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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The possiblity of conducting remote wind measurement in real time using only cw laser equipment located on the ground at a given point is very attractive and may offer wide-spread applications in atmospheric research and operations. This research program therefore investigated laser techniques for remote sensing of atmospheric flow. It emphasized the development of methods for single-ended remote wind speed measurements. These methods provide high spatial resolution and potentially long range with low laser power and minimum measurement time. Realistic performance criteria was formulated in order to understand

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20. ABSTRACT CONTINUED

the potential of a given technique and field wind measurements were performed to evaluate its feasibility and usefulness. The existing laser Doppler velocimeter was investigated in this way, and it was found to be out-performed, under practical conditions, by a new laser time-of-flight velocimeter discovered during the course of this program.

Final Report

REAL-TIME REMOTE MEASUREMENT OF WIND SPEED BY LASER BACK-SCATTERED SINGLE PARTICLE CORRELATION TECHNIQUES

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CONTENTS

October 31, 1977

GRANT NUMBERS

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GRANT AND DURATION

The total amount of the research grant was $77,089 for a duration of three and one-half years from April 1, 1974 to September 30, 1977.

STATEMENT OF THE PROBLEM

The possibility of conducting remote wind measurement in real time using only cw laser equipment located on the ground at a given point is very attractive and may offer wide-spread applications in atmospheric research and operations. This research program therefore investigated laser techniques for remote sensing of atmospheric flows. It emphasized the development of methods for single-ended remote wind speed measurements. These methods provide high spatial resolution and potentially long range with low laser power and minimum measurement time. Realistic performance criteria was formulated in order to understand the potential of a given technique and field wind measurements were performed to evaluate its feasibility and usefulness. The existing laser Doppler velocimeter (LDV) was investigated in this way, and it was found to be out-performed, under practical conditions, by a new laser time-of-flight velocimeter (LTV) discovered during the course of this program.

TECHNICAL SUMMARY

When this program started, laser Doppler velocimeter (LDV) systems had, in the laboratory, established their value in providing a nearly perturbation-less measurement with relatively good spatial resolution. In the field, however, only one experiment of remote atmospheric wind measurements using a visible wavelength LDV with forward detection[1] had appeared in the literature.

At that time, the dual beam LDV was considered unfeasible for moderate and long range applications[2,3] except, perhaps, with a seeded flow. By recognizing the fact that the random positions of scatterers in the interference fringe system of a LDV may degrade the velocity signal,[4] we designed our system to detect individual signal particles for wind speed measurements.[5] This method of single-particle correlation led to a successful atmospheric wind measurement at a range of 60 m using a cw laser at 5140 Å with only 0.35 W of power. We have also developed performance criteria using the rate of unambiguous speed measurements as the figure of merit, F, for the field experiment. Judging from our experimental results at the NOAA Table Mountain facility near Boulder, Colorado,[5] this figure of merit provided a more meaningful and more accurate evaluation of the system performance than the usual signal-to-noise consideration.[2,4,6]

More recently, we have developed a new technique of single-particle correlation for measuring the speed of a cross wind by determining the time of flight of an aerosol particle across two closely spaced, approximately parallel beams.[7] This new laser time-of-flight velocimeter (LTV) suffers less atmospheric effects and requires no coherence between two beams. As a result, single-ended speed measurements of unseeded atmospheric wind at a range of 100 m using a 0.2 W laser power at a range of 1 sec^{-1} have been successfully made at Fort Collins, Colorado. On a different night, the same measurement rate was achieved at a range of 50 m with only 0.015 W laser power. One basic difference between LDV and LTV is that the two beams with fixed relative phases are needed in LDV to form interference fringes, while the two beams in LTV need not be coherent.

It is well known that aerosol concentration varies according to weather conditions. We have found that the concentration of larger particulates, which provide signal particles for our speed measurements, may fluctuate by as much as two orders of magnitude from night to night. Under ordinary circumstances in Colorado, a 20% fluctuation in a few hours is common. Therefore, it would be desirable to have an independent and nearly simultaneous monitoring device for aerosol detections during the wind speed measurement. For practical purposes, we may assume that the aerosol size distribution is unchanged and need to know only its concentration for evaluating the performance of velocimeters. In order to monitor the aerosol concentration by backward scattering, we recognized the effects of Gaussian beam profile and photon statistics on the measured scatter intensity distribution. Laboratory experiments have shown[8] that these effects may be accounted for if the Junge size distribution is replaced by an apparent aerosol size distribution

$$\frac{dN}{dr} \approx c_o' \, r^{-5} \qquad (1)$$

Under a given experimental arrangement for our mathematical analyses, the effective aerosol concentration parameter c_o' is proportional to the backscattered average count rate C_A; it can be measured by the same equipment used for the speed measurement.[8]

The figure of merit for our velocimeters depends on the arrival rate of signal particles. This rate can be written as

$$F = \frac{c_o' v}{8f^2} \frac{V \tau_o^2}{\rho^5} \left(\frac{A K_o \eta}{\pi h \nu}\right)^2 \frac{P_o^2}{R^4} \qquad (2)$$

where v, V, τ_o, ρ, P_o and R are, respectively, wind speed, viewing volume, correlation time per channel, beam radius, incident laser power and range. Other parameters, which are constants for a given experimental arrangement, were defined previously.[5] In the laboratory, $V \tau_o^2/\rho^5$ can be kept constant; the $F \propto P_o^2 R^{-4}$ dependence can be and has been tested.[8] Experimentally, this relationship holds up well in the laboratory where c_o' is nearly constant. In the field, the same dependence exists, because $V \propto \rho^3$, $\tau_o \propto \rho$, and $\rho \propto R$, assuming that focussing to the diffraction limit is achieved. Using our LTV results at 50 m with only 15 mW laser power, Eq. (2) scales atmospheric wind measurements to a range of 1 km with 6 W laser power at a rate of one per second. Atmospheric turbulence would alter this conclusion somewhat. Due to the fact that we are measuring the speed of a single dust particle, the measurement time of a given speed measurement is typically less than one millisecond; the long-term turbulence effects reported in the literature, such as beam wander, can be ignored. The short-term effects defocus the beam at long range. Using the experimental results of beam spreading,[9] the diameter of beam spot due to turbulence is calculated to be about 2 cm at a range of 1,000 m. Although this diameter is about 4 times larger than the diffraction limit of a 10 cm focussing telescope, a 2 cm beam is certainly adequate for LTV measurements at a range of 1,000 m.

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IMPORTANT RESULTS

The following significant results have been achieved.

(a) We have introduced the concept of single particle correlation for remote sensing, which eliminates previously expected requirements of wanting more and more scatterers in the viewing volume. We have derived performance criteria which predicts the performance of our system under given conditions.

(b) Using the crossed dual beam backscattered LDV, we have successfully performed wind speed measurements at a range of 60 m with only 0.35 W of laser power.

(c) We have introduced a new dual beam technique which measures wind speed by determining the time of flight of aerosol particles. Using this laser time-of-flight velocimeter (LTV), we have measured wind speed in natural night air at a range of 100 m with 0.2 W of laser power. These were real-time measurements at a rate about one per second. On a different night, the same measurement rate was achieved at a range of 50 m with only 0.015 W laser power.

(d) Using the probability density analysis, we have developed a simple technique for determining the overall aerosol strength with only a quick measurement of the average count rate. This simple method using the same measuring equipment is sufficient for the assessment of the velocity measurement performance in the field.

(e) Sufficient laboratory experiments were made to determine a realistic scaling law for the measurement rate F as a function of incident laser power P_o and the range R. Under a given aerosol condition, $F \propto P_o^2 R^{-4}$. Using our experimental results, we can predict atmospheric wind measurements to a range of 1 Km with 6 W laser power at a rate more than once a second using our LTV technique. Clear air turbulence should not alter the above conclusion much for ranges up to 1,000 m.

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