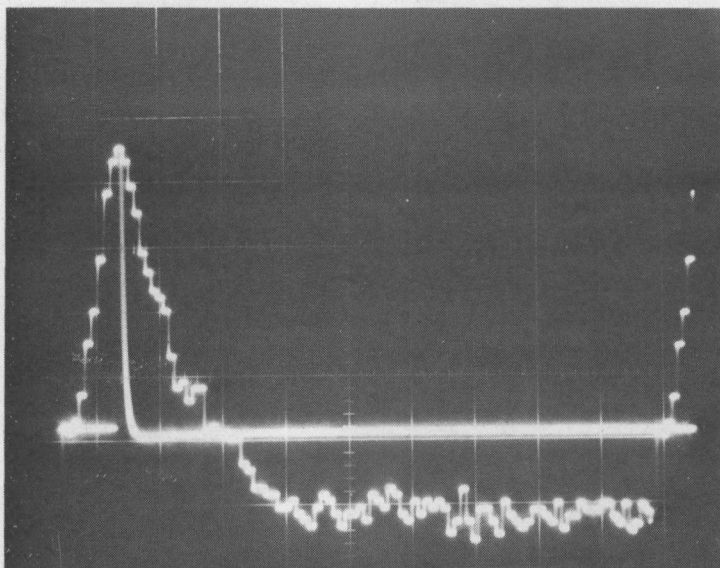
Figure 16. Effects of Changing Laser Power on the Peak of the Correlagram.



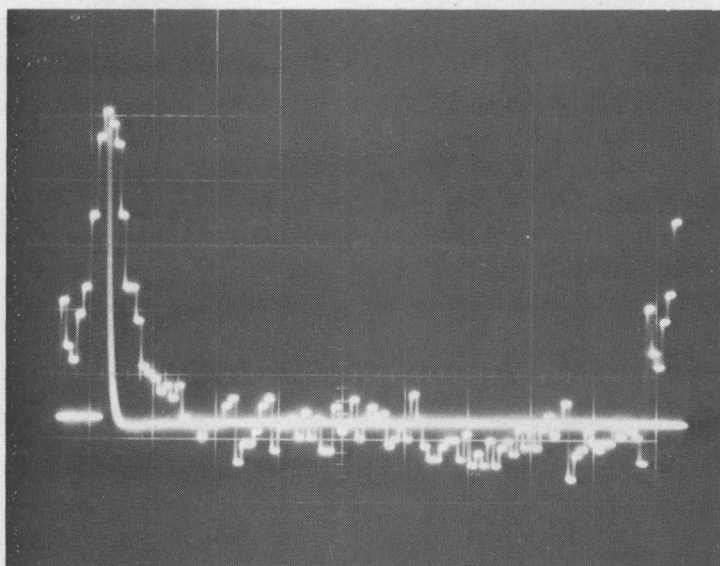
.5 msec per bin

peak bin #4

Figure 17. Correlagram for Background Wind at 50m.



.1 msec per bin, peak bin #9



Range 100 meters

.2 msec per bin, peak bin #7

Figure 18. Correlagram for Background Wind at 50m and 100m.

next day approximately 15 minutes apart. At a range of 50 m with 2 watts laser power and 700 v on the PM tubes, a Δt of 0.9 msec was measured for a velocity of 2.11 m/s. At a range of 100 m with the same laser power, but with 800 v on the PM tubes, a Δt of 1.4 msec was measured for a velocity of 2.07 m/s.

The results shown in Figures 14 through 18 show that the velocimeter system does yield good results at ranges of up to 100 m. As can be seen from the correlagrams for the background wind, low speed flows provide much better results, as would be expected. The final system described in the next chapter should allow measurements of much higher flow speeds with more accuracy than was attained in this experimental arrangement.

CHAPTER VI

SUMMARY

The 2 spot laser velocimeter system described in Chapter V has been shown to provide good data at ranges up to 100 m. The velocimeter system has also been tested, using a 4-inch lens for a receiver and a 3-inch transmitter lens, at a range of 5 m, and shown to provide accurate results. Therefore, with only minor modifications the system can be used over a range of 5 to 100 meters.

A major advantage of this system is that since a dichroic beam splitter is used in the receiver the receiver does not have to be rotated when the spots are rotated. In order to improve the accuracy of the results and to increase the data accumulation rate, further improvements must be made in the electronic processing of the signals. This is especially true if turbulent flows are to be measured since at present it takes from 2 to 3 minutes to accumulate a sufficient number of signals to generate a good peak on the correlogram for flows at 50 to 100 meters, so the flow must be constant over that time span.

The final stage of this study, the construction of a mobile velocimeter system, has not been completed since the presently available argon laser is too large for such a system. A 4 watt argon laser is being acquired for use

in such a system and will be mounted in an enclosed box with the transmitting optics, as shown in Figure 19.

The transmitter and receiver will then be mounted together, as shown in Figure 20, so the entire system can be easily transported to a test site.

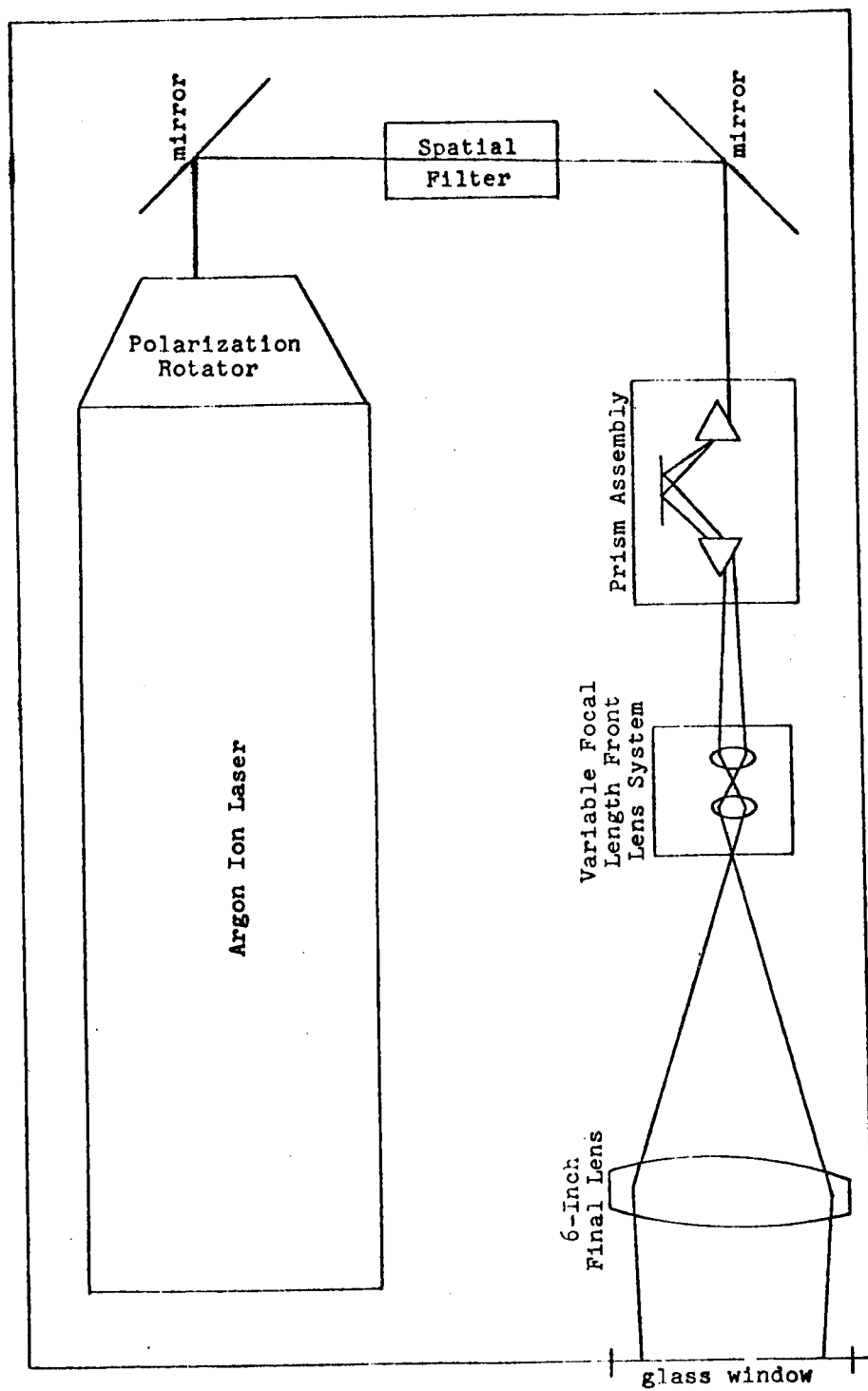


Figure 19. Transmitting System.

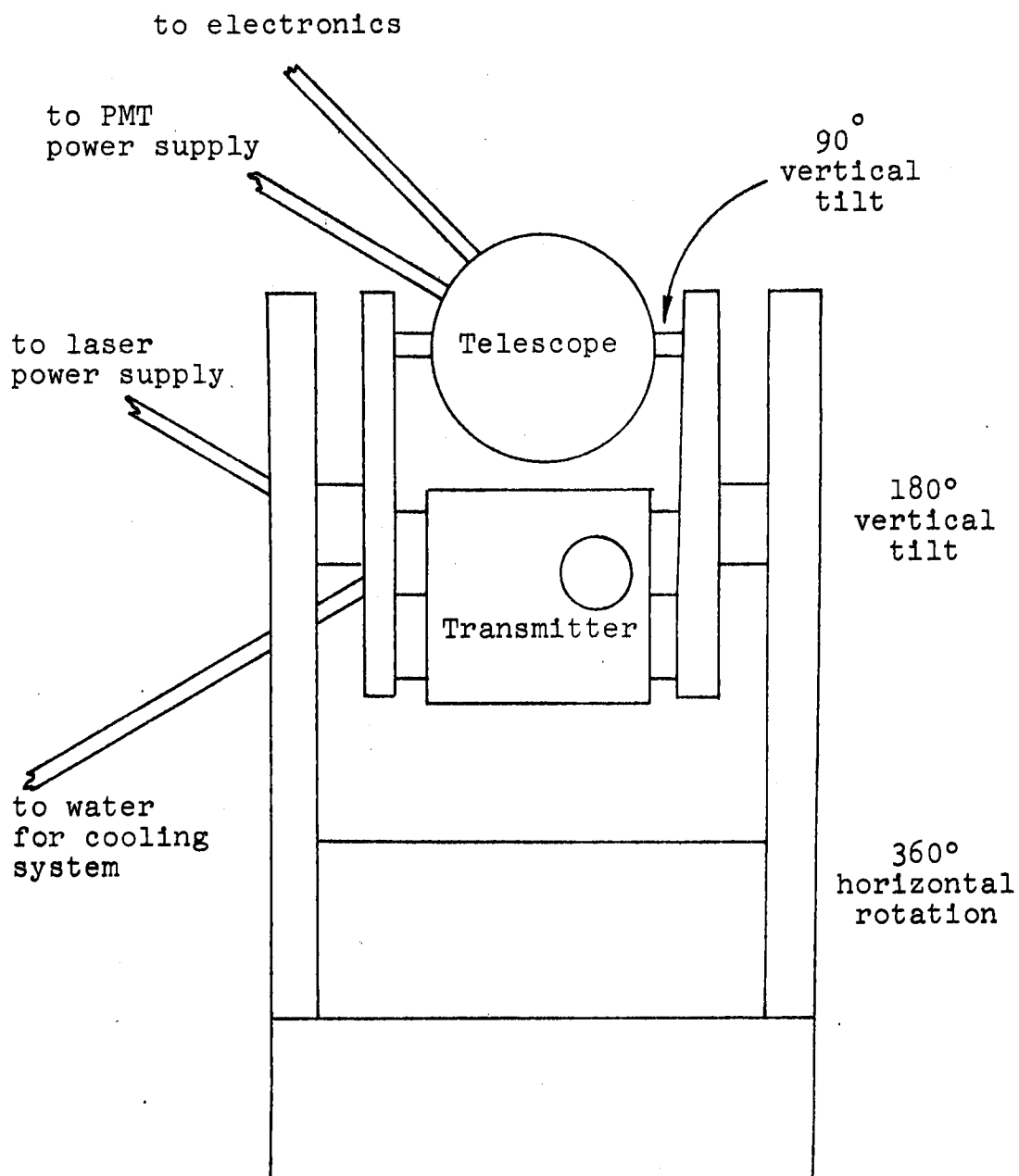


Figure 20. Mobile Velocimeter System.

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APPENDIX

APPENDIX

In order to derive Equation (16) from Equation (12), z_1 is located at the initial beam waist $R_1 = \infty$ and $b_1 = b_{w1}$. Therefore, when z_1 is located at the beam waist, Equations (5) and (6) become

$$b_2 = b_{w1} \left[\left(\frac{z_{12}}{z_{R1}} \right)^2 + 1 \right]^{1/2} \quad \text{and} \quad (A-1)$$

$$R_2^- = z_{12} \left[\left(\frac{z_{R1}}{z_{12}} \right)^2 + 1 \right], \quad (A-2)$$

where $z_{R1} = \frac{b_{w1}^2}{\lambda}$.

Now by using this value of R_2^- in Equation (11), we obtain

$$R_2^+ = \frac{z_{12}^f}{z_{R1}^2 f + z_{12}^f - z_{12}}. \quad (A-3)$$

Then by using $z_{R2} = \frac{b_2^2}{\lambda}$, Equation (12) can be rewritten in the form

$$b_3 = b_2 \left[\left[\left(\frac{R_2^+}{z_{R2}} \right)^2 + 1 \right]^2 + 2 \left(\frac{z_{23}}{R_2^+} \right) + 1 \right]^{1/2}. \quad (A-4)$$

Substituting (A-1) and (A-2) into (A-4) yields

$$b_3 = b_{w1} \left[\left(\left(\frac{z_{12}}{z_{R1}} \right)^2 + 1 \right) \left[\frac{z_{12}^f + z_{R2} z_{R1}^2 f + z_{12} z_{R1} f - z_{12} z_{R2}}{z_{R2} z_{R1}^2 f + z_{12} f - z_{12}} \right]^2 \right. \\ \left. \cdot z_{23}^2 \left[\frac{z_{R1}^2 f + z_{12} f - z_{12}}{z_{12} f} \right]^2 + 2 z_{23} \left[\frac{z_{R1}^2 f + z_{12} f - z_{12}}{z_{12} f} \right] + 1 \right]^{1/2} . \quad (A-5)$$

After considerable but straightforward algebraic manipulation, this equation can be reduced to the simpler form

$$b_3 = \frac{1}{b_{w1} f} \left[z_{12}^2 f^4 + z_{23}^2 f^4 + z_{12}^2 z_{23}^2 f^2 + 2 z_{23} z_{12} f^3 - 2 z_{23} z_{12} f^4 \right. \\ \left. - 2 z_{23} z_{12}^2 f^3 + b_{w1}^4 f^2 - 2 z_{23} b_{w1}^4 f + z_{23}^2 b_{w1}^4 \right]^{1/2} , \quad (A-6)$$

which can be rewritten as

$$b_3 = b_{w1} \left(\frac{z_{12}}{z_{R1}} \right) \left[\left(1 - \frac{z_{23}}{z_{12}} - \frac{z_{23}}{f} \right)^2 + \left(\frac{z_{R1}}{z_{12}} \right)^2 \left(1 - \frac{z_{23}}{f} \right)^2 \right]^{1/2} . \quad (A-7)$$

VITA

Howard Bruce Barnes was born in Birmingham, Alabama, on March 16, 1956. He entered Auburn University in Auburn, Alabama, in September 1974, and in March 1978 he received the Bachelor of Science degree in Physics. He entered The University of Tennessee Space Institute, Tullahoma, Tennessee, in September 1978. He was awarded the Master of Science degree in Physics in August 1979.