UNSTEADY DENSITY AND VELOCITY MEASUREMENTS IN THE 6' x 6' WIND TUNNEL

by

William C. Rose
Rose Engineering and Research, Inc.
Incline Village, Nevada 89450

and

Dennis A. Johnson
NASA - Ames Research Center
Moffett Field, California 94035

SECTION I

INTRODUCTION

The propagation of coherent radiation through a gaseous turbulent flow medium is known to be affected by the intensity of the fluctuations in the index of refraction and the correlation volumes of the index throughout the flow medium. With aerodynamic instrumentation it is possible to measure the intensities and correlation volumes of the density fluctuations, and through the Gladstone-Dale relationship, the required index of refraction intensities and correlations. The degradation of beam quality as it traverses the turbulence is of interest to the propogation of high energy laser beams from airborne platforms out to distant targets, optical imaging, and other sensor performance.

Recent Air Force Weapons Laboratory (AFWL) research programs have established the correlation between directly measured beam degradation and the density fluctuation levels and spatial scales as measured by aerodynamic instrumentation. This demonstrated correlation is important since, in many instances, it may be easier to make the required aerodynamic measurements than to make meaningful measurements of loss in optical quality. Computer codes are available for transforming information concerning the density and velocity fields to optical propogation information.

Over the past five years, the AFWL, in cooperation with NASA's Ames Research Center and Air Force Flight Dynamics Laboratory (AFFDL), has been conducting a continuing research program into the interaction of aerodynamics and optical performance. This program, known as the Aero-Optics Program, has produced significant results that further the understanding of aero-optical interaction.

Four major wind tunnel tests have been conducted in the NASA-Ames 6' x 6' wind tunnel: the first in the summer of 1975 and the second in the summer of 1976. A third test was completed in the fall of 1977. The first test served primarily as an introduction to the problems faced by both aerodynamicists and opticians. In the second test, both density fluctuation levels and their scales were obtained within the boundary layer and shear layer for several flow models. These aero-dynamically measured data appear to correlate well with the optical degradation data obtained for the same flow models. The third test investigated the effect of nonadiabatic wall temperature on optical degradation. A section of the model was heated to about 50°C above the adiabatic plate temperature to induce measurable total temperature fluctuations in the boundary layer.

As difficult and complex as these previous test programs appear to be, they have modeled only an ideal case of a beam looking normal to the plane of a two-dimensional shear layer representative of those occurring over open and closed port geometries. Presently conceived methods for beam exits involve the use of turrets and fairings which produce highly three-dimensional turbulent flow fields. The fourth test in the Aero-Optics Program was conducted in the fall of 1978. A small scale (approx. 1/40) turret and fairing combination was mounted on the same plate as used in previous tests. The turret was a 12.7 cm ceolostat with a 2.5 cm aperture that could be remotely rotated from 60° to 150° in azimuth angle. Flow characteristics affecting optical performance were studied along imaginary beam paths of 60°, 90°, 120° and 150°.

All of the Aero-Optics tests were carried out over a range of Mach numbers between 0.6 and 0.9 with one set of data in A-O IV being obtained at M=1.5. The Reynolds numbers for these tests ranged between $6 \cdot 10^6$ and $12 \cdot 10^6$/m. Various thickness shear and boundary layers were generated so that the tunnel Reynolds number may not be as important as the shear-layer thickness Reynolds number, for example. The reader is referred to Reference 1 for further details of model geometry and flow configuration identification.

This report presents a brief summary of the results obtained in the four tests and the methods to obtain them. All of the information obtained in these tests has been presented in detail previously (see References 2, 3, and 4) and is, therefore, only summarized here.

SECTION II

INSTRUMENTATION AND DATA REDUCTION

Two proven systems for making the aerodynamic measurements necessary for inferring optical degradation due to a region of turbulent flow are the hot-wire anemometer and laser velocimeter. Their application and use in high subsonic and transonic flows has been discussed in detail in Reference 1. In order to present a description that can be read by those interested in fields other than aerodynamics, a brief description of the instrumentation and data reduction procedures used is given in this section. The discussion is included here since many of the concepts and techniques used in this report stemmed directly from the needs created by the Aero-Optics Program.

The laser velocimeter in its many forms is a nonintrusive optical device for measuring particle velocity in a moving stream. Successful measurements have been made in both water and air. When the particles are small enough, their velocity (and changes in velocity) are essentially the same as that of the fluid. Thus, the velocimeter is an instrument capable of making pure kinematic measurements, independent of the thermodynamic state of the fluid.

On the other hand, the hot-wire anemometer is an instrument that senses heat transfer from a fine wire; and thus it senses a combination of kinematic and thermodynamic flow properties. In a turbulent compressible flow (i.e., $M \geq \approx 0.3$) all of the thermodynamic and kinematic flow properties can vary with time and space. The time variations are known as fluctuations and their long-time averages are characterized by the rms of the quantity. The spatial variations are generally complex, being strongly dependent on the history of the fluid prior to reaching the location of interest. A method of characterizing the large effects of spatial variations is that of correlation volume, which is essentially the volume in the fluid over which a turbulent burst or eddy retains its identity. Both rms values of the fluctuation levels of the fluid density and their correlation volumes affect optical degratation; hence, to characterize the optical effects, one must measure both properties of the flow.

Since there are no proven instruments for directly sensing fluid density or its time and spatial variations, other techniques must be employed to obtain information about the density. As noted above, the laser velocimeter can measure velocity fluctuations (u'). A very hot wire will measure the mass flux (product of density and velocity) fluctuations [$(\rho u)'$]. Another fluid parameter, the total temperature T_t, can also fluctuate and can be measured by an unheated wire sensor. The anemometers used for these two measurements (i.e., the electronics used to process the signals from the sensor wires) are a constant-temperature system for the mass flow and a constant-current system for the total temperature.

The interrelationship between the fluctuating variables in a compressible flow is not completely obvious; however, the thermal energy equation

$$T_t = T + u^2/2c_p \tag{1}$$

constrains the way in which thermodynamic and kinematic variables may fluctuate. The logarithmic differential form of equation (1) involving the fluctuating quantities can be written as:

$$\left(1 + \frac{\gamma-1}{2}M^2\right)\frac{T_t'}{\bar{T}_t} = \frac{p'}{\bar{p}} - \frac{\rho'}{\bar{\rho}} + (\gamma-1)M^2\,\frac{u'}{\bar{u}} \tag{2}$$

where the primed quantities are the real time fluctuations. Equation (2) is the basis for the aerodynamic data reduction employed throughout the Aero-Optics tests. The Mach number in (2) is that of the gas moving past the sensor while all of the barred quantities are the respective time averaged, local mean values. Since the fluctuating fluid density appears in equation (2) and cannot be measured directly, this relationship must be investigated to the fullest in order to use what can be measured to deduce information about the density, and, hence, the required optical information.

Some important implications of equation (2) are now discussed. If, somehow, the T_t' and p' terms are negligible compared to the others, then what remains is just

$$\frac{\rho'}{\bar{\rho}} = (\gamma-1)M^2\,\frac{u'}{\bar{u}} \tag{3}$$

Thus, a knowledge of M^2, $\bar{\rho}$, and $u'/\bar{u}$ from a laser velocimeter would allow one to immediately obtain information about ρ'. The rms of the fluctuation at a point is the easiest quantity to obtain. The spatial scales or correlation volumes are more difficult to obtain since cross correlations of the output with various spatial separations of two sensing volumes would be required. To date, this has not been done, although, conceptually, it is possible given a high velocimeter data rate.

With respect to a hot-wire anemometer, the mass flux fluctuations do not appear in equation (2); however, the equation may be rewritten in either of two ways:

$$\left(1 + \frac{\gamma-1}{2}M^2\right)\frac{T_t'}{\bar{T}_t} = \frac{p'}{\bar{p}} - \frac{(\rho u)'}{\bar{\rho}\bar{u}} + [1 + (\gamma-1)M^2]\frac{u'}{\bar{u}} \tag{4a}$$

or

$$\left(1 + \frac{\gamma-1}{2}M^2\right)\frac{T_t'}{\bar{T}_t} = \frac{p'}{\bar{p}} + (\gamma-1)M^2\frac{(\rho u)'}{\bar{\rho}\bar{u}} - [1 + (\gamma-1)M^2]\frac{\rho'}{\bar{\rho}} \tag{4b}$$

Now consider a situation in which the p' term is negligible. Equations (4a) and (4b) provide a means of deducing either the u' term or ρ' term from direct measurements of T_t' and $(\rho u)'$. This is less restrictive than equation (3), since the presence of total temperature fluctuations can be accounted for in equation (4). If T_t' is significant, then a laser velocimeter alone cannot be used to infer the density fluctuations. If the p' term is significant, then an independent measurement of it is required to infer ρ' with either the hot-wire anemometer or the laser velocimeter. The spatial scales can be easily obtained by the hot-wire anemometer, since the cross correlation of two analog signals with increasing separation distance is straightforward. All density scale sizes reported in the Aero-Optics test results were obtained by the hot-wire anemometer.

SECTION III

RESULTS

Measurements of the nondimensional velocity fluctuations from two configurations (see Buell, Ref. 1, for configuration identification) using the laser velocimeter and hot-wire anemometer are shown in Figure 1. The velocimeter data were obtained with and without artificial seeding and indicate slightly larger fluctuations near the boundary-layer edge with seeding. The hot-wire values were obtained using equation 4b with $T_t' = p' = 0$. The agreement between the independent systems is quite good up to turbulence levels of 25%. This type of agreement is typical of that obtained throughout the Aero-Optics program. The solid curves represent the best estimate between the two measurement systems. The density fluctuations are shown for three configurations in Figure 2 for the low and high Mach number cases. The boundary layer (2a) exhibits the usual shape of the fluctuation profile. Configuration 2, a large fence, produces nearly twice the fluctuation levels over a larger distance, producing a substantial optical degradation. Figure 3, a good fence ahead of the cavity, produces nearly boundary layer-like values except in the thin shear layer.

Correlation of two wires in the beam direction, Z, produces the integral scale lengths shown in Figure 3. Note in Figure 3b the decrease in scale size in the thin shear layer. This somewhat offsets optical degradation caused by the increase in fluctuation level in that layer. All correlation data are best fit by an exponential curve rather than the Gausian assumed frequently.

Scaling the data to other Mach and Reynolds numbers is discussed in detail in Reference 3, however, the density fluctuation levels scale roughly as M^2 while Reynolds number effects the scale sizes and layer thicknesses in the usual way.

Heat addition to the boundary layer ahead of the measurement station was studied in Aero-Optics III. A section of the plate (see Ref. 1) was heated approximately 50°C above ambient which produced the change in total temperature profile shown in Figure 4. Little effect on velocity fluctuations was observed with the heat addition as can be seen in Figure 5. Density fluctuations, however, did increase by about 10-25% with heating (Figure 6). No effect on correlation length was observed with heat addition, indicating that the kinematics of the turbulence was not substantially altered by the amount of heating used here.

Results from the turret and fairing combination test (A-O IV) were typical of those shown in Figure 7 for a Mach number of 0.95. The rms velocity fluctuations, non-dimensionalized by their local mean value are shown in comparison to the mean Mach number distributions. Substantial velocity fluctuations are observed for the higher azimuth angles, although all the fluctuation data appear to be consistent with the presence of gradients in the mean flow. Some of these gradients are inviscidly generated (such as the supersonic "tongues" at 90° and

120°) and some viscously; however, no present means are available to distinguish between the fluctuations generated by various gradients. Fluctuations seen in the outer regions of these flows are probably caused by turbulence in the free shear layer associated with flow separation from the turret itself. Because the Mach numbers are observed to be much higher than the freestream, the potential for density fluctuations is quite large, since the mean density gradients will scale with the square of the local Mach number. The data at other Mach numbers all exhibit similar trends, however, for the lower Mach numbers, separation from the turret occurs at larger azimuth angles. In summary, the rather large values of density fluctuation appear to be the result of much higher Mach numbers than freestream and the violent turbulence in the flow as it separates from the turret.

A representative comparison of fairing on-fairing off rms density fluctuations shown in Figure 8 indicates essentially no effect at $M = 0.62$ and a small effect at $M = 0.95$. These data indicate that some slight improvement in optical quality can be expected with the addition of a fairing, although at $M = 0.62$ its effect would be nil. Fairings are very useful in controlling pressure loads on turrets, but will not have first order effects on optical quality.

Scale sizes increase dramatically with increasing azimuth angle as shown in Figure 9 for a representative condition. Since both scale-sizes and fluctuation levels increase (total turbulence path length also increases) with azimuth angle, substantial optical degradation might be expected. The Strehl ratio is shown in Figure 10 for the present data scaled up to a large turret in a flight environment. For shorter wave lengths, large degradations occur.

SECTION IV

CONCLUSIONS

1. State-of-the-art aerodynamic instrumentation and data interpretation methods allow the fluctuations in density and their spatial scales required to determine optical performance to be obtained in the most complex flows. In many cases it may be easier and/or more reliable to assess optical degradation due to an aerodynamic flow by aerodynamic measurements rather than direct optical techniques.

2. Wind tunnel testing at high subsonic and transonic Mach numbers usually produces wall conditions that are adiabatic, similar to those found in flight experiments. The amount of heat transfer from the surface that is required to produce observable increases in density fluctuations is at least an order of magnitude larger than that observed in flight.

3. The density fluctuations scale with a parameter that is essentially $q_\infty \ell_Z/\delta$ (the dynamic pressure times scale length divided by shear layer thickness). Correlation of the wind tunnel data using this scaling is very good. This parameter can account for variations of Mach and Reynolds numbers as well as variations in ℓ_Z/δ brought about by such things as strongly nonequilibrium turbulence behavior.

4. The loss in optical quality due to an aerodynamic fence is substantially larger than an attached boundary layer. The major source of this loss is the large density fluctuation level in the thin

shear layer that develops from the top of the fence. When a fence is present, its effect dominates any effect that the upstream boundary layer has on optical degradation.

5. For the small-scale turret and fairing combination, aerodynamic measurements of the fluctuation level and spatial scales of the density field have been made. Their effects on a coherent beam propagating through the flow have been made. Measurements were made around the turret at azimuth angles of 60°, 90°, 120° and 150° without the fairing and 60°, 90° and 120° with the fairing present. Considerable increases in density fluctuation level and scale size were observed with increasing azimuth angle, producing strong optical phase aberrations at the larger angles. Even for the 90° case, optical losses are observed to be higher than estimated on the basis of previous aero-optical investigations because the significant increase in Mach number over the flight Mach number around the turret was not considered previously. Attempts at scaling optical phase variance with aerodynamic parameters such as dynamic pressure were not successful. This was shown to result primarily from the nature of the flow causing the phase aberrations. For the turret, a large region of turbulent, separated flow exists which is only mildly influenced by Mach and Reynolds numbers and dynamic pressure; however, the large spatial scales arise almost uniquely as a result of the separation.

The addition of a fairing to the turret does little to aid in the optical quality, although fairings are quite useful in reducing aerodynamic loads on the surface and within the optical cavity of the aperture.

REFERENCES

1. Buell, D.A., "6' x 6' Wind Tunnel Aero-Optics Test Overview," Proceedings of the USAF/NASA Aero-Optics Symposium. August 14-15, 1979, NASA-Ames Research Center, Moffett Field, CA, Sept. 1979.
2. Johnson, D.A. and Rose, W.C., "Turbulence Measurements in a Transonic Boundary Layer and Free-Shear Flow Using Laser Velocimetry and Hot-Wire Anemometry Techniques," AIAA paper 76-399, San Diego, CA, 1976.
3. Rose, W.C., Measurements of Aerodynamic Parameters Affecting Optical Performance, AFWL TR-78-191, Air Force Weapons Laboratory, Kirtland AFB, NM, May 1979.
4. Rose, W.C., Optical Effects of Near-Field Turbulence About a Small-Scale Turret Model, AFWL TR-79-129, Air Force Weapons Laboratory, Kirtland AFB, NM, December 1979.

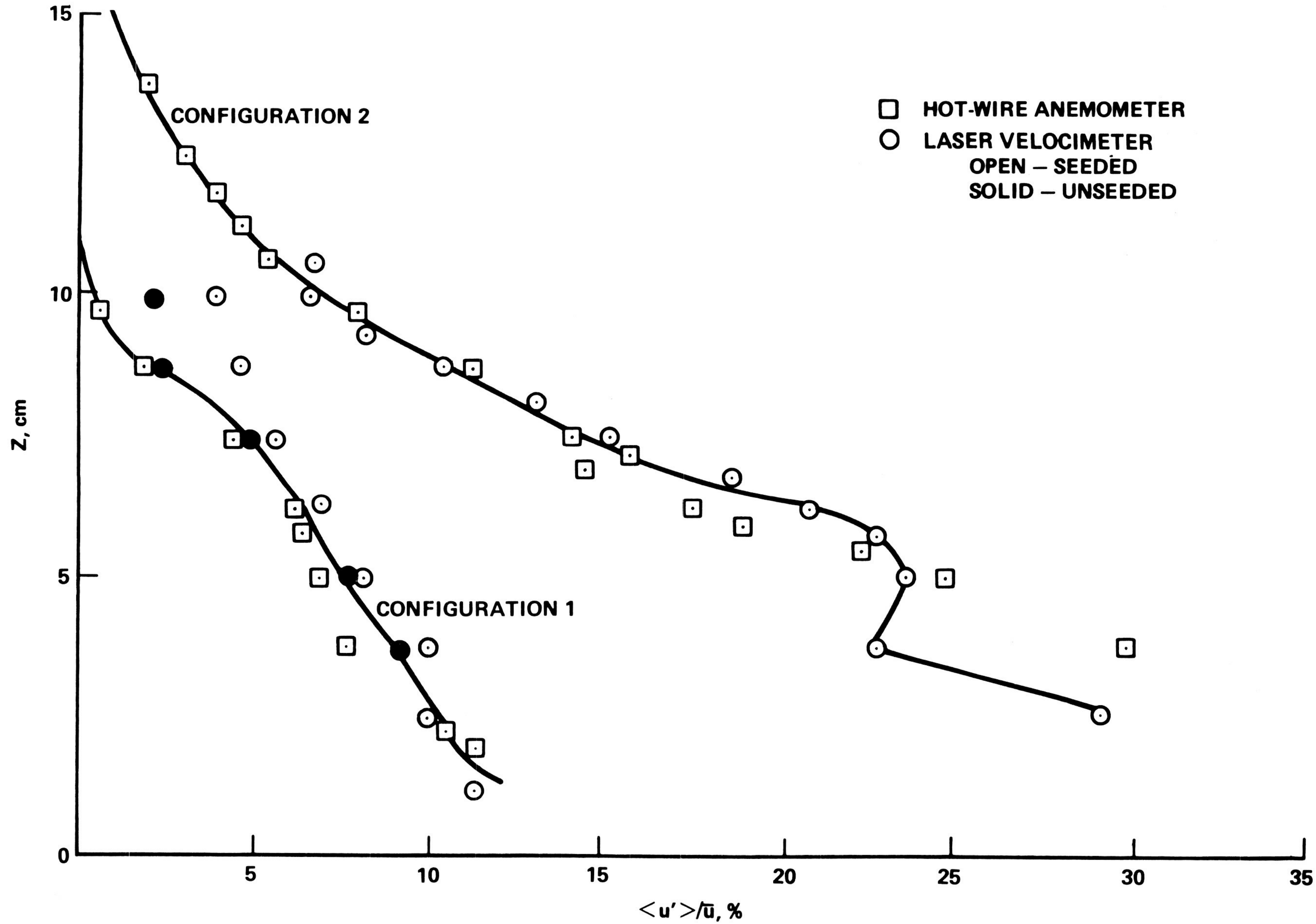

Figure 1. Velocity Fluctuations in Boundary and Shear Layers.

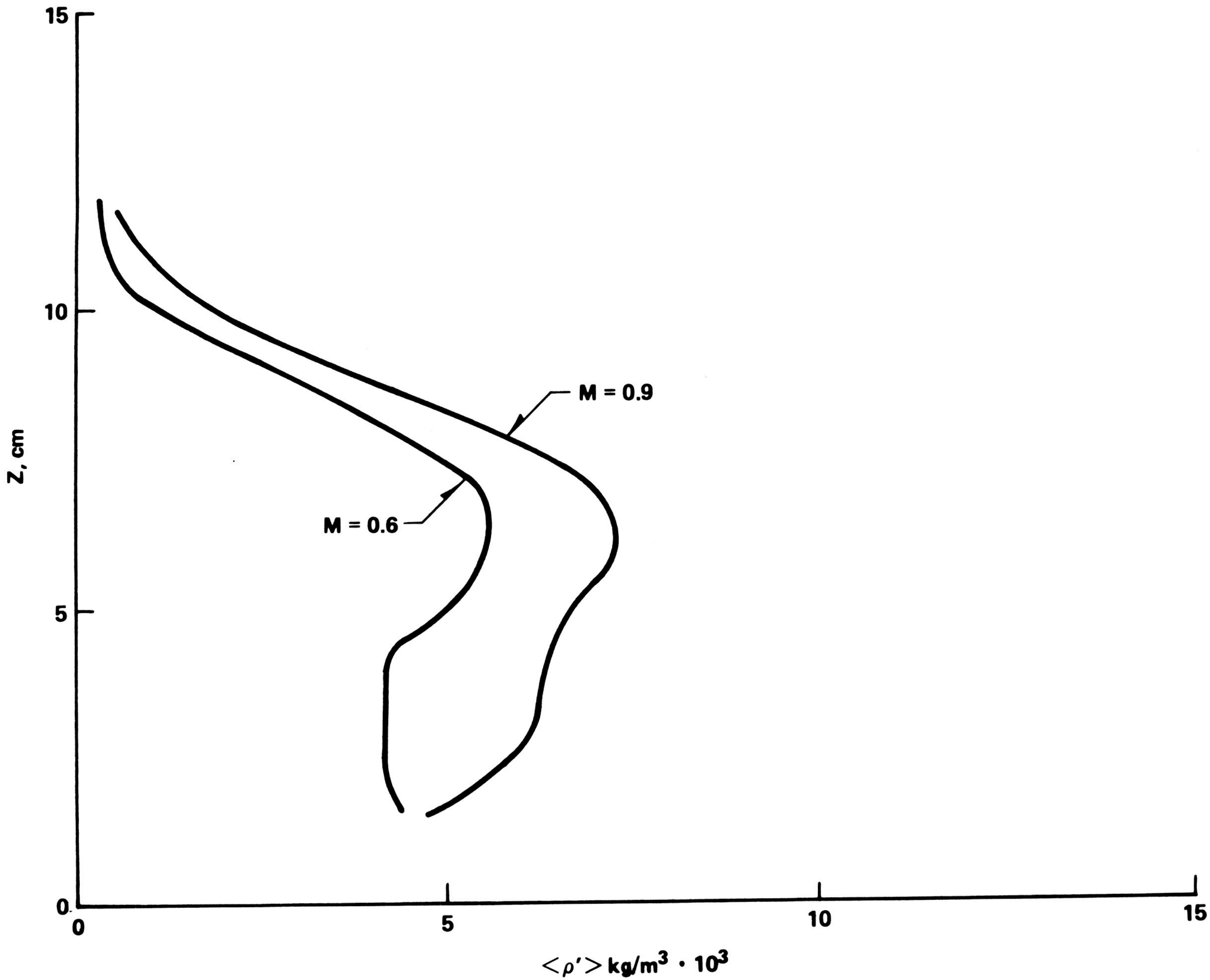

Figure 2. Density Fluctuations. a) Configuration 1.

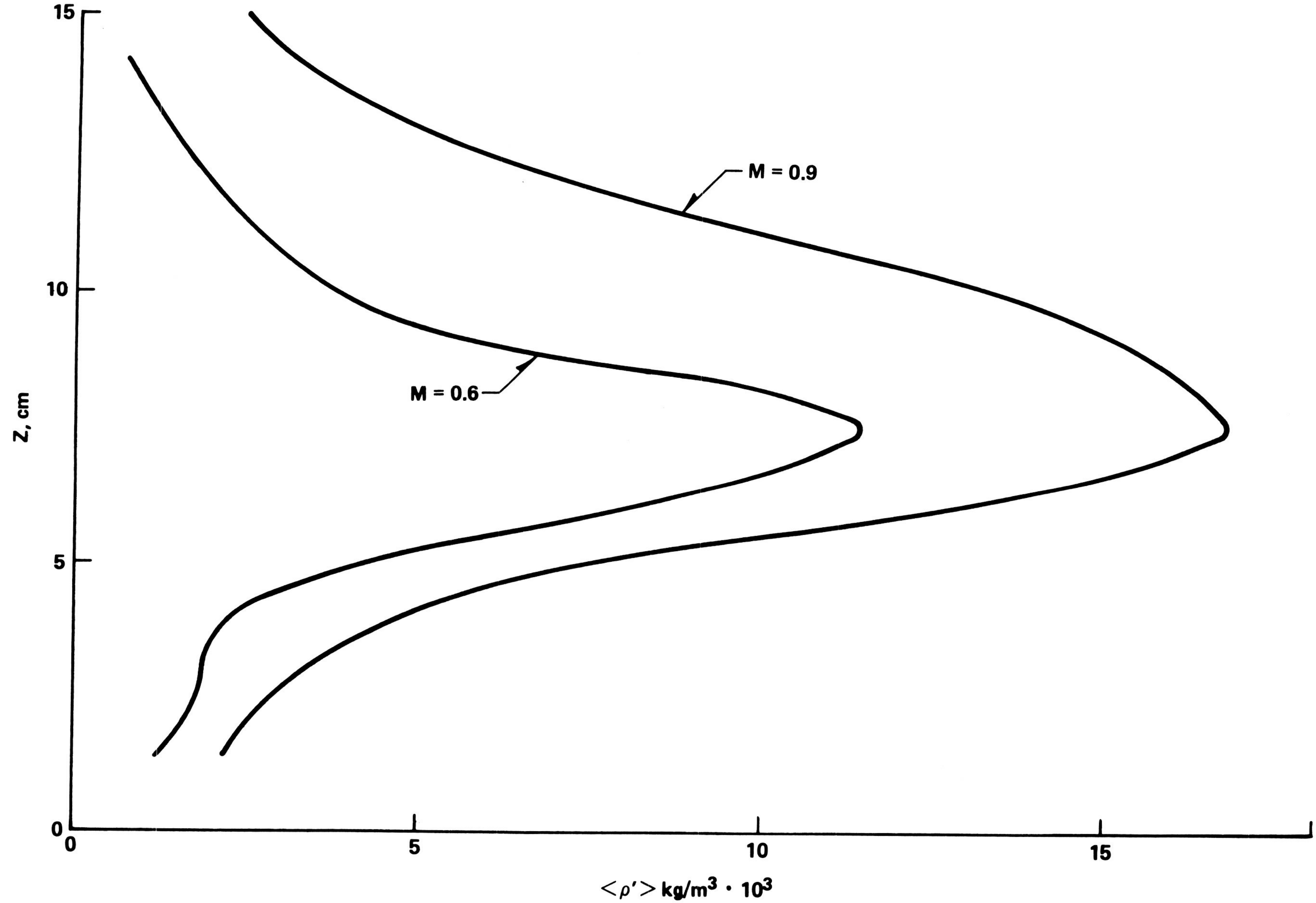

Figure 2. Density Fluctuations. b) Configuration 2.

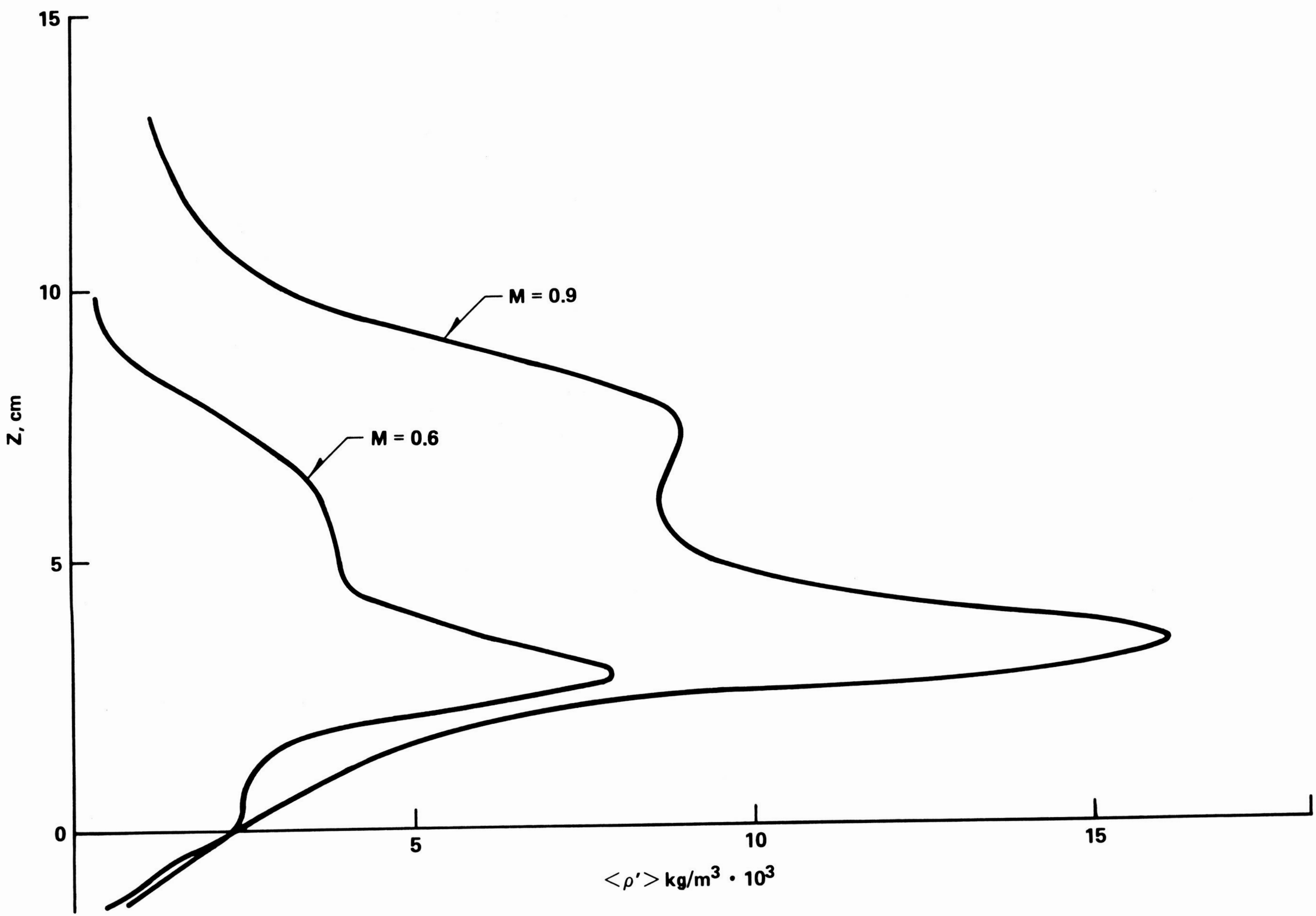

Figure 2. Density Fluctuations. c) Configuration 13.

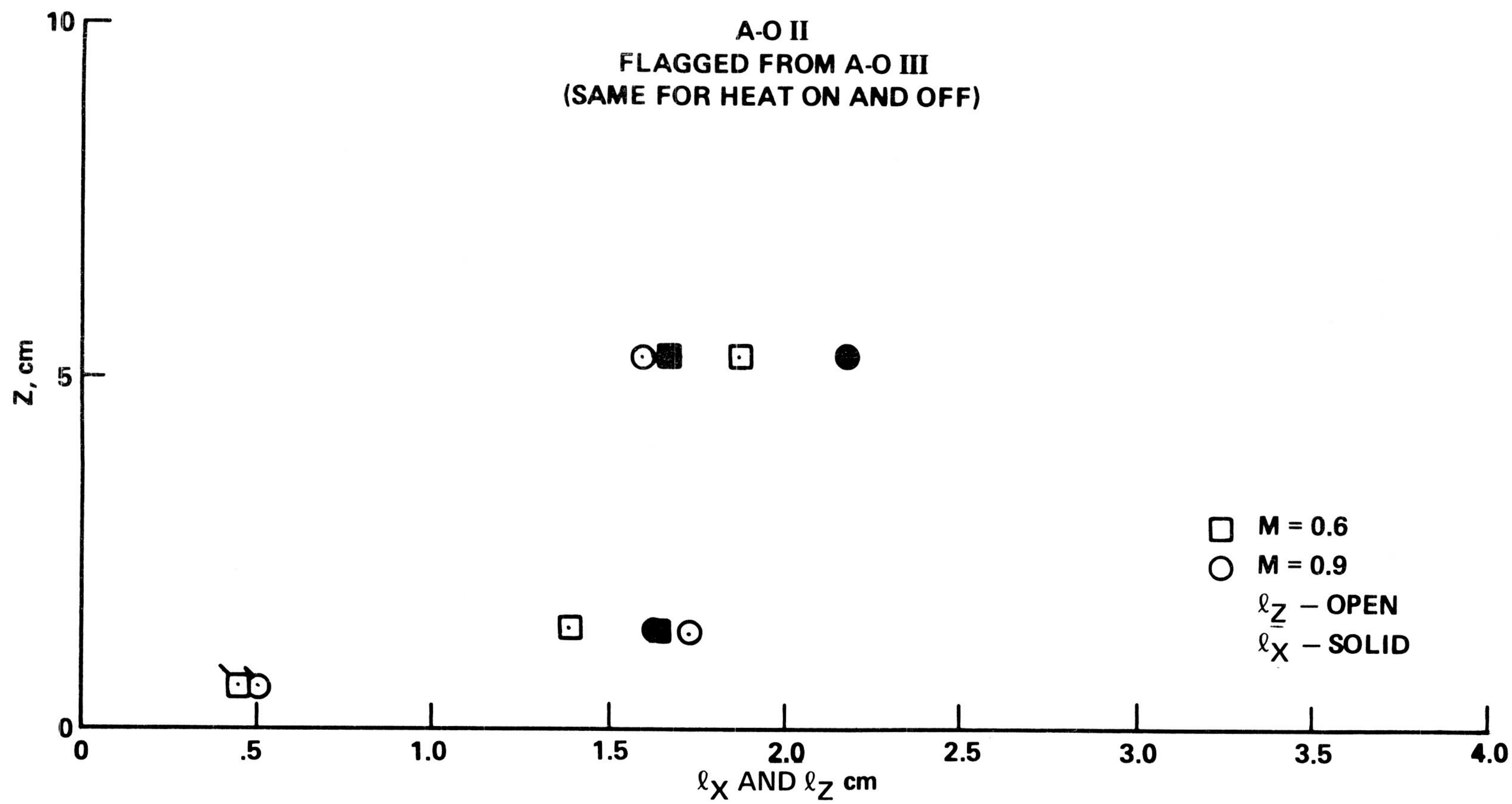

Figure 3. Correlation Lengths. a) Configuration 1.

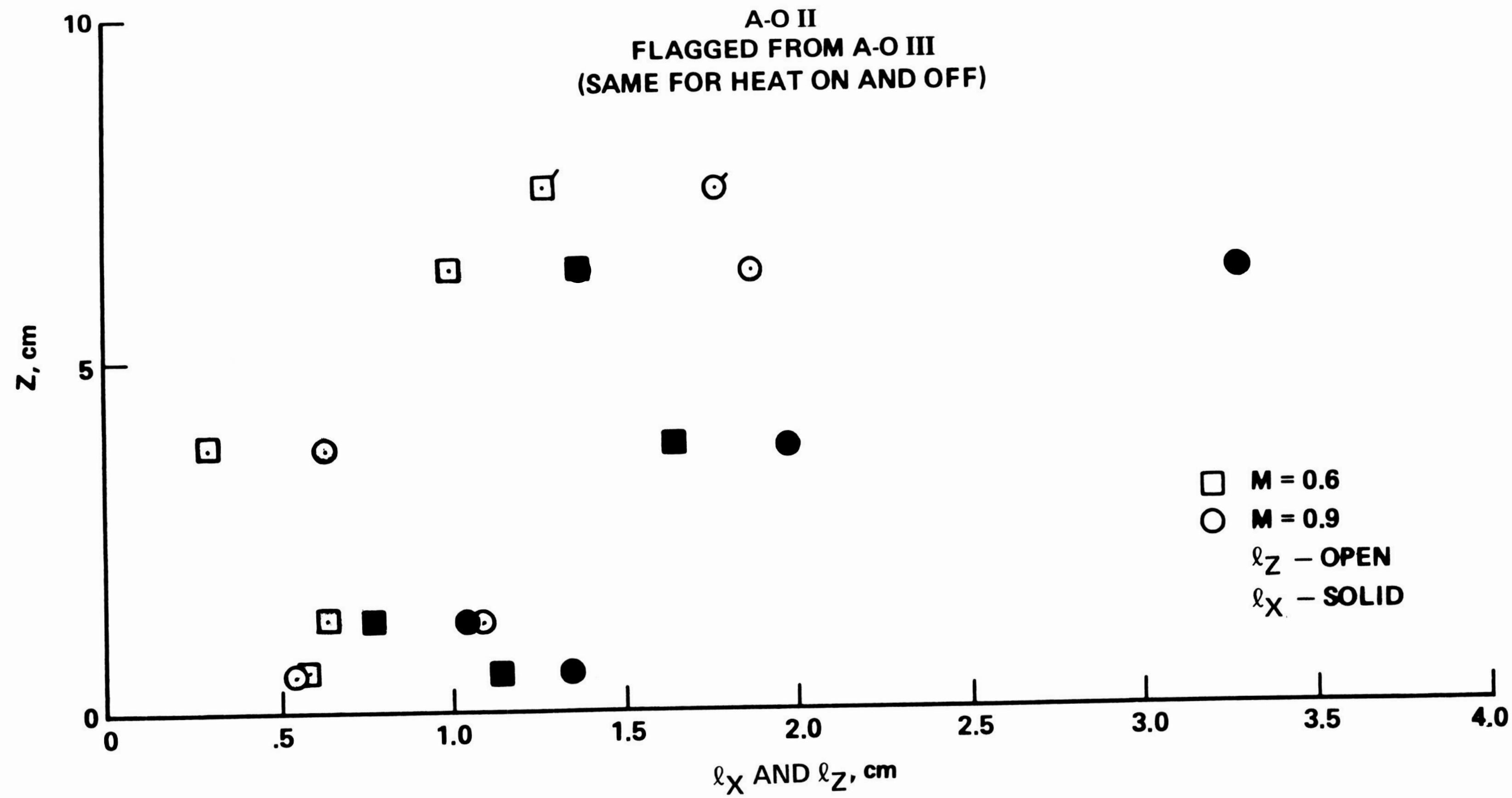

Figure 3. Correlation Lengths. b) Configuration 13.

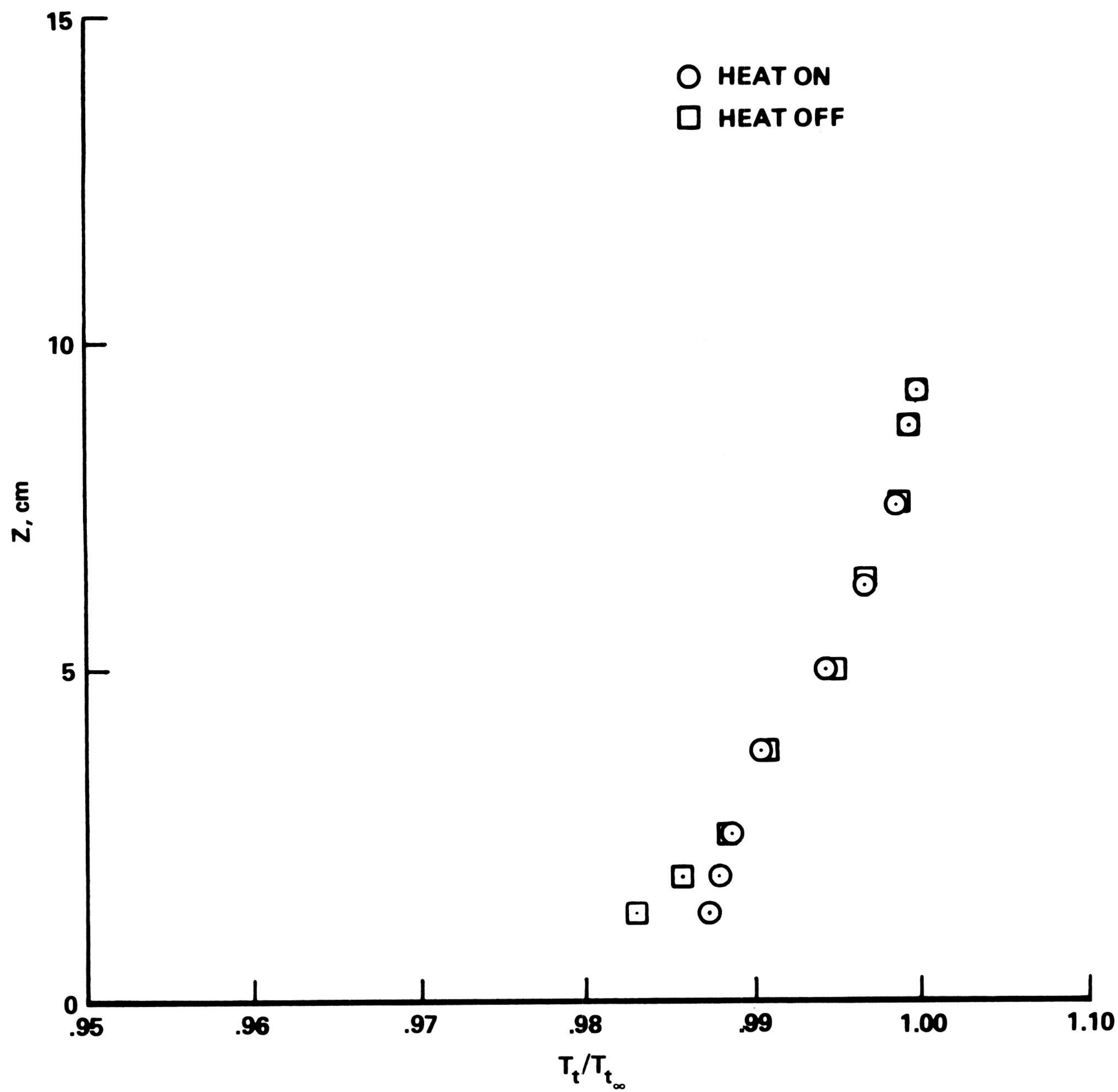

Figure 4. Total Temperature Profiles, Config. 1, M = 0.9.

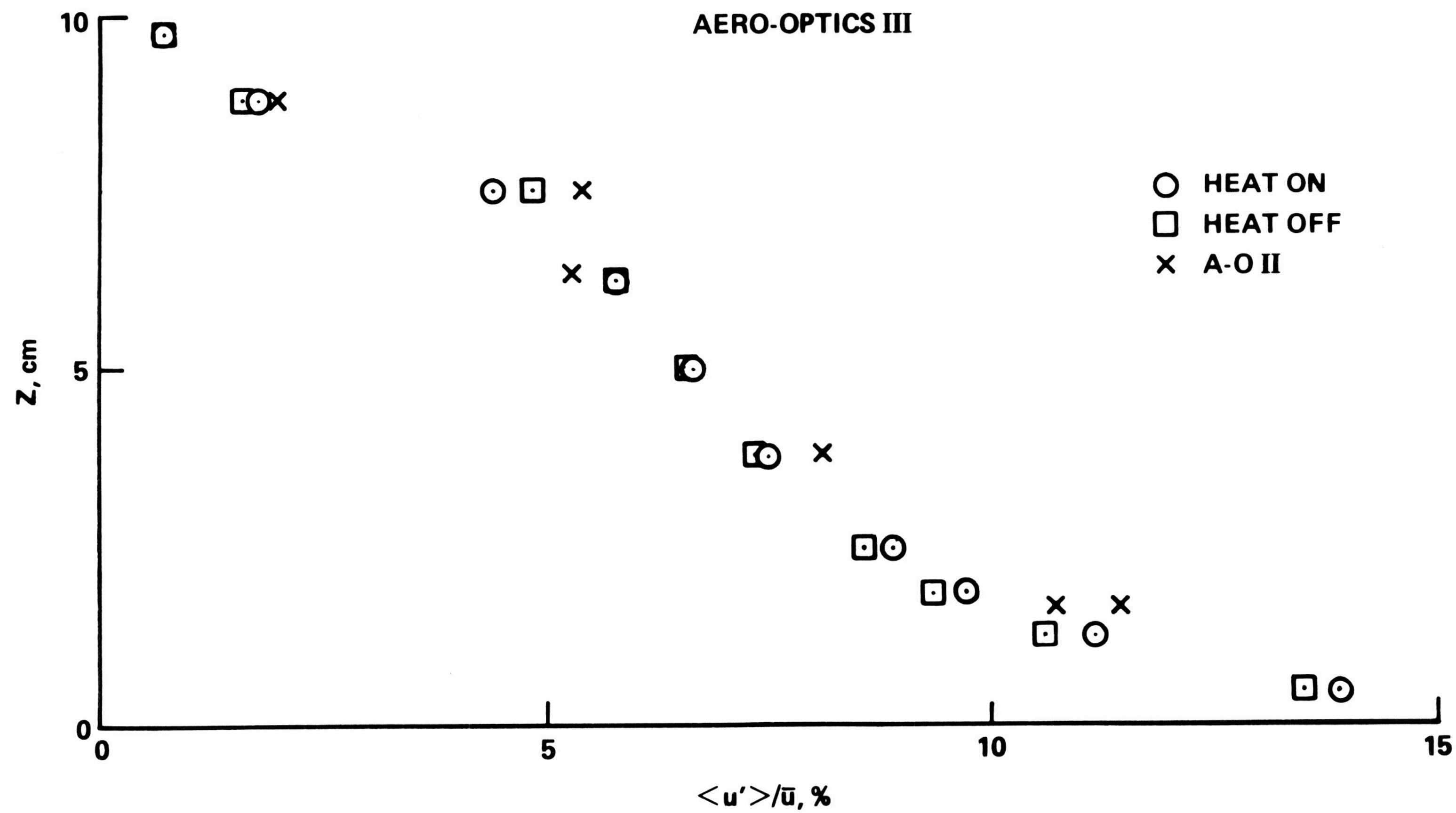

Figure 5. Velocity Fluctuations, Config. 1, M = 0.9.

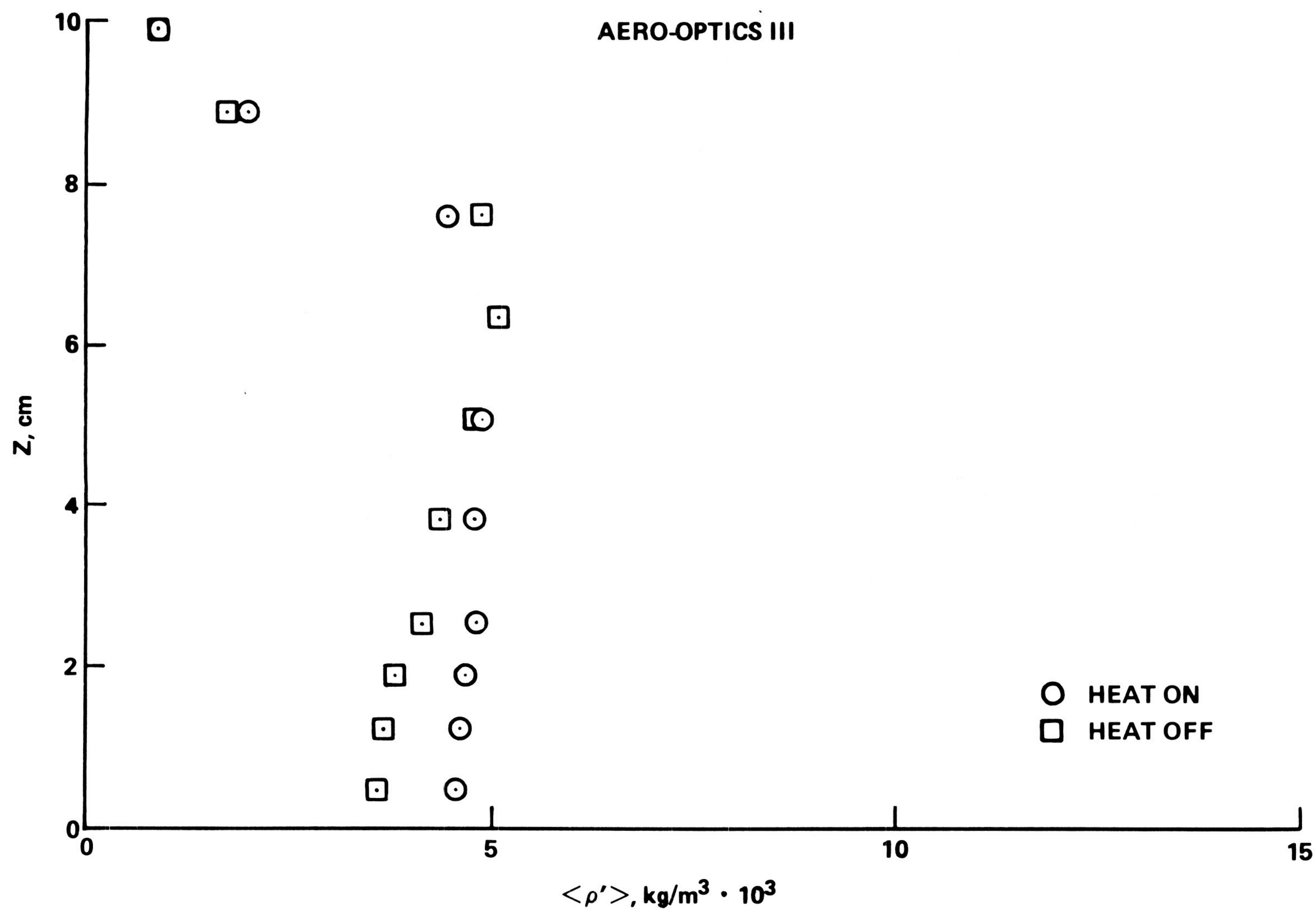

Figure 6. RMS Density Fluctuations, Config. 1, M = 0.9.

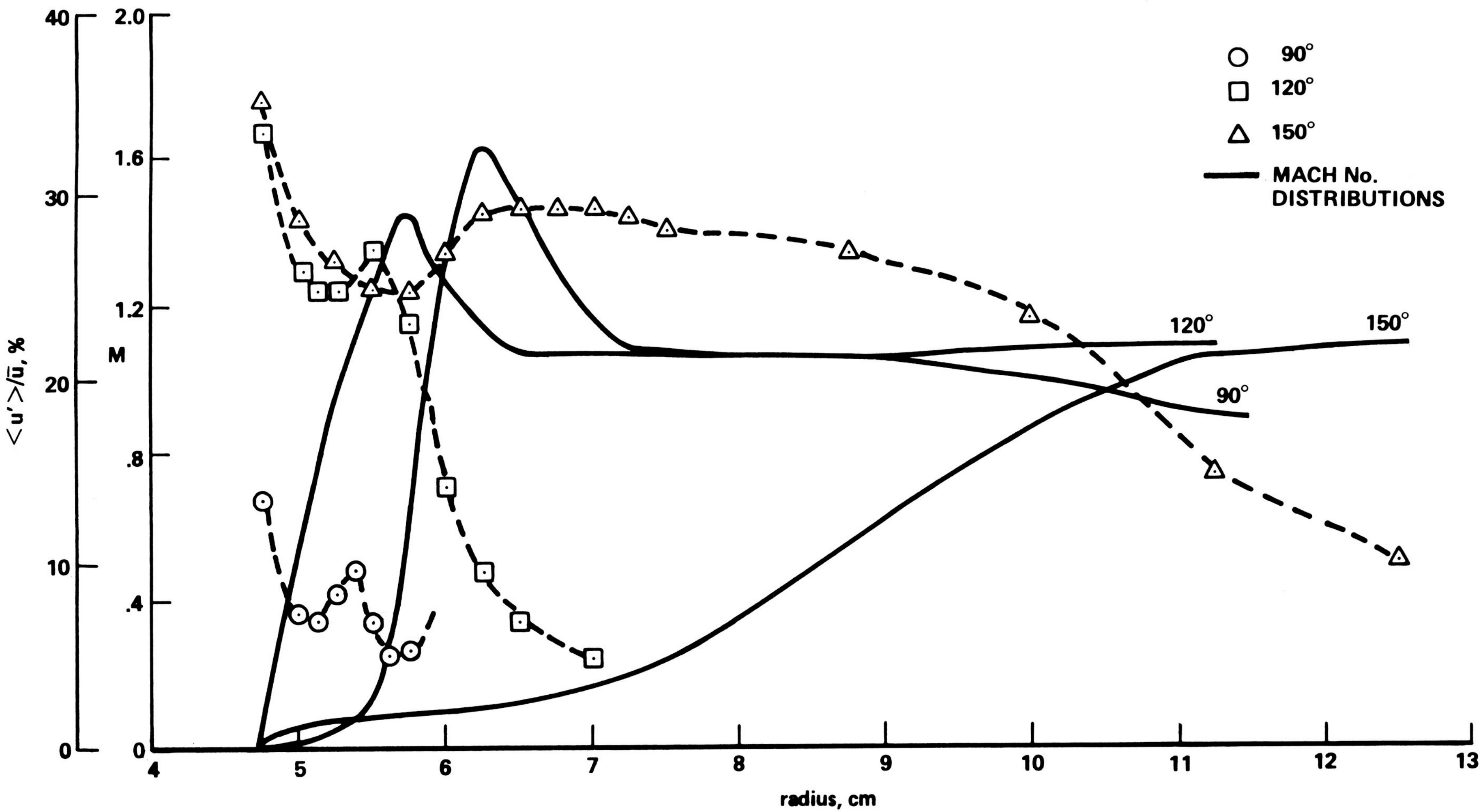

Figure 7. Kinematic (Velocity) Fluctuations and Mean Profiles from A-O IV.

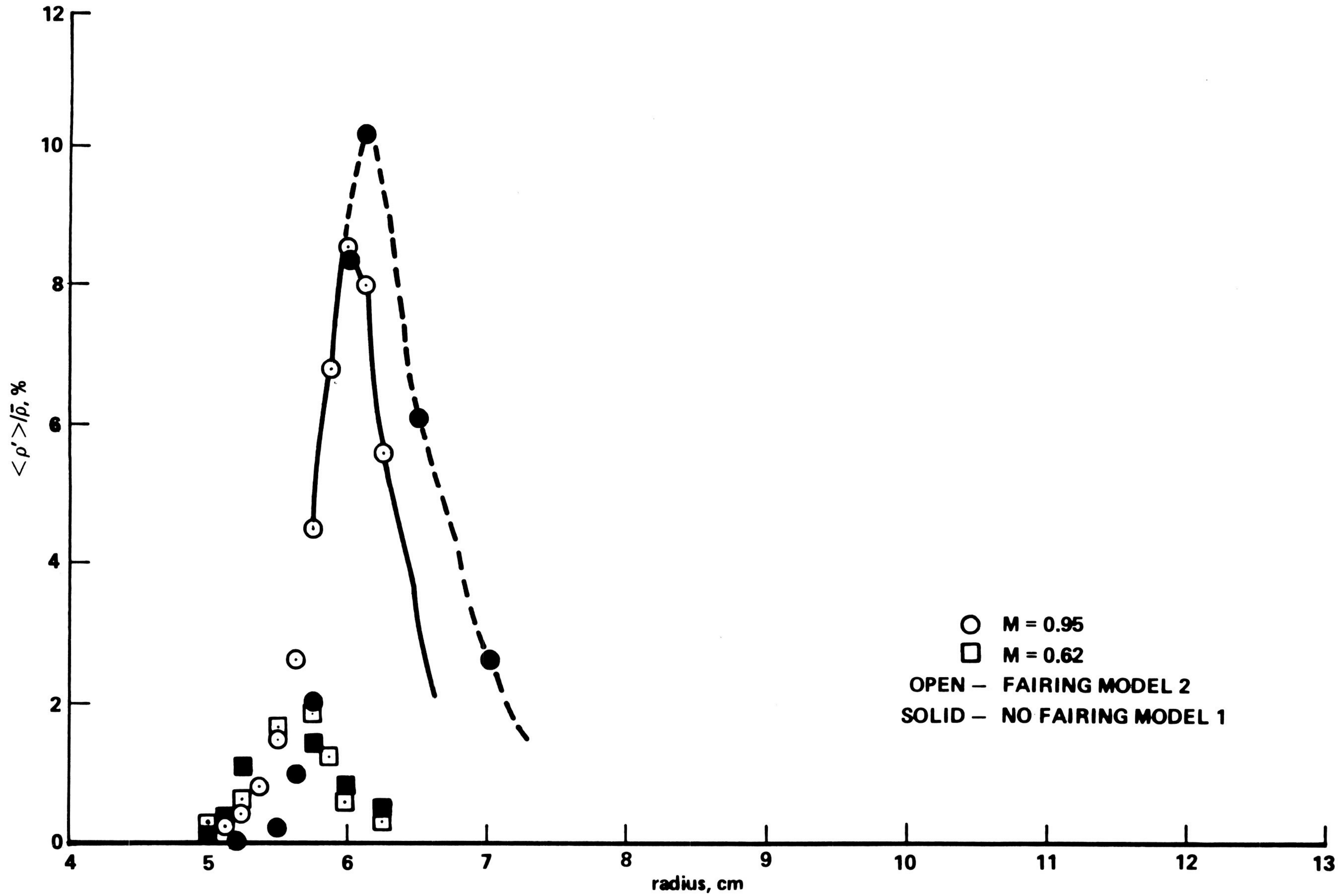

Figure 8. Effect of Fairing on Density Fluctuations at θ = 120°.

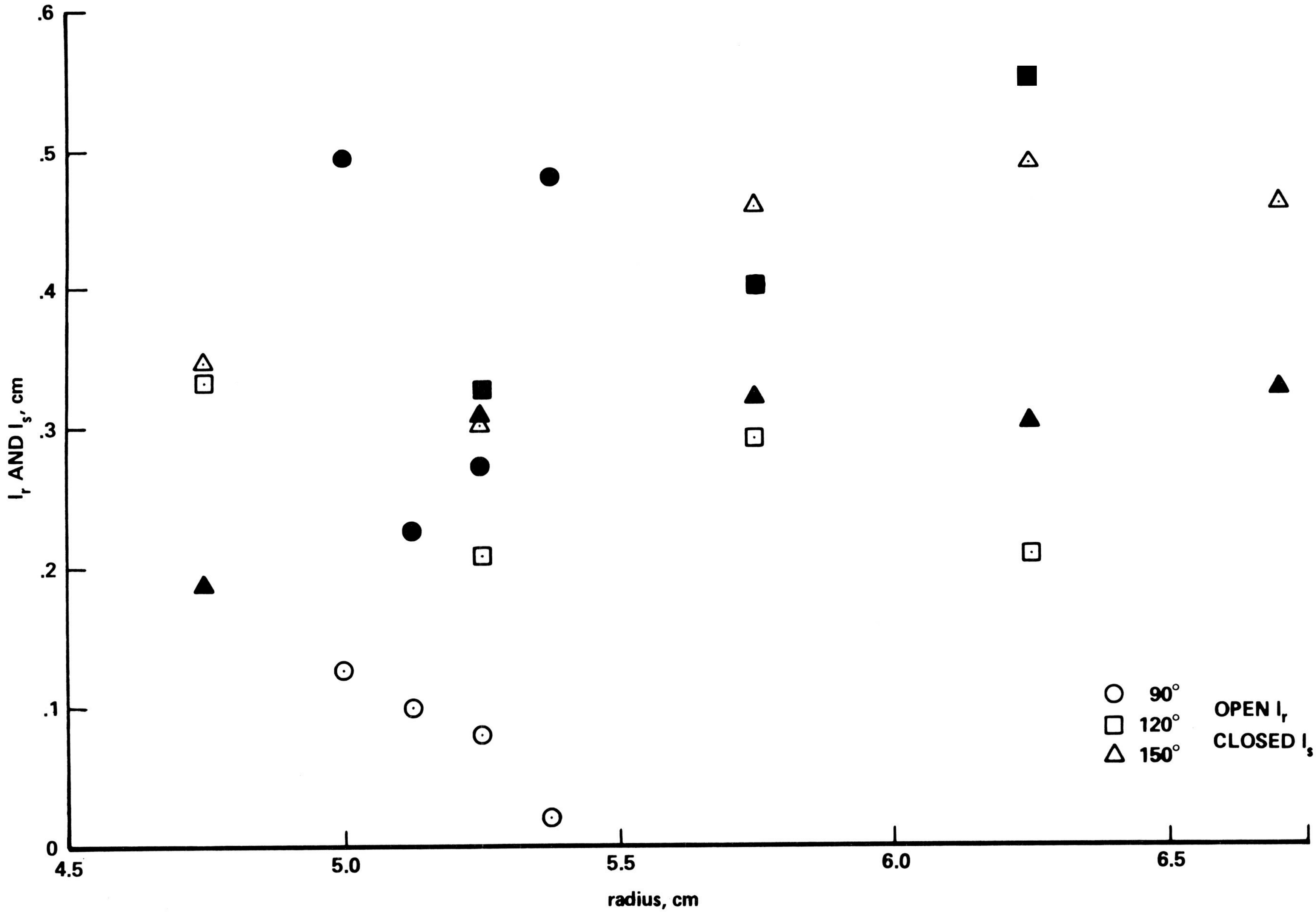

Figure 9. Effect of Azimuth Angle on Correlation Lengths.

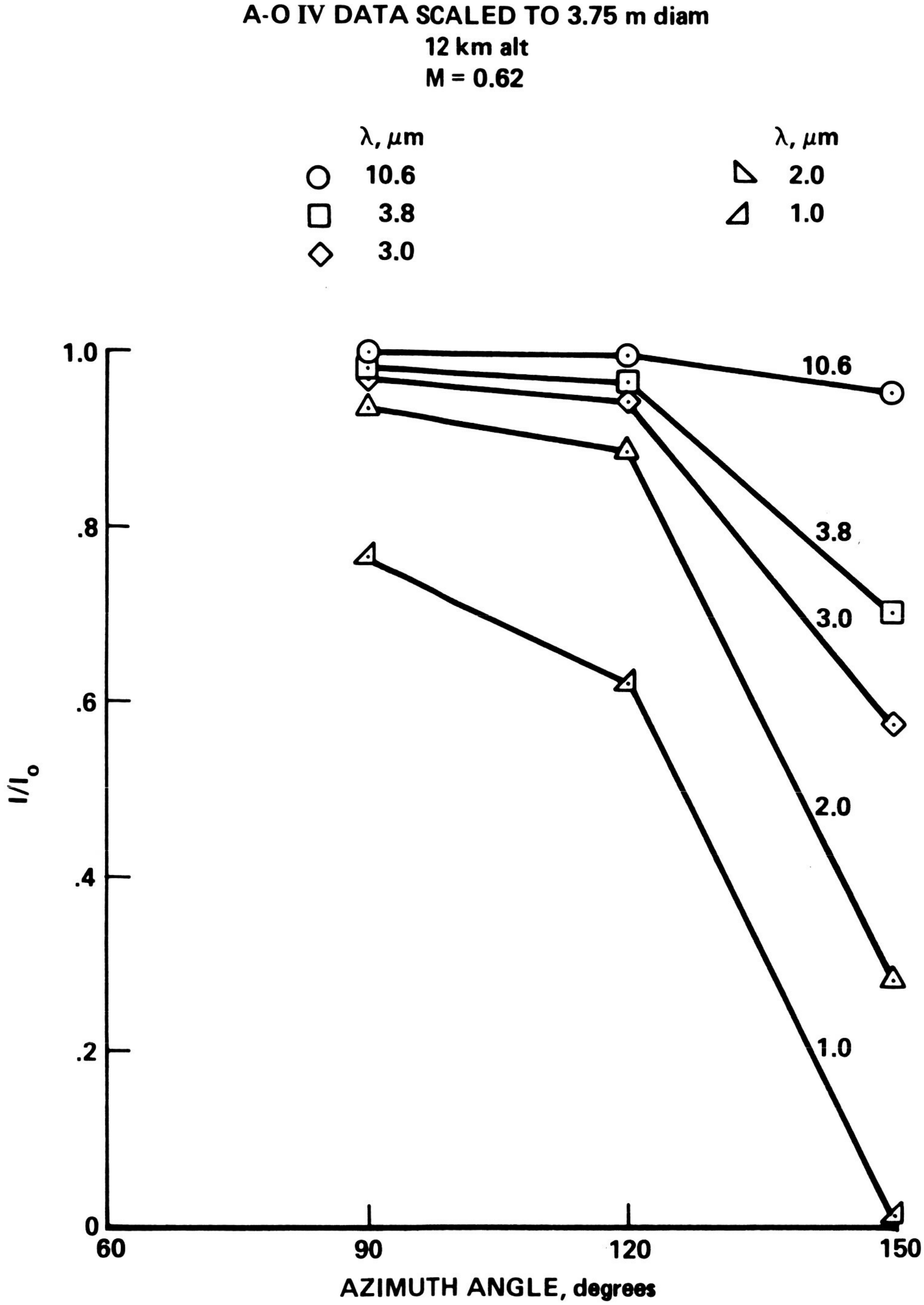

Figure 10. Effect of Wave Length on Optical Performance.