Laser Review

Mesospheric Na Wind/Temperature Lidar

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Meteoric ablation in the upper atmosphere is the source of a dense layer of atomic Na between 80-105 km with maximum densities averaging $4 \times 10^3 \text{ cm}^{-3}$. The Na layer is a sensitive tracer of the wind, thermal, and density structure of this region and can be probed with exceptional accuracy and resolution using resonance fluorescence lidar techniques. Modern narrow-band tunable lasers are now being used in Na lidar systems to measure routinely winds and temperatures with accuracies approaching $\pm 1 \text{ m/s}$ and $\pm 1 \text{ K}$. We describe the Na Wind/Temperature lidar technique and present examples of observations made during the recent ALOHA-93 Campaign in Hawaii.

Key Words: Lidar, Na, Winds, Temperature, Mesosphere

1. Introduction

Until recently, in situ rocket probes and powerful mesosphere-stratosphere-troposphere radars were the predominant techniques used to explore middle atmosphere composition and structure. However, during the past decade, numerous lidar techniques have been developed to probe this region with superb accuracy and resolution. Ozone, Rayleigh, aerosol, and resonance fluorescence lidars are now playing central roles in many middle atmosphere studies.

It has long been recognized that the Na layer is a sensitive tracer of the density, temperature, and wind structure between 80 and 105 km. Although the first lidar observations of Na density profiles were made in the 1960s, soon after the invention of the tunable dye laser, it was not until the mid-1980s that the linewidth and frequency stability of dye lasers improved sufficiently for reliable temperature observations to be conducted routinely^{1,2}. Further improvements in laser technology now make Na Doppler wind measurements possible.

Temperature and wind observations can be obtained by probing the fine structure of the Na D_2 fluorescence spectrum with a tunable narrow-band pulsed laser. For accurate temperature measurements ($\pm 2 \text{ K}$) the required absolute tuning accuracy

and frequency stability of the laser is 20 MHz rms or less. An order of magnitude improvement in absolute tuning precision and stability ($\sim 2 \text{ MHz}$) is required for accurate radial wind measurements ($\pm 1 \text{ m/s}$). These performance requirements can be achieved using state-of-the-art cw ring laser and pulsed amplifier technologies. Several groups have recently demonstrated Na wind and temperature measurement using this approach^{3,4}. In this paper we describe the measurement technique and present examples of mesospheric wind and temperature profiles acquired with the University of Illinois Na lidar system during the ALOHA-93 (1993 Airborne Lidar and Observations of the Hawaiian Airglow) Campaign.

2. Na Wind/Temperature Lidar Technique

The Na D_2 absorption spectrum consists of six hyperfine resonance lines that are broadened predominantly by inhomogeneous thermal processes. This spectrum is further broadened by the laser lineshape when probed in a lidar experiment. The broadened absorption spectrum is a doublet with the frequency of the major D_{2a} peak located approximately 1.77 GHz below the D_{2b} peak (Fig. 1a). The thermally broadened width of each doublet is approximately 1.1 GHz full width at half maximum (FWHM). The ratio of the absorption spectrum at

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Fig. 1 (a) Na D_2 thermally broadened absorption spectrum plotted as a function of frequency for three temperatures. The D_{2a} and D_{2b} hyperfine groups and the four laser frequencies used in the ALOHA-93 experiment are depicted as well. (b) Measured Na vapor fluorescence spectrum. The Doppler-free features at f_a and f_c are prominently displayed.

the minimum between the D_{2a} and D_{2b} peaks to the spectrum at the D_{2a} peak is a sensitive function of temperature. Similarly, the ratio of the spectrum on either side of the D_{2a} peak is a sensitive function of the Doppler shift. Temperature is sensed by tuning a narrowband pulsed laser alternately to the D_{2a} peak frequency f_a and to the crossover resonance frequency f_c , which is near the minimum between the D_{2a} and D_{2b} peaks (Fig. 1), and recording the backscattered fluorescence signal from the Na layer at each frequency. The Doppler shift and hence radial winds are sensed by tuning the laser alternately to two different frequencies in the wings of the D_{2a} absorption peak, viz., at $f_a \pm f_o$ where $f_o = 600$ MHz. Detailed theoretical discussions of the temperature and wind measurement techniques can be found in Bills et al.⁵⁾ and Papen et al.⁶⁾.

The narrowband laser used in the ALOHA-93 ex-

periment included a cw ring dye laser oscillator and three-stage pulsed dye amplifier with an average output power of 1 W at 30 pps. The cw laser oscillator was tuned precisely by observing the Doppler-free structure of the Na D_2 fluorescence spectrum in a vapor cell (Fig. 1b) and by monitoring the laser oscillator signal using a temperature-stabilized confocal etalon. The lidar was installed at the Air Force Maui Optical Site near the summit of Haleakala at an altitude of 3055 m and interfaced with the 0.8 m diameter Beam Director Telescope which provided full scanning capabilities. Vertical and horizontal winds were measured by pointing at zenith and 15° off zenith to the north and east. The power aperture product of the lidar system was 0.5 Wm².

Unlike conventional radar, the Doppler shift associated with fluorescence absorption is $-V_R/\lambda$, where V_R is the radial wind velocity toward the laser and $\lambda = 589.158$ nm is the center wavelength of the D_2 emission. The minus sign appears because the Na atoms are excited by a laser pulse that has been Doppler shifted to a higher frequency (assuming $V_R > 0$), which is equivalent to shifting the absorption spectrum to a lower frequency. The backscattered signal results from spontaneous emission of the excited Na atoms. Because the fluorescence signal is proportional to the absorption cross section and is detected by a broadband receiver, only the Doppler shift associated with the absorption process is observed. When the lidar is pointed to the east, the Doppler shift (f_d) is

$$f_d = -V_R/\lambda = (u/\lambda) \sin 15^\circ + (w/\lambda) \cos 15^\circ \quad (1)$$

where u is the zonal wind (eastward winds are positive) and w is the vertical wind (upward winds are positive). The shift is ~ 1.7 MHz/(m/s).

The primary sources of error are photon noise and laser frequency errors. By approximating the Na D_2 emission spectrum as the sum of two Gaussian distributions centered at the D_{2a} and D_{2b} frequencies, approximate expressions for the errors can be derived. The photon noise errors for radial velocity (V_R) and temperature (T) are Bills et al.⁵⁾; Papen et al.⁶⁾

$$\Delta V_R(\text{m/s}) \approx \frac{490 \text{ m/s}}{\sqrt{N_s(f_a, z)}} \quad (2)$$

$$\Delta T(\text{K}) \approx \frac{510 \text{ K}}{\sqrt{N_s(f_a, z)}} \quad (3)$$

$N_s(f_a, z)$ is the equivalent photon count in the range bin centered at altitude z , assuming the laser was tuned to frequency f_a during the time period that profiles were actually collected at

the four frequencies $f_a - f_o$, f_a , $f_a + f_o$, and f_c . N_s is given by the lidar equation and for typical system parameters can be written approximately as

$$N_s(f_a, z) = 40 P(W) A(m^2) \cdot n_s(cm^{-3}) \Delta t(min) \Delta z(km) \quad (4)$$

where P is the average output power of the laser, A is the aperture area of the receiving telescope, n_s is the Na density at altitude z , Δt is the time required to obtain the profiles at the four different frequencies, and Δz is the altitude resolution of the wind or temperature measurement.

At the peak of the Na layer near 92 km altitude the density averages approximately 4000 cm^{-3} and for ALOHA-93 the power-aperture product of the lidar was 0.5 Wm^2 . If the integration period is 6 min and the vertical resolution is 0.5 km, then $N_s(f_a, 92 \text{ km}) \approx 2.4 \times 10^5$ and the approximate radial velocity and temperature errors are respectively, 1 m/s and 1 K.

The radial wind and temperature errors contributed by laser frequency errors are given by

$$\Delta V_R(m/s) \approx 0.4 \Delta f(MHz) \quad (5)$$

$$\Delta T(K) \approx 0.1 \Delta f(MHz). \quad (6)$$

By using the Doppler free features in the Na cell fluorescence spectrum as frequency markers (Figure 1b) and modern ring-dye laser oscillators as we did for ALOHA-93, an absolute tuning accuracy of 2 MHz or better can be achieved. Consequently, the radial velocity and temperature errors caused by errors in laser tuning can be held to better than 1 m/s and 0.25 K.

3. Observations During the ALOHA-93 Campaign

To illustrate the capabilities of Na W/T lidars, contour plots of the Na density and temperature measured on 6 October 1993 during ALOHA-93 are presented in Fig. 2. Contour plots of the vertical and zonal winds measured on this same night are presented in Fig. 3. These data are interesting because a major sporadic Na layer formed near 92 km at approximately 0900 UT and then moved downward throughout the remainder of the observation period with an apparent velocity of approximately 15 cm/s. The temperature in the vicinity of the sporadic Na layer was considerably warmer than the surrounding region, reaching values higher than 240 K. The vertical wind velocity exhibited no unusual characteristics near the sporadic layer. The vertical velocity fluctuations throughout the height range of observations were approximately $\pm 5 \text{ m/s}$. In con-

trast the zonal winds varied between -80 and 100 m/s with a strong shear in the region of the sporadic Na layer. This is illustrated more clearly in Fig. 4 where the Na density, temperature, zonal wind, and vertical shear of zonal winds at 0905 UT are plotted versus altitude. The maximum shear occurred at the peak of the sporadic Na layer at 92 km. Throughout the sporadic layer the temperature was approximately 40 K warmer than the surrounding regions.

The chemical and dynamic processes responsible for the formation of sporadic Na layers are not yet well understood. However, data such as these truly understanding this puzzling phenomenon. These data also illustrate the potential of Na W/T

Fig. 2 Contour plots of the (a) Na density and (b) atmospheric temperature measured on 6 October 1993 at Haleakala, Maui during ALOHA-93.

Fig. 3 Contour plots of the (a) vertical and (b) zonal winds measured on 6 October 1993 at Haleakala, Maui.

lidars in mesospheric studies. The performance of existing systems is essentially photon noise limited.

Fig. 4 (a) Na density and temperature profiles measured at 905 UT on 6 October 1993. (b) Zonal wind profile and the vertical shear of the zonal wind profile measured at 905 UT on 6 October 1993.

Improvements in measurement accuracy and resolution can only be obtained by increasing the power aperture product of the lidar. By using 3 m class astronomical telescopes, improvements of 15 to 20 over the ALOHA-93 lidar are easily achievable, thus yielding measurements with significantly improved spatial and temporal resolution.

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