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REPORT DOCUMENTATION PAGE

AD-A201 736

DEC 0 6 1988

1a. REPORT U	1b. RESTRICTIVE MARKINGS
2a. SECURITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 20157.6-GS
6a. NAME OF PERFORMING ORGANIZATION Colorado State University / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Fort Collins, CO 80523	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office / 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-83-K-0095
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
A high-spectral-resolution lidar system: The use of atomic blocking filter for measuring atmospheric parameters. UNCLASSIFIED

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 7/83 TO 6/88	Oct. 1988	10

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Lidar, high-spectral-resolution, measurements, aerosol/molecule backscatter ratio, tropospheric temperature

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this project is to develop atomic-vapor absorption cells to be used as blocking filters for a high spectral resolution lidar (HSRL).

Experimental assessment of the proposed new high-spectral-resolution lidar technique for backscatter ratio and atmospheric temperature measurements in the troposphere is presented. The feasibility of the proposed concept has been demonstrated by laboratory measurements using a cw tunable laser with an atomic vapor filter constructed for this purpose. The status of current laboratory experiment with pulsed system suggests that field measurement of backscatter ratio can be made to 1% accuracy. A factor of 10 improvement in the accuracy in determining the molecular attenuation factor resulting from the atomic vapor filter is needed for field temperature measurement with 1 K accuracy.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

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Aeo 20157.6-GS

A high-spectral-resolution lidar system:
The use of atomic blocking filter for measuring atmospheric parameters

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STATEMENT OF THE PROBLEM STUDIED

The objective of this project is to develop atomic-vapor absorption cells to be used as blocking filters for a high spectral resolution lidar (HSRL). With this technique, measurements are to be assessed based on experimental results carried out in the laboratory using first a single mode cw dye laser and then a narrowband tunable pulsed laser.

SUMMARY OF THE MOST IMPORTANT RESULTS

Experimental assessment of a proposed new high-spectral-resolution lidar technique for backscatter ratio and atmospheric temperature measurements in the troposphere is presented. The feasibility of the proposed concept has been demonstrated by laboratory measurements using a cw tunable laser with an atomic vapor filter constructed for this purpose. The status of current laboratory experiment with pulsed system suggests that field measurement of backscatter ratio can be made to 1% accuracy. A factor of 10 improvement in the accuracy in determining the molecular attenuation factor resulting from the atomic vapor filter is needed for field temperature measurement with 1 K accuracy.

DESCRIPTION OF THE RESEARCH PROGRAM

I. Introduction

Remote measurements of atmospheric temperature with lidar have been of interest to applied physicists, engineers, and atmospheric scientists alike for obvious reasons. Three methods have been suggested and implemented to varied degrees: Raman scattering, differential absorption and Rayleigh scattering. In Raman scattering, temperature is determined either by the Stokes/anti-Stokes ratio or intensity distribution of rotational Raman components. With the differential absorption method, temperature is determined by comparing absorption cross section between two selected excitation frequencies. The conventional Rayleigh scattering method probes the atmospheric density distribution and the atmospheric temperature profile is calculated from the measured density profile by assuming hydrostatic equilibrium of the atmosphere. Due to its high scattering cross section, non-resonant Rayleigh scattering is no doubt the most sensitive method for remote atmospheric temperature measurements. This fact is well accepted and Rayleigh scattering is the only method practiced in the stratosphere where the air molecular density is low. Due to the abundance of aerosol in the troposphere which dominates quasi-elastic scattering and interferes with the molecular density measurements, the method of Rayleigh scattering as described above, unfortunately, cannot be used for atmospheric temperature measurement.

In 1983, we proposed[1] a high-spectral resolution lidar technique for backscatter ratio and atmospheric temperature measurements for tropospheric applications. In this method, we conceived the use of an atomic vapor filter (AVF) as a narrowband ($\sim$1 GHz) blocking filter to disentangle the molecular scattering from aerosol scattering. In this manner, the backscatter ratio may be measured[2] from which both aerosol and molecular density profiles can be determined. Using theory of Rayleigh-Brillouin scattering and two such blocking filters with different bandwidth to reject aerosol contribution, atmospheric temperature can also be determined directly. At Colorado State University, experimental efforts for implementing a proto-type lidar system based on this 1983 proposal have begun. Our experimental program has been divided into three stages of development. First, we develop barium atomic vapor filter (AVF) and test the feasibility of the technique for backscatter ratio and atmospheric temperature measurements with a tunable cw dye laser system. Second, we setup a pulsed laser system along with automated data acquisition to assess the laboratory experiment of atmospheric temperature with the pulsed system. Third, upon the successful development of the first two stages of the program, we setup a proto-type high spectral resolution lidar (HSRL) system for field measurements of tropospheric backscatter ratio and temperature profiles. The work of the first stage is supported by this ARO grant. The ongoing work of the second stage is supported jointly by this grant and the ARO Geoscience Center. And the work of the third stage of field experiment is being continued with the support of the ARO Geoscience Center.

This final report summarizes the work supported by this ARO grant. The success of the cw experiment which demonstrated the achievable experimental accuracies of the proposed technique will be first outlined. The progress of laboratory experiment using a pulsed laser system will then be presented. The presently achieved accuracy with the pulsed system will be assessed and methods for improving the accuracies suggested. Based on the status assessment, plans of the field experiment and its expected performance will be discussed in the conclusion.

II. *The Feasibility Demonstration Experiment*

The laboratory measurements of atmospheric temperature and backscatter ratio using a cw laser system have been completed. In this experiment, a barium heat-pipe oven has been constructed and operated in the vapor cell mode. By varying the oven temperature, the band width of this AVF may be varied from 1.4 GHz to 1.8 GHz with ease. The transmission profiles of the AVF at various settings, which are needed for the experimental determination of backscatter ratio and atmospheric temperature, are determined with a single frequency tunable dye laser. Typical transmission profiles of the AVF as measured with intensity stabilized cw dye laser (with a noise eater) are shown in Fig. 1. Setting the frequency of this narrow-band dye laser (band width of 1 MHz) at the center of the barium absorption (5537 A), the scattered light from a point in room air passing through the AVF is monitored on and off resonance at different oven settings. Using the formulae in Ref.1, the backscatter ratio and atmospheric temperature can be measured. In this manner, laboratory measurements of atmospheric temperature and backscatter ratio have been made, yielding measurement uncertainty of 1 K and better than 3%, respectively. The result of this ARO supported research has been published[3]. In addition, similar laboratory measurements of temperature under different atmospheric (temperature and pressure) conditions have been made[4]; they yield approximately the same accuracy of 1 K.

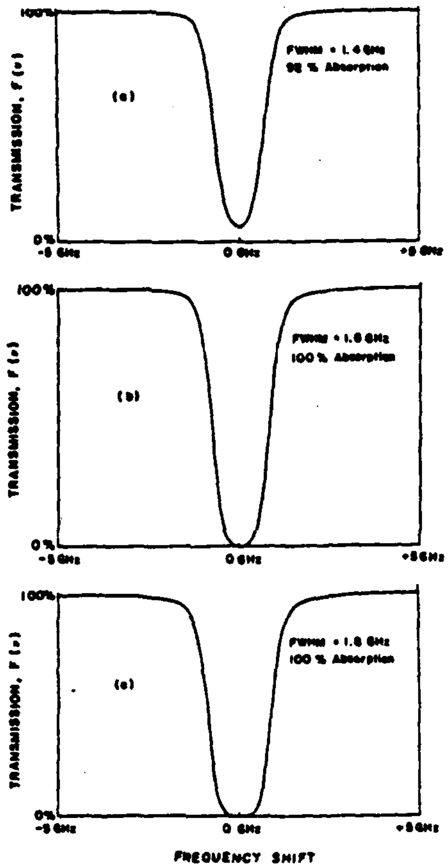

Fig. 1 Transmission spectra F(ν), of atomic-vapor blocking filter taken with a cw dye laser system for different filtration settings.

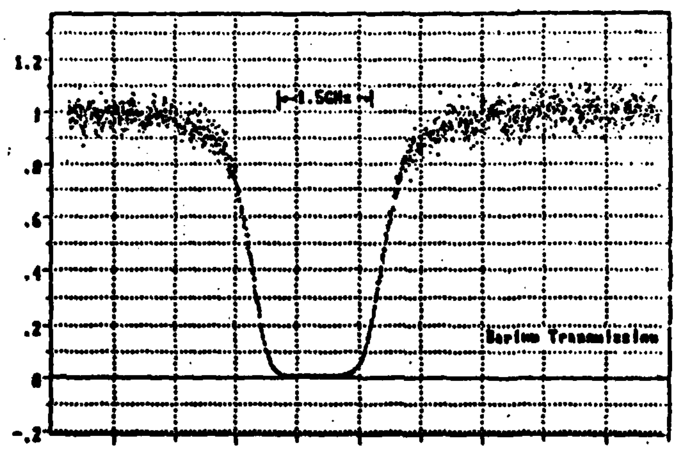

Fig. 2 A transmission profile of the Ba AVF taken with our pulsed laser system.

III. Laboratory Experiment With Pulsed System

The characterization of atomic vapor filter under pulsed excitation has begun initially with a homemade pulsed dye amplifier and existing laser system. With the equipment support of the ARO Geoscience Center, a tunable pulsed dye laser system consisting of several commercial lasers have been installed and made operational. This laser system starts from a cw single mode dye laser tuned to the wavelength of interest. Its output is amplified by a pulsed dye amplifier pumped by a doubled YAG laser at 20 Hz. The output of this system consists of tunable megawatt narrow band (around 100 MHz) pulses at 20 Hz. Using this tunable source, the transmission profiles of the barium AVF at different oven temperatures have been taken almost immediately. In this initial experiment, the spectrum is taken by a computer which scans the frequency of the laser system and at the same time records the intensity transmitted through the Ba filter. As the frequency of the laser is scanned, a spectrum analyzer with 1.5 GHz free-spectral-range is used as an independent frequency monitor. One of these initial transmission profiles is shown in Fig. 2.; it clearly demonstrates that (1) our computer automated data acquisition system is working, (2) the pulsed laser system has high enough spectral resolution around 100 MHz and (3) the laser output is nearly free from broad-band amplified spontaneous emission. Although there is still room for improvement, we felt that our pulsed laser and data acquisition system were ready for experimental use.

In fact, a laboratory experiment for atmospheric temperature measurements using the pulsed laser and data acquisition system had been made shortly after. Using only one barium vapor heat-pipe, the procedures of our previous cw experiments were carried out. By varying the heat-pipe oven temperature, the transmission profiles of the AVF at several settings, which correspond to different bandwidths are taken sequentially. Immediately after the measurement of a transmission profile, the frequency of the pulsed output is set at the center of the Ba absorption (5537 A) and the light scattered from a small volume in room air passing through the AVF is monitored. Using the formulae in Ref. 1, scattering counts passing through any two vapor filters with 100% peak absorption along with their respective transmission profiles are used to calculate the measured atmospheric temperature at a local point. Unfortunately, the accuracy of this experiment was much worse than the one degree accuracy obtained previously with the cw system.

In order to understand the inaccuracy of the pulsed experiment as compared to the previous cw experiment, we recall the expressions[1,3] for determining the backscatter ratio, r, and temperature, T:

$$r = (N_1/N_2)\, f_m, \qquad N_2/N_2' = f_m/f_m' \qquad (1)$$

and

$$f_m = \int R(\nu, P, T)\; F(\nu)\, d\nu \qquad (2)$$

where N_1/N_2 and N_2/N_2' are respectively the measured ratios of the total scattering signal to that attenuated by the AVF and the attenuated signals by different AVF's. The factors f_m and f_m' are the molecular attenuation factors of the atomic vapor filters with the spectral transmission function $F(\nu)$ and $F'(\nu)$ respectively. The function $R(\nu,P,T)$ is the normalized molecular scattering function which is calculated from theory[5]. By comparing the calculated temperature-dependent ratio (at a given atmospheric pressure) f_m/f_m' with

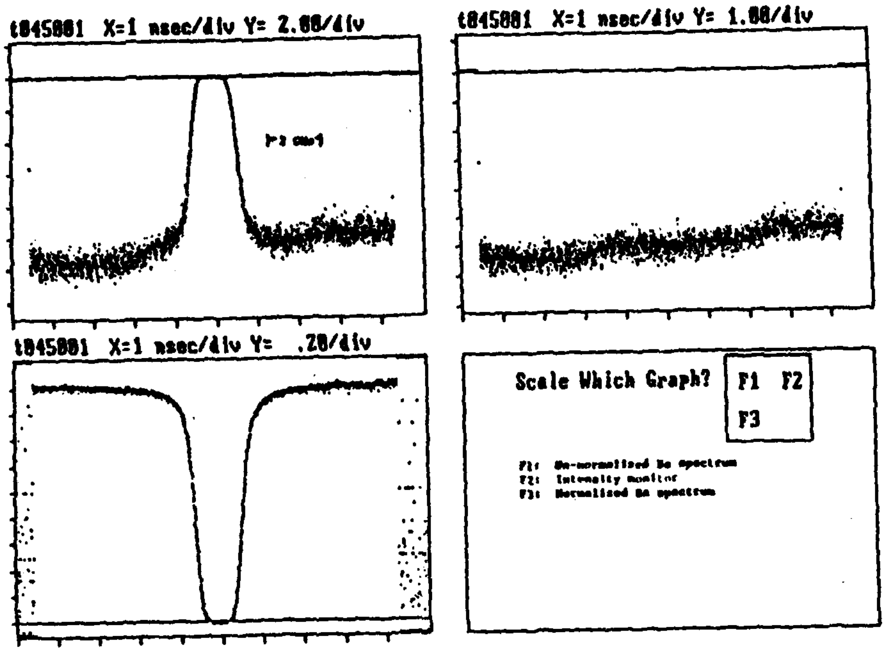

Fig. 3. A Ba transmission function (F1) along with power monitor (F2) and normalized spectrum (F3).

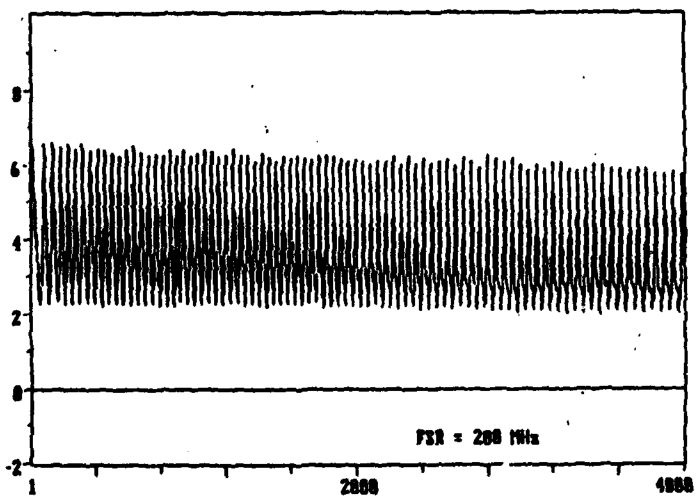

Fig. 4 A transmission profile of an interferometer for monitoring dye laser wavelength. Free-spectral-range = 200 MHz

the measured ratio of the filtered backscatter signal counts, N_2/N_2', the atmospheric temperature can be determined. It is clear, though perhaps not immediately obvious, that in addition to the measured signal counts, the accuracy of both backscatter ratio and temperature measurements depend upon the accuracy of f_m obtainable. This factor, according to Eq.(2), depends on the measured function F(v) whose accuracy depends on the stability of both intensity and frequency of the laser beam used for its measurement. Two major difficulties exist in the pulsed laser system : intensity fluctuations and nonlinear scan in laser frequency, both affecting the accuracy of F (v) and f_m. A laser power monitor has been installed to normalize both slow and pulse-to-pulse fluctuations. That our power monitor apparently worked well can be seen in Fig. 3 where the normalized transmission profile is much closer to the expected function. In the cw experiment, a noise eater was used which had kept the laser power constant within and between scans thus avoiding the need for power normalization. Another difficulty lies in the scanning mechanism of our cw tunable dye laser. It has unpredictable nonlinearity; this introduces uncertainties in the frequency scale of the measured Ba transmission profiles. To minimize the impact of scan nonlinearity, we have constructed a Fabry-Perot interferometer with 200 MHz free-spectral-range to measure the relative frequency of the laser output accurately and independently. A transmission profile of this interferometer as a function of laser scan is shown in Fig. 4. With this simultaneously measured frequency calibration, the problem of minor nonlinearity in frequency scan has been minimized. Figure 5 shows backscatter signal as the frequency of of the pulsed laser is scanned across the Ba absorption of the filter. It shows clearly that the aerosol scattering which is evident off-resonance is absent on-resonance. Least-square fitting the convolution between the filter transmission and theoretical backscattering function to the experimental scattering scan will permit the determination of backscatter ratio.

With above mentioned improvements, the molecular attenuation factor f_m can now be determined to within 1% accuracy. This suggests that the backscatter ratio can be measured to 1% accuracy as well. The accuracy of temperature measurement depends on the relationship between temperature and the calculated ratio f_m/f_m'. To assess this accuracy, we reproduce two such relationships in Fig. 6. Figure 6a which suggests an uncertainty of 0.3% per degree is the result of a calculation assuming Doppler broadening in Ba vapor taken from Ref. 1. On the other hand, Fig. 6b which suggests an uncertainty of 0.03% per degree is the result of a calculation using the measured transmission profiles of our Ba filters taken from Ref. 3. In either cases, our presently achieved accuracy in f_m of 1% is not good enough for temperature determination to within 1 degree as proposed. We are in the process of further improving the accuracy by investigating methods such as better temperature controls for our filters.

The discrepancy between the results suggested by Fig. 6a and Fig. 6b is both interesting and of practical importance. We tentatively explain the discrepancy by noting that the line broadening mechanism of our Ba filter is dominated by the collision between Ba and argon atoms (buffer gases) which leads to pressure broadening (Lorentzian lineshape) not Doppler broadening (Gaussian lineshape) as assumed in Ref.1. Since a Lorentzian lineshape tends to attenuate high frequency molecular spectrum more than a Gaussian lineshape would, Fig. 6b (pressure broadened case) would be less sensitive to atmospheric temperature changes than Fig. 6a. We have indeed performed saturation spectroscopy experiment to confirm this explanation[6]. The practical implication of this discrepancy (by a factor of 10) is obvious. It on the one hand suggests that our cw experiment had reached an accuracy in f_m (0.03%) better than that anticipated in our original proposal; on the other hand, we still have to improve our pulsed accuracy of f_m from 1% to 0.03% unless a different type of AVF is used. We are in the process of

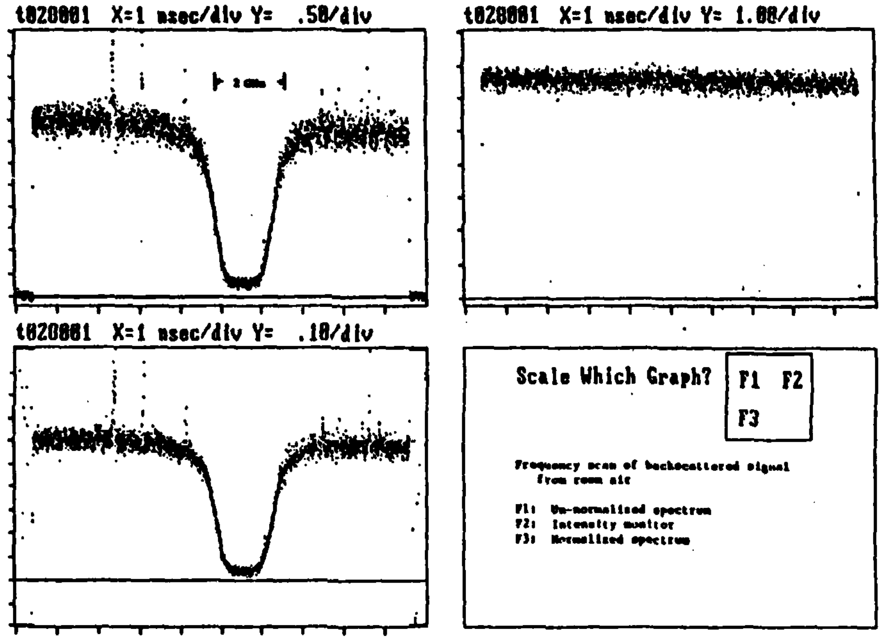

Fig. 5 A frequency scan of backscattered signal from room air showing aerosol scattering off-resonance and only molecular scattering on-resonance.

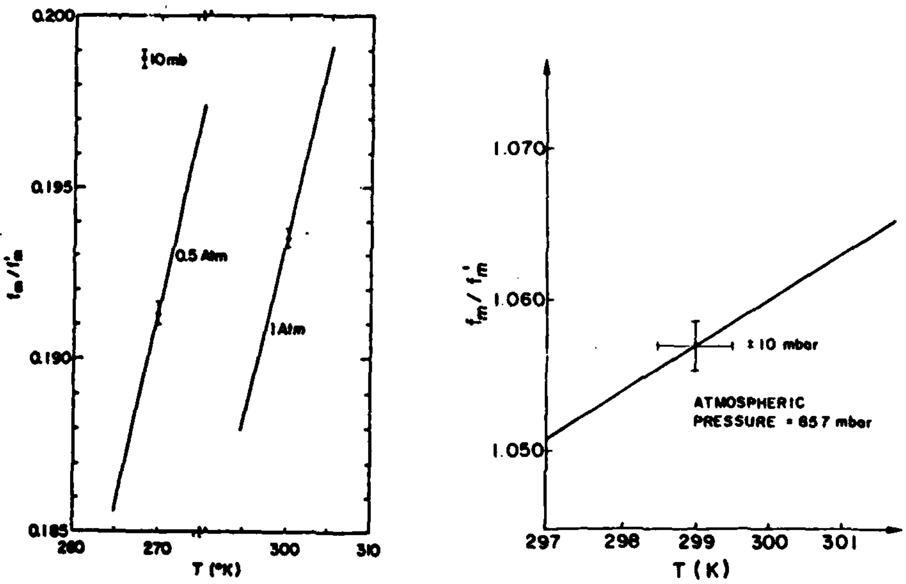

Fig. 6 Examples of temperature dependence of the ratio of molecular attenuation factors: using (a) calculated from Doppler broadened F(ν) and (b) measured F(ν) which is mainly pressure broadened.

investigating the possibility of reducing the buffer gas pressure in our filter and of using a filter with Ba vapor only.

IV. Conclusion

The proposed high-spectral-resolution lidar technique for measuring backscatter ratio and temperature of the troposphere using barium atomic vapor cell as blocking filter has been successfully tested experimentally by a cw tunable dye system. Difficulties that affect measurement accuracy when a pulsed system is used have been identified. The uncertainty of the molecular attenuation factor, f_m, with pulsed system after the *implementation of intensity and simultaneous frequency monitor* has been reduced to within 1%; this can be further improved. With the present uncertainty of 1% in f_m, the backscatter ratio profile can be determined to the same accuracy. In order to measure atmospheric temperature to 1 K accuracy with the pulsed system using the atomic filter presently used, the uncertainty of f_m must be reduced to within 0.03%. It is felt that by decreasing the effect of pressure broadening in the vapor cell, the acceptable uncertainty of f_m for temperature measurement with 1 K accuracy can be relaxed to 0.1%; this should be experimentally achievable by improving the stability of the temperature controller. Therefore, the continued research with the support of ARO Geoscience Center pursues the field experiment of backscatter ratio on the one hand and and improvement of f_m with laboratory experiment on the other. In this manner, we hope that profiles of atmospheric backscatter ratio and molecular density with a few per cent accuracy can be measured at the earliest possible date. Assuming hydrostatic equilibrium, atmospheric temperature profiles can also be indirectly determined. When the factor f_m can be accurately determined, direct temperature profiles as originally proposed will then be measured in the field. It should be pointed out that the validity of the direct method does not depend on the assumption of hydrostatic equilibrium; it should be more accurate than the indirect method, especially for the troposphere. A comparison of the results between indirect and direct temperature measurements would be interesting and awaits for field experimentation.

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PUBLICATIONS

The following are papers and published reports written under the sponsorship of this ARO grant:

1. F. J. Lehmann, S. A. Lee, and C. Y. She, "A direct measurement of backscatter ratio with an atomic blocking filter", Abstract and presentation in CLEO, June, 1986.
2. H. Shimizu, K. Noguchi, and C. Y. She,"Atmospheric temperature measurement by a high spectral resolution lidar", Appl. Opt. 25, 1460 (1986).
3. C. Y. She,"High spectral resolution lidar for tropospheric temperature profiling", Abstract and presentation in the Annual OSA meeting, Oct. 1986.
4. F. J. Lehmann, S. A. Lee, and C. Y. She, "Laboratory measurements of atmospheric temperature and backscatter ratio using a high-spectral-resolution lidar technique", Opt. Lett. 11, 563 (1986).
5. F. J. Lehmann, " Laboratory measurements of atmospheric temperature and backscatter ratio using a high-spectral-resolution lidar technique", Ph. D. Thesis, Colorado State University (1987).
6. C. Y. She, R. J. Alvarez II, H. Moosmuller, and D. A. Krueger, "Implementing a new high-spectral-resolution lidar technique for backscatter ratio and atmospheric temperature profiling", Abstract and presentation in OSA topical meeting on "Laser and optical remote sensing: instrumentation and techniques", North Falmouth, Mass, September 28-October 1, 1987.
7. C. Y. She, R. J. Alvarez II, H. Sun, H. Moosmuller, and D. A. Krueger, "High-spectral-resolution lidar technique for backscatter ratio and atmospheric temperature profiling", Abstract and presentation in the 14th International Laser Radar Conference, Innichen-San Candido, Italy, June, 1988.

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