

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

TECHNICAL REPORT

Task Order HT-129
Contract NAS 9-11500

IMAGE DEGRADATION IN AERIAL IMAGERY DUPLICATES

Prepared By

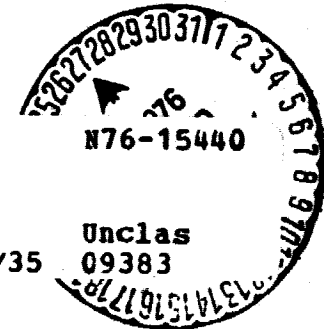
Harold E. Lockwood
Photoscience

September 1975

(NASA-CR-144649) IMAGE DEGRADATION IN
AERIAL IMAGERY DUPLICATES (Technicolor
Graphic Services, Inc.) 47 p HC \$4.00

CSCL 14E

G3/35



Photographic Technology Division
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058



**BEST COPY
AVAILABLE**

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

IMAGE DEGRADATION IN AERIAL IMAGERY DUPLICATES

This report has been reviewed
and is approved.

SUBMITTED BY:

Harold E. Lockwood
Harold E. Lockwood, Photoscientist

APPROVED:

Gerard E. Sauer
Gerard E. Sauer, Manager
Photo Science Office

CONCURRENCE:

D. Howe
Denis H. G. Howe, Operations Manager

APPROVED:

Noel T. Lamar
Noel T. Lamar, Technical Monitor

CONCURRENCE:

R. C. Thompson
John R. Brinkmann, Chief
Photographic Technology Division

ORIGINAL PAGE IS
OF POOR QUALITY



IMAGE DEGRADATION IN AERIAL IMAGERY DUPLICATES

Introduction

Investigators working with JSC Earth Resources Aircraft Program (ERAP) imagery seldom have access to original camera films for analysis. They work with either a second or third generation duplicate.

The procedure for investigators to obtain duplicates, until recently, was specification of a second generation duplicate (made directly from the original) which was made and delivered by JSC. The current procedure calls for many investigators to order their duplicates from the EROS Data Center (EDC) in Sioux Falls, South Dakota.

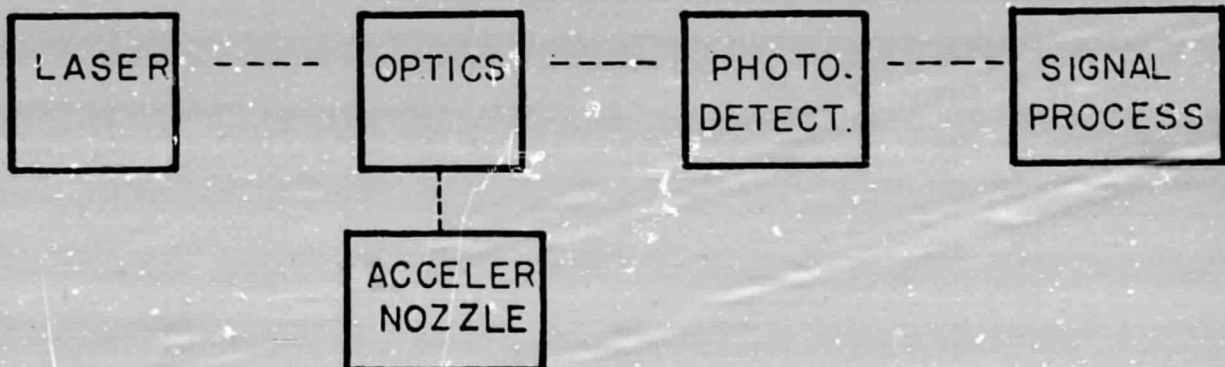
JSC delivers a second generation duplicate to EDC therefore many investigators would receive a duplicate of that duplicate, a third generation copy of the original test film.

θ is the angle between the incident light direction and the scattered direction where polarized light is used, I_0 is the incident light intensity $k = 2\pi/\lambda$, λ is the wavelength of the light being used, V is the volume of the scattering particle, R is the distance from the scattering particle to detector, which receives light of intensity I , and n is the index of refraction of the scattering particle, the aerosol. It is unfortunate that the term involving n has the difference between l and n therein. A perusal of standard handbooks of physical properties of elements and compounds shows n varies widely, from 0.82 for cadmium to 2.78 for thallium iodide. These are some of the extremes but the variation within these limits is rather wide, for example some of the elements being studied in the trace element study by neutron activation have compounds with indices: Pb from 1.89 to 1.97, Hg from 1.49 to 2.45, Hf at 1.56, Pt 1.63 to 1.76 and so on. Because these occur in the term $(n-1)$ the variation is large. Because this $(n-1)$ term is squared the "error" is doubled.^{2,3} Very substantial errors can therefore be introduced using the conventional approach indicated in Reference 1. Recently there has appeared in the literature an apparatus using light scattering which purports to obviate or minimize this index of refraction error.⁴ This apparatus, however, still suffers from the small particle limitation cited above.

Thus it seems that it would be advantageous in the studies of suspended aerosols to develop a method similar to light scattering in that it incorporates its advantages yet minimized its shortcomings.

The LADS

A block diagram for the LADS appears in the figure below.



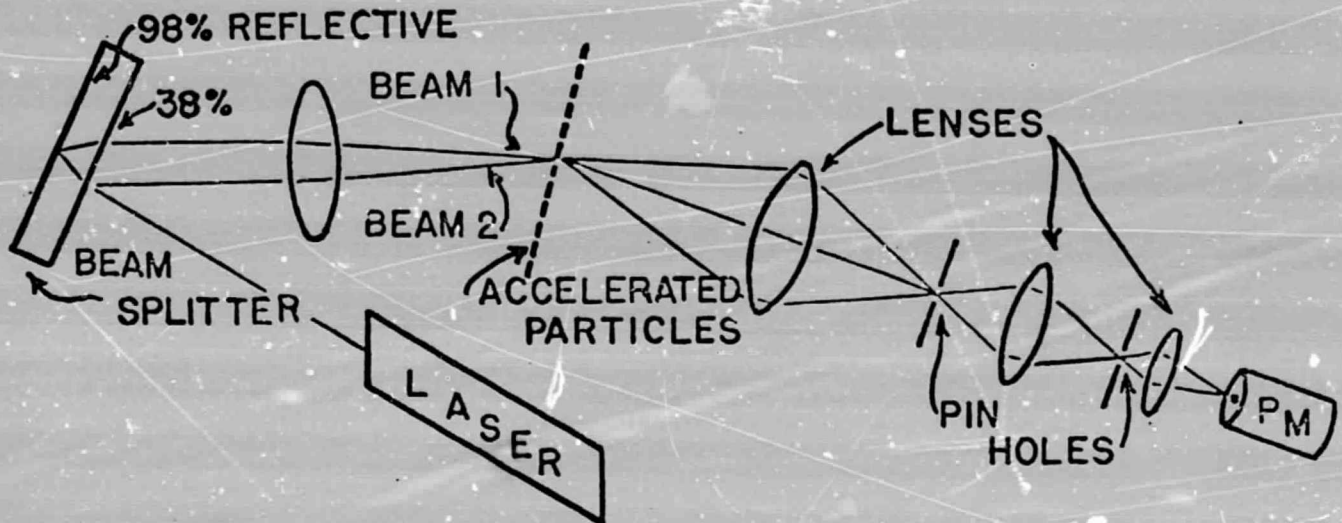
Each of these will be described now.

I. Laser: this is a standard commercially available low power (~ 1 mw) continuous wave He-Ne laser. Its cost is less than \$400. This laser gives sufficient intensity with careful optical design to "see" 0.481μ particles, by actual light scattering measurements. (No smaller aerosols are yet available in this laboratory.) It appears that the signal to noise ratio with 0.481μ particles will allow detection of 0.2μ particles without significant signal processing (i.e., using

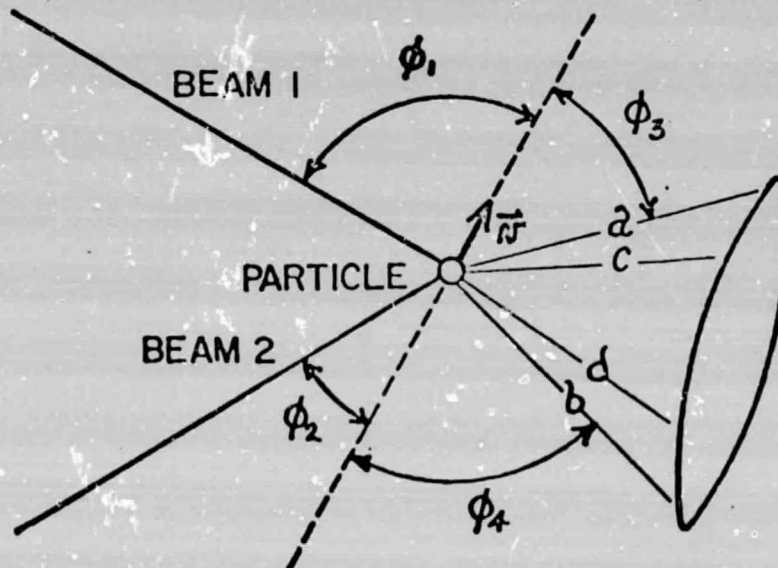
ORIGINAL PAGE IS
POOR QUALITY

only a low-pass filter). This limit, with only elementary signal processing, can be extended downward by simply increasing the power of the laser. It is, however, better to extend the lower limit by more sophisticated signal processing, which for reasons to be given later are not possible in conventional light scattering.

II. Optics and Photomultiplier



This optical system is a heterodyne system. That is, information about the velocity of the accelerated particles is gleaned from the difference in frequencies between the light scattered from beam 1 and that from beam 2, when the two are mixed in the optical system following the particles. A blow up of the intersection of beams 1 and 2 is given below.



From the special theory of relativity⁵ the Doppler frequency is

$$\gamma = \gamma_0 [(1 \mp v_{||}/c)/(1 \pm v_{||}/c)]^{1/2}$$

for away/toward where γ is the frequency of light received, γ_0 is the frequency of light of the source, $v_{||}$ is the speed of the moving receiver (or source) in the direction of the light beam and c is the speed of light in a vacuum. We compute the frequency of light received by the scattering particle due to this Doppler shifting.

For beam #1, the particle has a velocity $v_{||} = v \cos\phi_1$. Hence the frequency that is received by the particle due to beam #1 is

$$\gamma_1 = \gamma_0 [(1 + \frac{v}{c} \cos\phi_1)/(1 - \frac{v}{c} \cos\phi_1)]^{1/2}$$

(the pair of sign that are chosen are due to the particle's moving toward the source).

For beam #2, the received signal similarly is

$$\gamma_2 = \gamma_0 [(1 - \frac{v}{c} \cos\phi_2)/(1 + \frac{v}{c} \cos\phi_2)]^{1/2}$$

Some simplifying algebra, plus the excellent approximation $v^2/c^2 \ll 1$ so that $\frac{v^2}{c^2}$ can be ignored with respect to 1 permits writing

$$\gamma_1 = \gamma_0 (1 + \frac{v}{c} \cos\phi_1)$$

$$\gamma_2 = \gamma_0 (1 - \frac{v}{c} \cos\phi_2)$$

The particle now scatters these two frequencies, but the scattered light is also Doppler shifted, and in this Doppler shifting the " γ_0 " is the γ_1 or γ_2 received from the original laser source. Hence for beam "a"

$$\gamma_1' = \gamma_1 [(1 + \frac{v}{c} \cos\phi_3)/(1 - \frac{v}{c} \cos\phi_3)]^{1/2}$$

which when the expression for γ_1 above is substituted, becomes

$$\gamma_1' = \gamma_0 (1 + \frac{v}{c} \cos\phi_1)(1 + \frac{v}{c} \cos\phi_3)$$

ORIGINAL PAGE IS
OF POOR QUALITY

when terms on the order of $\frac{v^2}{c^2}$ with respect to unity are ignored.

Similarly when we consider the light scattered from beam #2 in the direction of beam a, we get to the same approximation

$$\gamma_2' = \gamma_0 \left(1 - \frac{v}{c} \cos \phi_2\right) \left(1 + \frac{v}{c} \cos \phi_3\right)$$

The subsequent optics combine these two beams and "beat" them together giving the difference frequencies into the photomultiplier (p.m.). Hence the signal to the p.m. is

$$\begin{aligned} \frac{\gamma_1' - \gamma_2'}{\gamma_0} &= \left(1 + \frac{v}{c} \cos \phi_3 + \frac{v}{c} \cos \phi_1 + \frac{v^2}{c^2} \cos \phi_1 \cos \phi_3\right) \\ &\quad - \left(1 + \frac{v}{c} \cos \phi_3 - \frac{v}{c} \cos \phi_2 - \frac{v^2}{c^2} \cos \phi_2 \cos \phi_3\right) \end{aligned}$$

Making the same approximations as above, we get

$$\frac{\gamma_1' - \gamma_2'}{\gamma_0} = \frac{v}{c} \cos \phi_1 + \frac{v}{c} \cos \phi_2$$

If we let $\gamma_B \equiv \gamma_1' - \gamma_2'$, where γ_B is the beat frequency, then

$$\gamma_B = \frac{\gamma_0 v}{c} (\cos \phi_1 + \cos \phi_2)$$

But $\gamma_0/c \equiv 1/\lambda_0$ is the vacuum wavelength of the original laser radiation, then

$$\gamma_B = \frac{v}{\lambda_0} (\cos \phi_1 + \cos \phi_2)$$

Note the important result that no matter what angle through which the scattering occurs, the heterodyne or beat frequency is the same. This permits studies of much smaller particles than are possible in conventional light scattering since light scattered can be collected over a large solid angle, instead of through a narrow slit as is done in conventional light scattering.

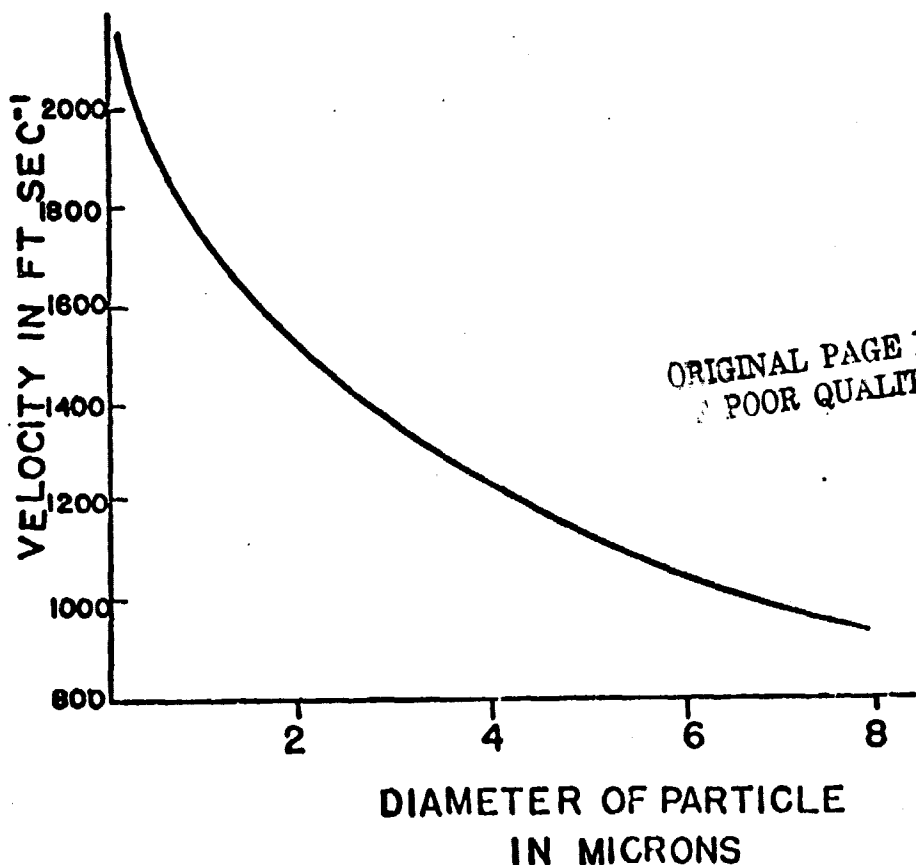
Hence we may determine the particle velocity from this final expression solved for v

$$v = \frac{\lambda_0 \gamma_B}{\cos \phi_1 + \cos \phi_2}$$

III. Particle Accelerator.

It is desired here to accelerate particles in such a way that the final velocity of these particles is some known function of their size. Thus we can measure this final velocity using the heterodyning technique described above, and consequently infer the particle size.

There are some theoretical difficulties here. The transport of particles by a gas stream e.g. through a nozzle accelerating the gas flow has not been settled in the literature, i.e., one using different treatments, gets different results. Thus I will report the unpublished results of Yanta, which he has checked against experiments for spherical particles, that are accelerated through a small supersonic nozzle, such as shown in Appendix I. These results are seen in the following graph, where on the ordinate has been plotted the particle velocity, and on the abscissa, the diameter of the particle in microns. Thus in use one would measure the frequency, perform the calculation indicated in the above equation to find v , go to the graph or interpolate into the tables from which the graph came, and find the corresponding particle size. These results were computed for spherical oil droplets of density assumed equal to 1 gm/cm^3 . We are currently working on still smaller nozzles, which will provide for higher Mach numbers achieved in shorter distances. The one currently under construction will be capable of imparting to the gas molecules accelerations up to 9 million "g's"! The particle lag and therefore the particle size differentiation should be significantly greater than shown below in the Yanta work.



It is important to advert to the 1 gm/cm^3 assumption. In effect it states that the particle size determined by this method is that of the equivalent sphere of density $\sim 1 \text{ gm/cm}^3$. This is a limitation in this method but perhaps not as serious a one as say, the assumption made in conventional light scattering of the atmospheric aerosol having the same index as the calibrating polystyrene. To see this, we need refer to one of the published theories for the Dynamics of Dusty Gases⁷.

$$u_s^{(1)}/a^0 = \left(\frac{\lambda}{L}\right) \frac{1}{\bar{\gamma}} \frac{1}{p} \frac{dp}{d\zeta}$$

where $u^{(1)}$ is the first order calculation of the difference between the gas velocity and the particle velocity, called the particle slip, a^0 is the speed of sound at the point of measurement of slip velocity, $\bar{\gamma}$ is the average ratio of specific heats, for air ~ 1.4 , $\lambda = m/6\pi\eta\sigma$ where m is the particle mass σ is the Stokes radius, η is the viscosity of air, p is the pressure of the gas, and ζ is the scaled length, x/L , L being the total length and x is the distance along the nozzle. Substituting into this expression typical values for viscosity, velocity of sound, etc., we have at $x = L$

$$u_s^{(1)} = 2.2 \times 10^9 m u_0 \frac{\Delta p}{\sigma L p}$$

where Δp is the pressure difference across the nozzle and p is the pressure at $x = L$, and u_0 is the gas velocity at the same point $x = L$.

Let us now assume a spherical shape for the particle. This is not a serious limitation as we are interested in the equivalent spherical shape for aerosols in their propagation studies, etc., specifically their propagation in aerodynamic situations, e.g. flow, dispersion, and passage through the human respiratory system. Hence we can write

$$u_s^{(1)} = \frac{4}{3} \frac{\pi \sigma^3 \rho}{\sigma} u_0 \frac{\Delta p}{L p} \times 2.2 \times 10^9, \text{ or}$$

$$u_s^{(1)} = 9 \times 10^9 u_0 \frac{\Delta p}{L p} \sigma^2 \rho$$

Now $v \equiv u_0 - (u_0 - v)$

$v \equiv u_0 - u_s^{(1)}$. Hence

$v = u_0(1 - 9 \times 10^9 \frac{\Delta p}{L p} \sigma^2 \rho)$, which we can combine with the heterodyne

equation at the bottom of page 5 to get for the spherical (Stokes) radius:

ORIGINAL PAGE IS
OF POOR QUALITY

$$\sigma(\text{cm}) = \frac{1}{\rho^{1/2}} \sqrt{\frac{L_p}{9 \times 10^9 \Delta p} - \frac{\lambda_0 \gamma_B L_p}{9 \times 10^9 \Delta p u_0 (\cos \phi_1 + \cos \phi_2)}}$$

It is important to see that $\sigma \propto \rho^{-1/2}$ so the effect of the density variation is greatly diminished. (The "error" is divided in half as opposed to being doubled as is done in conventional light scattering.) It must be pointed out, however, that this dependence on $\rho^{-1/2}$ may introduce significant errors especially in aerosols of the heavy metals.

IV. Signal Processing.

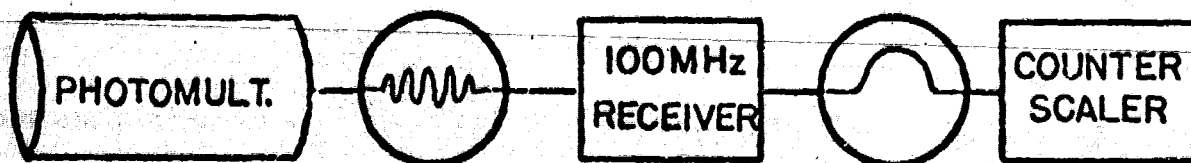
Undoubtedly the strongest asset of the LADS with respect to conventional light scattering is the fact that the signal output from a scattering particle has the size information in the form of a fixed frequency--that is, the frequency of the radiation varies as the size of the scattering particle. This is in contrast to conventional scattering in which the amplitude of the pulse of radiation is proportional to the particle size.

Because of a wide band pass amplifiers must be used in conventional light scattering (in order not to destroy the pulse-height size information) one is limited in ultimate size because the small particles begin to look like the dark current noise, and the size information is lost in this noise.

In contrast, the LADS signal may be amplified by a very narrow band pass amplifier without losing any of the signal size information, but cutting out most of the noise. Consequently the signal to noise ratio is greatly enhanced and the ultimate particle size can be extended downward most significantly. For example, with the current LADS and some differencing of signals, preliminarily studied, the unprocessed signal to noise ratio for 0.48 μ particles is about 6 or 8 to 1, with processing by using a narrow band pass amplifier, the signal to noise ratio is improved at least 10-fold. This implies that the ultimate size which can be studied is on the order of about 1/10 of what can be studied in conventional light scattering, if the only limitation is due to detectability. Note, however, the smaller particles are significantly more difficult to accelerate, and therein might lie the preponderant limitation in the method. Presently, then, using the supersonic nozzle described in Appendix I, the lower limit on size seems to be 0.25 μ . If this nozzle is scaled down in size, as with the new nozzles there is no apparent reason why particles as small as 0.1 μ and perhaps smaller cannot be accelerated to the speeds necessary for measurement.

Some mention has been made previously about processing the signal from the photomultiplier. It seems that a simple, yet very sensitive procedure is to use a radio receiver which has its output connected to a counter. The arrangement is seen in block form below.

ORIGINAL PAGE IS
OF POOR QUALITY



As a particle of a particular size comes through the nozzle, the output is as shown, i.e., a pulse modulated sinusoid. This is very preferentially amplified by the narrow band pass amplifier (the receiver) and the demodulated output--a pulse--is fed into the counter. If the flow rate is known and the counter is set to count for a fixed time, the number of this particular aerosol per unit volume, can thus be accurately, sensitively and inexpensively determined. This method is somewhat restrictive in that the scanning must be manually performed, i.e., a certain frequency is "dialed" and the counts are made. If, however, the receiver is modified slightly, replacing the tuning capacitor with a varactor, the tuning can be done electrically by a small potential change, making scanning programmable and automatic. It seems possible to replace the counter/scaler in this later scheme and use an x-y plotter. On the y-axis would be plotted the number of counts, on the x-axis the potential across the varactor, which would indicate the frequency of the scattering particle, which would indicate its velocity, which in turn would indicate its size. Consequently a count versus size plot could be printed out virtually in real time, automatically.

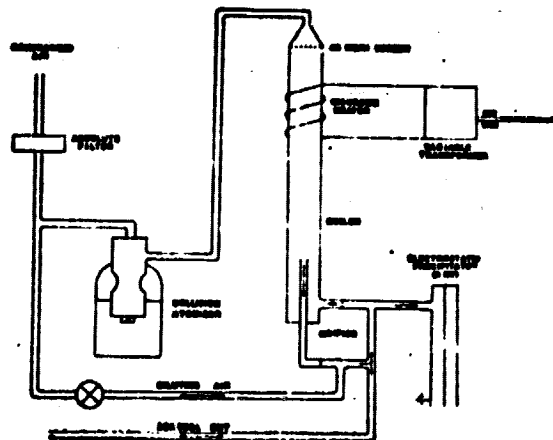
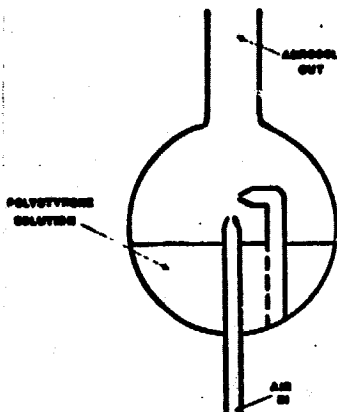
Facilities available for the work:

The Physics Department occupies about 5000 square feet in the basement of the Instructional Laboratory building. We currently have available for research approximately \$50,000 worth of test equipment. Also components, amplifiers, power supplies and oscillators which originally amounted to \$230,000 when they were assembled into a radiometer the Department evaluated now belong to the Department of Physics. Additionally, we have a complete machine shop including lathe, milling machine, drill press, grinder, power hacksaw, belt sander, etc. Also we have two complete high-vacuum systems, one of which can serve as vacuum evaporator for aluminizing mirrors, etc. Finally our advanced laboratory which is used formally in instruction of our advanced students provides on a loan basis another \$50,000 worth of sophisticated equipment to include counter scalars, power supplies, and the like. Currently there is an unused laboratory of approximately 720 square feet available for this project.

STATUS OF THE WORK:

Aerosol generation:

Essentially the entire LADS system has been completed but the calibration and checking is not yet finished. To do this requires generation of known-size test aerosols. We are currently using two aerosol generators seen in the figures below. One (on the left) is simply an aspirator of water suspended aerosol



particles (latex spheres available from Dow Chemical Corporation). While electron micrographs of these aerosols show great homogeneity, in practice because of the electrostatic attraction, dimers and higher combinations are generated, and the aerosol loses its required monodispersed quality. Also water droplets tend to be atomized and while drying is attempted (in an agitation tube where the aerosol is mixed with nitrogen), it is not always successful, and another source of extraneous aerosols is introduced. Additionally the water vapor tends to freeze into small ice crystals upon experiencing the large temperature drop upon passage through the supersonic nozzle, causing further problems.

For these reasons the generator on the right has been constructed. It is a modification of the generator of Liu et. al.⁶ in which aerosols are generated by condensation of vapor on impurities in the original Di-octyl phthalate (DOP).

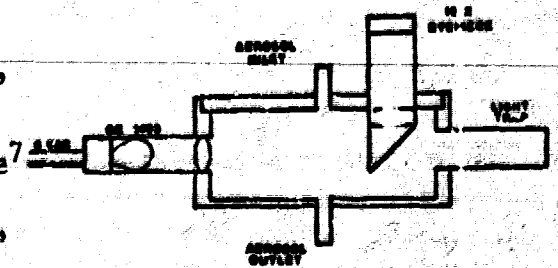
The size of the aerosols thus formed is determined sensitively by the percent volume concentration of DOP in alcohol in the collision atomizer and not so sensitively by the temperature of the nichrome heater as shown. We have successfully used this system to get aerosols from about 0.05 μ to several micrometers diameter. This system has many advantages over the simple aspirator system, a very important one being that alcohol instead of water is used, greatly eliminating the problems of small droplets and ice crystals which give extraneous aerosols in the aspirator generator.

Because the homogeneity of the aerosols formed in the condensation generator, it is possible to check the size of the aerosols being generated by an optical

"owl," shown in the figure on the right. Here the aerosols to be checked for size enter from the top, scatter collimated light to a right angle prism which may be rotated about a vertical axis to any angle of scattering. Tyndal scattering takes place and if one rotates the prism and attached eyepiece until the Tyndal red scattering "line" is obtained, he can use the relationship

$$D_p = 10\theta^{-0.7}$$

where D_p is the diameter of the particle in microns and θ is the scattering angle in degrees at which the red scattering line is observed. Actually a sharp line is not seen, rather a broad (a couple of degrees broad) region of pinkish red is observed. One can estimate the middle of this region to about one degree, making readings for D_p to be precise to about $\pm 2\%$. Thus from the data reported by Liu et. al. for given concentrations of DOP and given heater voltages, one can predict the approximate aerosol size to be generated. This can then be checked as the aerosol is passed through the "owl." In the one size range under study, the theory of Liu et. al. predicts $0.61 \mu \pm 0.01 \mu$ diameter particles, and the "owl" measures $0.61 \mu \pm 0.012 \mu$. The agreement is excellent.



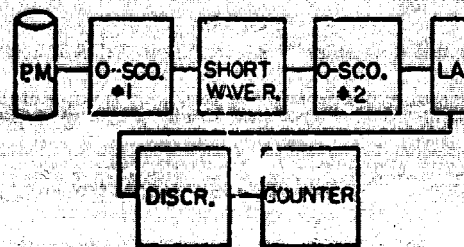
Nozzle development:

It has been observed that the nozzle shown in Appendix I requires an impractically large mechanical pump to reach the requisite pressure ratio for the Mach 5 flow which is desired. Two alternatives have been used: a) a ballast tank-- here a tank of about $0.5m^3$ was found, cleaned and checked for vacuum tightness. It was found to be able to hold a vacuum of 5 or 6×10^{-6} mm Hg. In use the ballast tank is pumped down to its ultimate vacuum and then the pumping system is closed off. The evacuated ballast tank is then connected to the Mach 5 nozzle, and the pressure ratios required for Mach 5 flow should ensue. However, we have not been able to find particles moving at Mach 5 speeds, when this method is used. Also the "run" lasts only 20 or 30 seconds, with a time delay for the next run of from 15 to 20 minutes as the ballast tank is re-evacuated. Additionally the tank itself becomes coated with DOP or polystyrene aerosols, making subsequent "pump-downs" even more time consuming. Because of these difficulties, a family of nozzles has been designed with very small throat diameters. These are very intricate and the techniques of drilling holes of 0.0135 in., with conical tapers had to be developed. This was done, however, and satisfactory supersonic nozzles of the type seen in Appendix II were developed and used. With these very small supersonic nozzles, it is unnecessary to have the ballast tank, eliminating the number of difficulties cited above. We do have the difficulty of not having a very large fore pump. With the system of nozzle and fore pump we have available, it is possible to get continuous Mach 2.7 flow. This is most satisfactory as it allows for continual adjustments to be made on the system, checking for alignment, tuning of the receiver, etc. However in the final configuration of the system higher Mach flows will be required. These can be achieved by either having higher speed pumps or using the ballast tank procedure. If the latter is chosen, runs greatly in excess of 20 or 30 seconds will be possible because of the relatively small apertures of the nozzles now in use. After the

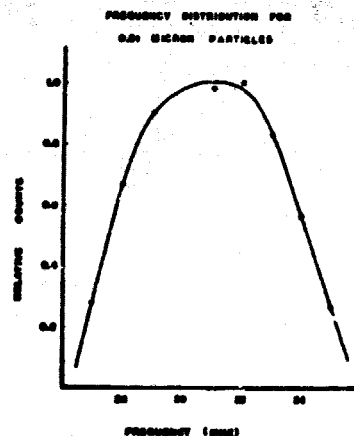
alignment, tuning, etc., have been established, then not being able to make continual measurements and being required to "cycle" will not be a serious problem, as measurements could be made every fifteen minutes. Use of the ballast tank would obviate the need for a large (and expensive) mechanical pump, and thus it is the preferred method for the final instrument.

Signal processing:

There have been some refinements of the signal processing described earlier in this report. These can be seen in the figure on the right. ("O-SCO." represents the word "oscilloscope"). Here it is important to have used amplifiers with proven high frequency response. A good bit of trouble was experienced early in the work when the high frequency component of the signal was lost in a linear amplifier. It is recommended that a r.f. oscillator capable of putting out the expected heterodyne be used to simulate the signal to be amplified. The discriminator is used to screen out the low level noise, not representing particles of the size being studied.



Preliminary results: Seen in the figure on the right are some of the frequency versus counts data for 0.61 micron sized particles. The theoretical peak occurs at 31 MHz; the actual experimental peak is seen to be close to the theoretical value at about 31 MHz, with a half-width of about 10 MHz. It is not known why the width is so large, nor has there been any attempt to take data at different points along the flow. Much work needs to be done here as well as taking data as a function of different positions in the flow. (The present nozzle and test chamber can be moved in 3 orthogonal directions with respect to the intersecting beams, so that readings can be made at any place in the flow.)



Summary:

An apparatus for particle size measurements has been constructed which obviates most of the limitations of conventional light scattering: it does not depend on the index of refraction of the aerosol being measured (it does depend in an insensitive way upon the aerosol density), it has significantly smaller particle size study capability-- perhaps down to 0.1 μ particles, and it is relatively inexpensive allowing deployment on a wide scale for continual monitoring of the concentration and size of the atmospheric aerosol at specific sites.

The apparatus has been tested for a single size aerosol. What is needed further is calibration, further testing, and remote deployment. As a major alternate energy source seems to be coal, rather noted (infamous) for its particulate emission, small-particle particulate monitoring becomes even more important than it has been in the past. Further, this monitoring must be essentially in real time as high particulate emission needs to be curtailed rapidly to preclude serious wide-spread respiratory afflictions. The present apparatus may well offer these capabilities.

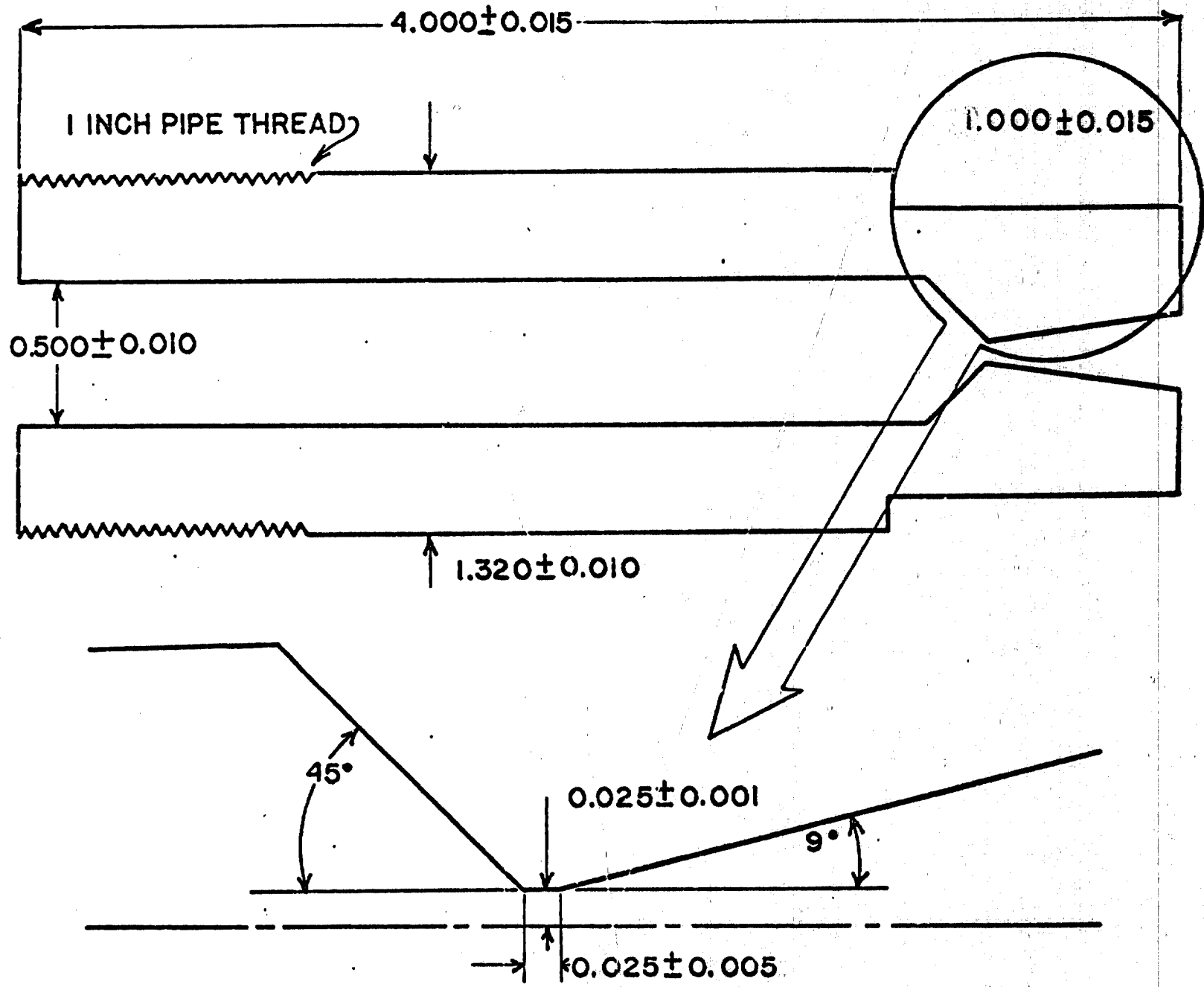
**ORIGINAL PAGE IS
OF POOR QUALITY**

References

1. Vande Hulst, Light Scattering by Small Particles, p. 65 Wiley.
2. Quenzel, H. "Influence of Refractive Index on the Accuracy of Size Determination of Aerosol Particles with Light Scattering Aerosol Particle Counters." Appl. Opt. 8, 1, 165-169 (Jan. 1969).
3. Whitby, K.T., and Vomela, R.A., "Response of Single Particle Optical Counters to Non Ideal Particles," Enviro. Sci. Tech. 1, 10, 801-814 (Oct. 1967).
4. Gravatt, C.C., "Real Time Measurement of the Size Distribution of Particulate Matter in Air by a Light Scattering Method." J. of Air Poll. Control, in press.
5. French, A.P., Relativity and Modern Physics, p. 137 W.W. Norton, MIT Intro. Series.
6. Liu, Y.H., Whitby, Kenneth T., Yu, Henry H.S., "A Condensation Aerosol Generator for Producing Monodispersed Aerosols in the Size Range 0.036 μ to 1.3 μ ," Journal de Recherches Atmospheriques, p. 397 (1966).
7. Liu, Y.H., Marple, V.A., Yazdani, "Comparative Size Measurements of Monodisperse Liquid Aerosols by Electrical and Optical Methods," Enviro. Sci. Tech. 3, No. 4, p. 381 (1969).

SECTIONAL VIEW OF NOZZLE

MACH 5 NOZZLE



Appendix I

MACH 2.7 NOZZLE

$$P_{\text{EXIT}} / P_0 = 0.0423$$

EXIT RADIUS 0.01212"

THROAT RADIUS 0.00675"

