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A mobile computerized laser radar system for observing rapidly varying meteorological phenomena

H. SHIMIZU, Y. SASANO, N. TAKEUCHI, O. MATSUDO, M. OKUDA
National Institute for Environmental Studies, Environment Agency, Yatabe Tsukuba Ibaraki 305, Japan

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A high repetition, mobile laser radar system with a computerized real-time data acquisition and display system is described. Signal-to-noise levels of the system are compared with theoretical values, and it is found that they are affected by the shot noise in the system. An example of a stack plume observation is also presented to show the performance of the system.

1. Introduction

Laser radar observations provide useful information for studies of meteorology and air pollution, and laser radar systems using Mie scattering have been extensively developed over the past decade. Fiocco and Smullin [1] reported the first atmospheric measurement with a ruby laser radar. The recording technique used in early laser radar systems was to photograph the backscattered signal intensity which was displayed on the face of a wide-bandwidth oscilloscope. This technique limited the application of laser radars as sensors of meteorological phenomena because the hand-processing of photographed laser echoes was very time-consuming.

Uthe *et al.* [2] first used a video recording technique for data processing. The video disc system greatly increased the real-time applications of laser radar and the subsequent analysis of time and space variations. However, the narrow bandwidth limited data resolution and degraded the quality of the data for quantitative use.

Digital techniques using a transient recorder and computer system have much to offer in handling laser radar data. Uthe *et al.* [3], McCormick [4] and Grams *et al.* [5] developed systems using these techniques. The benefits of digital systems are that the data handling and display have real-time capability and large amounts of data can be acquired.

In digital systems, ruby or dye lasers have been mainly used as a laser source. We believe that these lasers limit the benefits and applicability of digital systems compared with Nd:YAG lasers from the stand point of reliability, high power, cheapness, long-life and high repetition rate, although this must be traded off against the use of S-1 photomultipliers whose response is down at least an order of magnitude.

This paper describes a compact, mobile, laser radar with a digital data processing system and a high-repetition Nd:YAG laser. A system analysis was made to show the performance of the system. Application of the laser radar in tracking a stack plume is also described to show the capability of the system.

2. Description of the system

The system was developed for field use in air pollution studies. The requirements of such a system are high-speed data acquisition, real-time data analysis and display, and mobile operation. This system should allow automatic and easy operation. The real-time automatic capability and ease of operation were satisfied by using a computer system. Mobile operation was enabled by constructing the components small enough to be able to mount on a van using anti-shock mounts composed of rubber blocks. The high-speed data acquisition was accomplished with the use of a

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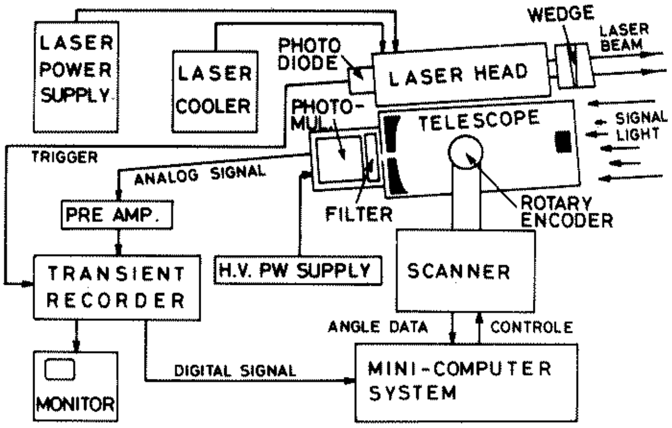

Figure 1 Schematic diagram of the computerized laser radar system.

high-repetition Nd:YAG laser, a high-speed scanner and a mini-computer system.

A schematic diagram of the system is shown in Fig. 1. The basic specifications are given in Table I. The Nd:YAG laser (Toshiba LAY 117) has a maximum repetition rate of 40 pps, with pulse duration of about 10 ns and output energy of about 100 mJ/pulse. The output from the laser passes through a beam director which is constructed from two wedge-shaped glass plates. Beam direction can be selected arbitrarily by rotating these plates. The scan is made along azimuth and elevation axes and the maximum scan speed is 10 deg s^{-1}. The speed is controlled by a 150 W motor. The receiver in this configuration is a 30 cm diameter Cassegrainian telescope. An iris to limit the receiver acceptance angle and a 1 nm narrow-band interference filter is included as part of the receiver optics. The detector is an RCA-7102 photomultiplier tube. The output from the photomultiplier is sent to a PAR-model 115 wide-band amplifier and then to a Iwasaki-DM 901 transient recorder that digitizes the

TABLE I Specification of the laser radar system

(a) Laser	
Type	Nd:YAG laser [LAY 117 (Toshiba)]
Wavelength	1.064 μm
Output energy	0.1 J/pulse
Pulse duration	10 ns
Maximum repetition	40 pps
(b) Telescope	
Type	Cassegrainian
Aperture	30 cm diameter
Focal length	179 cm
(c) Pre-amplifier	Model 115 (PAR)
Band width	d.c. ~ 50 MHz
Amplification	10, 100
(d) Transient recorder	
Type	DM 901 (Iwasaki)
A/D conversion time	10 ns min
Accuracy	8 bits
Memory	1024 bytes/ch
Channel numbers	2
Sensitivity	50 mV full scale

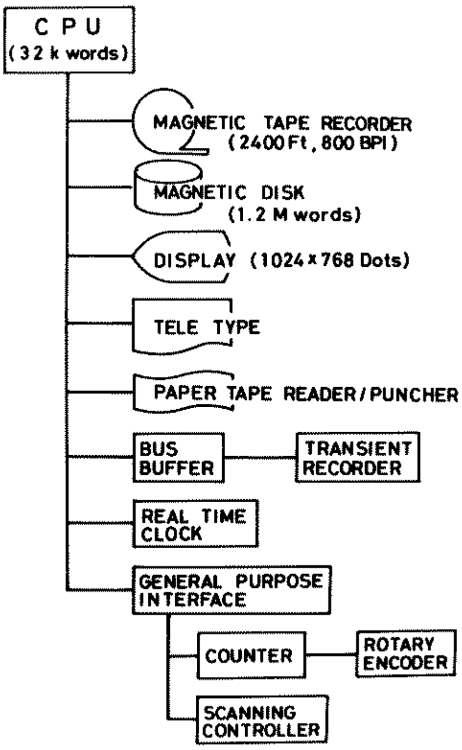

Figure 2 Mini-computer system components.

TABLE II Specification of the mini-computer system

(a) CPU	
Type	NOVA–02
Access time	1.2 μs
Memory	32 kwords
Bit number	16 bits/word
(b) Magnetic tape recorder	
Type	VD 75 (Victor Data)
Memorizing density	800 bytes in^{-1}
Truck number	9 truck
Tape length	2400 feet
Start–stop time	5.6 ms
Data transfer rate	60 kbytes s^{-1}
(c) Magnetic disc	
Type	CD 3100 (Hokushin Electric)
Memory	1.2 Mbytes
Disc diameter	15 in
Waiting time	20 ms
Data transfer rate	781 kHz
(d) Display	
Type	4010 (Tektronix)
Display area	19.1 × 14.3 cm
Line number	35 lines
Character number	74 characters/line
Character writing speed	1200 characters/s
Point density	1024 × 768 points
(e) Teletype	
Type	33 (Teletype Corp.)
(f) Paper tape reader	
Type	PTR 4001 (Ricoh Electric)
(g) Paper tape puncher	
Type	TP 60 P (Ricoh Electric)

received signal. The transient recorder samples the return signal every 10 ns. The output from the transient recorder goes to a NOVA–02 mini-computer which performs real-time basic data analysis and writes data onto magnetic tape.

The configuration of the mini-computer system is shown in Fig. 2 and its specifications are shown in Table II. The mini-computer is used both for control functions such as scanning of the telescope and for acquisition and processing of data from measurements. A magnetic tape recorder is used to store the laser radar data, angle data of the telescope and other experimental parameters. The magnetic disc stores the data acquisition and processing programs. A real-time indication of the data is available from a graphic display device.

A photograph of the system loaded on a van is shown in Fig. 3. The van is equipped with an electric lifter to raise the telescope and laser head above the roof during measurements.

3. System software

Development of system software is one of the most important steps in constructing the measurement system. The basic data-handling sub-programs are written in a combination of assembly and Fortran languages, and are linked with a NOVA Real-time Disc Operating System. These routines can be called through a teletype keyboard.

Fig. 4 illustrates a program flow chart for one set of experiments. This program controls telescope scanning, and data acquisition and display. The transient recorder control functions, laser repetition rate and scanning rate are set and adjusted by the operator. The measuring parameters controlled by the program are the number of data words transferred from the transient recorder to the CPU, the number of laser pulses for one scan, the number of data summations, the time interval of scan and the scan direction.

In the program, data words are transferred to the CPU and laser radar signals of successive firings (from 2 to 128 firings) are averaged to improve the signal-to-noise ratio. The transferred signal is monitored by an oscilloscope. After the specified number of summations is made, the results are immediately written on magnetic tape along with angle data and other parameters, such as time and firing number. When the laser repetition rate is slow, data is processed and displayed in real time; for high repetition rates, the recorded data is played back and processed at a later time.

The calculation and display process is shown in Fig. 5. The process includes:

(a) d.c. level subtraction from the laser radar signal.

(b) Correction of the laser radar trace for the inverse range-squared dependence and instrument response functions.

(c) Calculations, such as co-ordinate transformation from polar to Cartesian co-ordinates, and logarithmic conversion.

(d) Averaging and smoothing of data to improve the signal-to-noise ratio.

(e) Print out or plot of the processed laser radar pattern signal on a line printer or a display screen.

An example of the processed data display shown in Fig. 6 shows an A-screen (lower), and

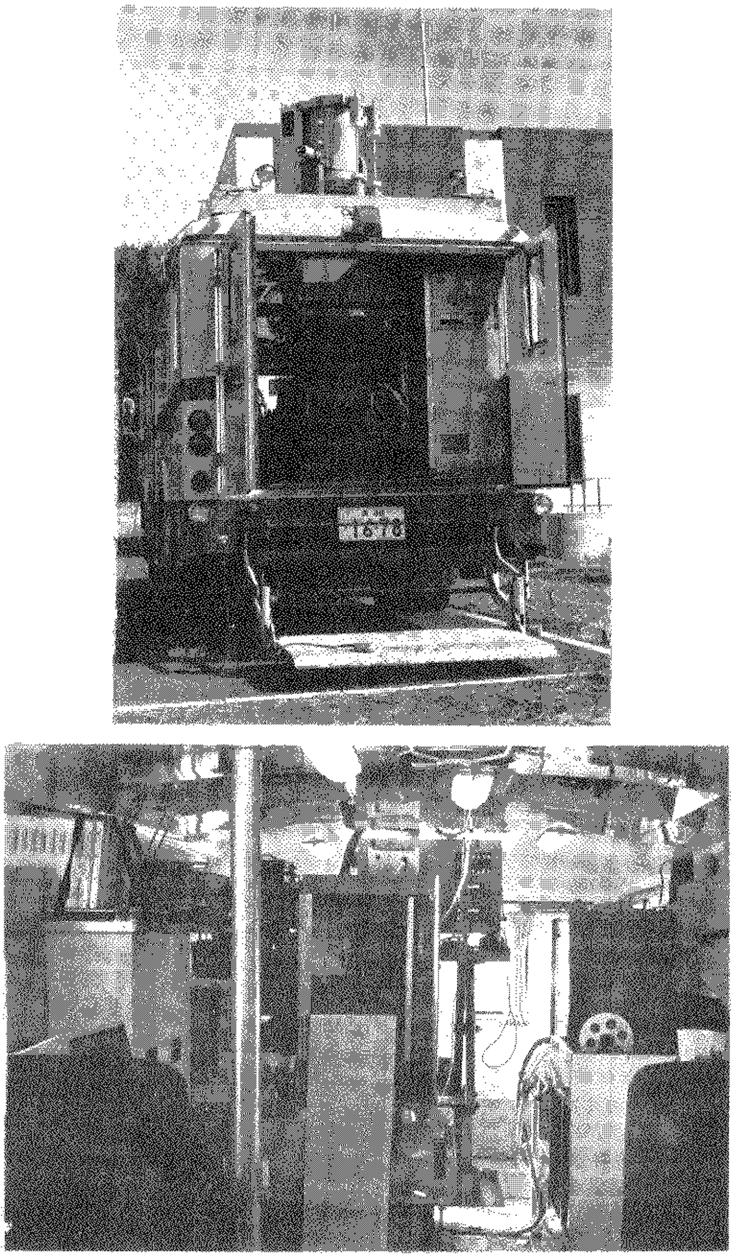

Figure 3 A photograph of the laser radar system loaded on a van, inside view (left) and outside view (right).

range corrected and logarithmic converted (upper) presentation displayed on a graphic terminal screen. The sharp negative spikes near 2000 m and 2800 m represent the zero level point. This figure was obtained by the real-time display technique.

The maximum laser repetition rate is limited by the computer processing time. Each processing time shown in Table III depends on the number of data words transferred from the transient recorder to the CPU. The maximum repetition rate is 38 pps with summation and 15 pps without summation for 1024 words per laser pulse.

4. System analysis

The best way to estimate the performance of a laser radar is to compare the signal-to-noise ratio (S/N) calculated from the laser radar equation [6] and theoretical (S/N) [7].

$$n(R) = n_0 L K \beta T^2 A_r Y_r \eta / R^2 \qquad (1)$$

$$(S/N) = M^{1/2} n(R) / [n(R) + 2(n_b + n_t)]^{1/2} \qquad (2)$$

where $n(R)$ is the number of photoelectrons emitted from a photo-cathode of the photomultiplier irradiated by signal light scattered from distance R, n_0 is the number of photons per laser pulse, L is the range resolution, K is the total

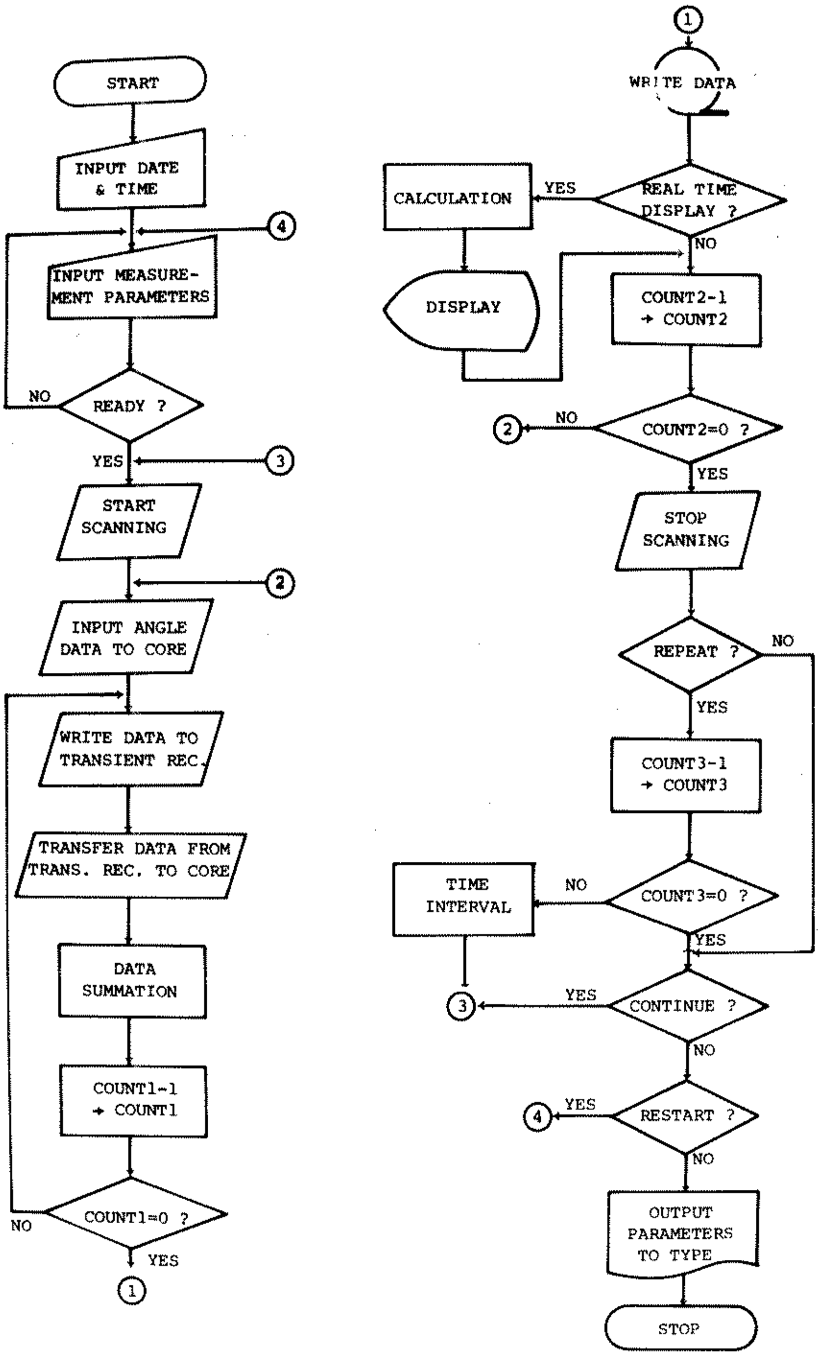

Figure 4 Flow chart of the program for one set of experiments.

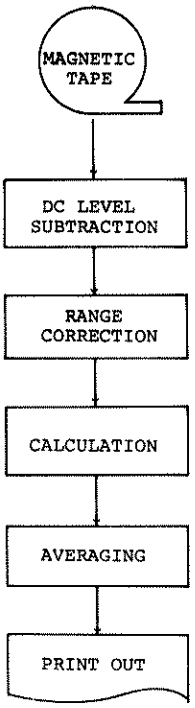

Figure 5 Flow chart of calculation and display processes.

TABLE III Mini-computer processing time

Job	Processing time
Data writing routine	4.5 ms
Data transfer routine	2.0 ms + 2.5 μs/word
Averaging routine	1.8 ms + 15.6 μs/word
MT output routine	20.5 ms + 37.5 μs/word
Calculation for display	4.0 ms/word

efficiency of the optical system, β is the Mie volume backscattering coefficient, T is the transmittance of the laser beam, A_r is the effective aperture of the telescope, Y_r is the overlapping factor of the transmitting beam and telescope acceptance angle, η is the quantum efficiency of the photomultiplier, M is the number of laser pulses and n_b and n_t are the number of electrons emitted from a photomultiplier by background and thermal noise, respectively.

The value of the parameters for our system are given in Table IV. The (S/N) was calculated from these values and Equations 1 and 2. The result is shown in Fig. 7. The theoretical (S/N) have some ambiguities because the values of parameters have some errors. The hatched area in Fig. 7 represents the theoretical (S/N). The measured (S/N) (dots) is also shown in Fig. 7. The laser repetition rate was 2 pps, averaging was done for 20 firings, total data number was 60 and total measuring time was 10 min.

Fig. 7 shows that there is a good agreement between the theoretical and measured values. The slight difference around 600 m is probably caused by fluctuations in air conditions. The result indicates that the (S/N) is limited by the shot noise in our system.

5. An example of system application

The capability of the high repetition digital laser radar system is illustrated by the following example of the monitoring of a stack plume.

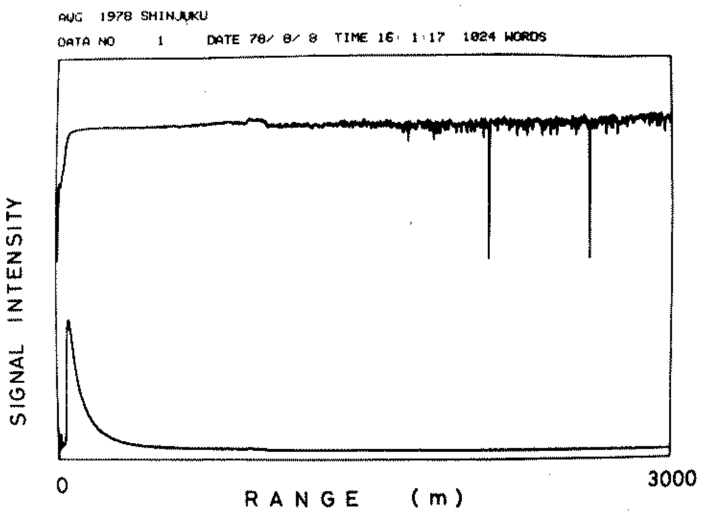

Figure 6 Example of an A screen (lower) and range corrected and logarithmic converted (upper) presentation.

TABLE IV Parameters of the system used for calculation of (*S/N*)

Symbol	Definition	Value
n_0	Photon number	5.4×10^{17} photons/pulse
L	Range resolution	20 m
K	Efficiency of optics (transmitter 0.5, telescope 0.7, filter 0.4)	0.14 ± 20%
A_r	Effective telescope aperture	$0.059\,\mathrm{m}^2$
Y_r	Overlapping factor	1
η	Quantum efficiency of photomultiplier	0.02 ~ 0.05%
β	Mie volume backscattering coefficient	$4 \times 10^{-6}\,\mathrm{m}^{-1}\,\mathrm{sr}^{-1}$ (V = 10 km)
n_b	Electron number by background	33 electrons/gate time
n_t	Electron number by thermal noise	2.2 electrons/gate time

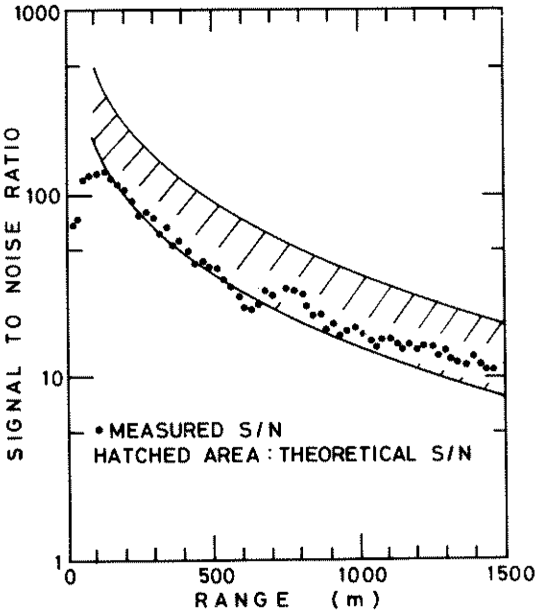

Figure 7 Calculated and measured values of (*S/N*) as a function of range.

Fig. 8 shows a cross-section pattern of a stack plume, which was measured at a downwind distance of about 40 m from the stack. The laser radar was located approximately 900 m away from the stack. The height of the stack is 40 m and the stack diameter is 1.5 m. The vertical scan was made approximately perpendicular to the wind direction, with a scan rate of 1 deg s^{-1}. The laser repetition rate was 20 pps and the laser was fired 200 times for one scan, so the time for one scan was 10 s. In Fig. 8, the data was processed by a large computer and printed out on a line printer. The pattern is expressed by the over-printing technique to show the intensity and the shape of the plume clearly, where the intensity level was sliced in ten grades.

Such measurements were made successively, with a time interval of several seconds, to observe the diffusion effects of the plume. The information obtained from these measurements comprises the position of the centre of gravity, the width of the plume and their respective movements. Data like

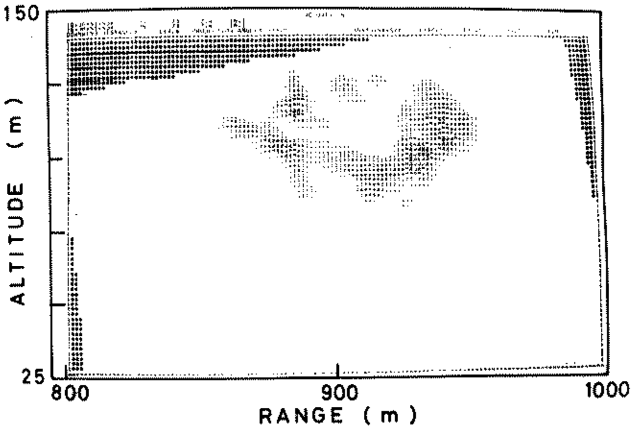

Figure 8 Example of an over-printed output of stack plume data.

these are important in the study of diffusion effects, and can be obtained in the field by such a high-speed laser radar system.

It is important to estimate the repetition rate and scan rate of the laser radar to be able to observe a stack plume within the period that the shape of plume is conserved. If Pasquill curves are used, the averaged stack plume does not spread wider than 400 m [8]. The instantaneous diameter of the stack is 100 m at most [9]. The uniformity of the plume can be characterized roughly by the atmospheric turbulence scale length. This scale can be obtained by the spectral distribution of atmospheric turbulence. The non-dimensional frequency of turbulence Λ is

$$\Lambda = \frac{fz}{V} \tag{3}$$

where f is the frequency of the turbulent eddy, z is the altitude and V is wind velocity. Λ depends on the atmospheric stability and has a value less than 1 [10]. The time scale t of the turbulent field is,

$$t = \frac{1}{f} \simeq \frac{z}{V} \tag{4}$$

t is 4 s for a stack height of 40 m and wind velocity of 10 m s^{-1}. Using this result, the laser repetition rate should be more than 17 pps when the sampling rate is fixed to be 10 ns, and the scan rate should be more than 1.5 deg s^{-1} assuming that the measurement is made from a distance of 1 km from the plume. In the developed system, the maximum repetition rate is 26 pps when the range of measurement for the laser beam direction is 400 m. And the maximum scan rate is 10 deg s^{-1}. These values satisfy the above condition. Thus, the developed system can be used for tracking stack plumes.

As was shown in the above example, this laser radar system can measure the instantaneous spatial aerosol density distributions. This capability can be applied to many types of field measurements by using the variation of aerosol distributions as tracers. The applications are:

(a) diffusion effects of areosols from many kinds of sources, such as stacks, automobiles, aircrafts, ships, dust storms, sea sprays, etc.,

(b) three-dimensional visualization of the structures and the movement of clouds and fogs,

(c) wind direction and velocity [11],

(d) meteorological phenomena in the atmospheric boundary layer, such as inversion layer and internal gravity waves.

We have used this system for more than ten weeks in field measurements around the Kanto district in Japan. It was proved that the system was not affected by vibration of the van and operable during all seasons of the year.

These measurements showed that this system has many practical uses because of its convenient and rapid automatic operation and sturdiness.

6. Conclusion

A high repetition laser radar system for mapping three-dimensional contours of an aerosol backscattered signal has been developed. This system can be operated at a maximum laser scanning rate of 10 deg s^{-1}, and a maximum distance of several kilometers.

The system development was oriented toward real-time acquisition and analysis of data by the use of an on-line mini-computer system with graphic display. The capability of the system was considerably improved by the mobile configuration. In addition, this system is very easy to use for a person who is not expert in laser radars.

The purpose of the measurements is to observe rapidly-varying phenomena. We showed one example of a stack plume here, and theoretical estimation showed that this system can generally be used for such measurements. We believe that this kind of system will have increasing applications.

References

1. G. FIOCCO and G. GRAMS, *J. Atmos. Sci.* 21 (1964) 323–24.
2. E. E. UTHE and R. J. ALLEN, *Opt. Quant. Elect.* 7 (1975) 121–29.
3. E. E. UTHE and W. B. JOHNSON, Final Report, SRI project 7929, AEC contract AT(04-3)-115 (1971).
4. M. P. McCORMICK, 'Remote Sensing Energy Related Studies', (edited by T. N. Vezeroglu), (Hemisphere Press, Washington, 1976) pp. 113–218.
5. G. W. GRAMS, E. M. PATTERSON and C. M. WYMAN, *Opt. Quant. Elect.* 7 (1975) 187–91.
6. H. INABA, T. KOBAYASHI, T. ICHIMURA, H. MORIHISA and H. ITO, *J. Inst. Elect. Commun. Eng. Japan* 51-B (1968) 425–31.
7. H. SHIMIZU, T. KOBAYASHI and H. INABA, *ibid* 60C (1977) 162–69.
8. F. PASQUILL, 'Atmospheric Diffusion' (D. Van Norstrand, London, (1974).

9. J. O. HINZE, 'Turbulence' 2nd ed. (McGraw Hill, New York, 1975) p. 538.

10. J. L. LUMLEY and H. A. PANOFSKY, 'The Structure of Atmospheric Turbulence' (Wiley Interscience, New York, 1964) p. 170.

11. N. TAKEUCHI, H. SHIMIZU, H. UEDA, Y. YASUOKA and M. OKUDA, *8th International Laser Radar Conference*, Philadelphia, Pennsylvania (1977).