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Abstract. The Na temperature lidar data taken during the nine nights in springs 1990 and 1991 at Fort Collins, CO, have been re-analyzed by a refined procedure, which takes into account the effects of (i) the more accurately determined lidar operational frequencies, (ii) the proper inclusion of extinction in the Na layer and (iii) additional temporal and spatial smoothing. Depending on altitudes, the new lidar frequencies and the effect of Na extinction combined to lower the calculated temperature values by 2–8 K. Although the occasionally noted large rapid change (in 15 min) in the centroid temperature is reduced from ~40 K to ~20 K due to the added smoothing first employed by Bills and Gardner, the general conclusion presented in the recently published paper [1] remains valid. In this paper, we also present the analysis of new data (a total of seventeen nights) taken during spring 1992 which further substantiates the fact that the averaged mesopause in spring rises from a lower altitude before midnight to a higher altitude after midnight. In addition, parameters depicting atmospheric gravity-wave perturbations have been derived from the measured temperature profiles. Using the data collected in 26 spring nights, we have determined the averaged relative density (temperature) perturbation, Brunt Vaisala period and Richardson number to be, respectively, 5.1 ± 1.1%, 5.1 ± 0.3 min, and 1.8 ± 1.0.

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In a recent paper [1], the Colorado State Na temperature lidar was described. To demonstrate the effectiveness of this new two-frequency narrowband Na lidar technique for atmospheric temperature measurements in the mesopause region, the initial data taken nine nights in springs 1990 and 1991 at Fort Collins, CO, were analyzed by a straightforward procedure outlined in our first publication [2] without considering certain smoothings to remove high-frequency noise contamination. After installing a Na temperature lidar similar to ours, the Illinois group has refined the data analysis procedure [3] and employed it to evaluate the initial temperature structures of the mesopause region at Urbana [4]. At the expense of some spatial and temporal resolutions, the refined procedure gives rise to more reliable temperature measurements. Upon resolving the hyperfine features in the Na Doppler-free fluorescence spectrum [5], the sharpest frequencies in the $D_{2a}$ peak and crossover resonance have been determined to be $v_a = -652.0$ MHz and $v_c = 118.0$ MHz instead of the old values [1] of $v_a = -656.7$ MHz and $v_c = 203.9$ MHz. The effect of using the newly determined frequencies yields a temperature about 2–3 K lower. The temperatures calculated by the refined procedure are generally lowered by more than this amount due to the inclusion of Na extinction in the formulae for both temperature and Na density determination. In view of these developments, one purpose of this paper is to report the re-calculated temperatures and the associated Na abundance of the mesopause region from data taken during the nine nights in springs 1990 and 1991. It will be shown that the refined analysis gives rise to temperatures lower by 2–8 K depending on altitude, reduces the occasionally noted large fast (~15 min) changes in the centroid temperature from around 40 K to more believable 20 K, and leaves the general conclusions presented in the recently published paper [1] unchanged. In addition, we present the analysis of new data (a total of seventeen nights) taken in spring 1992, along with the determination of atmospheric gravity-wave parameters from data taken in springs 1990, 1991 and 1992 (a total of twenty-six nights, each for a period longer than 4 h) to elucidate the gravity-wave dynamics of the mesopause region at Fort Collins, CO, (40.6°N, 105°W) in the spring season.

1 Analysis of Na Temperature Lidar Data

The new Na temperature lidar system and data taking procedure have already been described [1, 5] and will not be repeated here. The raw data consist of photocount files taken alternatively at the Na $D_{2a}$ peak and crossover frequencies $v_a$ and $v_c$, separated by a pre-selected interval $\Delta t$, typically 75 s. Until recently, the center-of-mass of
the Na $D_{2a}$ peak and crossover fluorescence features at $-656.7$ MHz and $203.9$ MHz were regarded as the lidar operational frequencies and the temperature and Na density profiles are determined from the measured photocount profiles by a straightforward data analysis procedure, along with the use of properly chosen weighting factors to eliminate Na density variations up to the fifth order affecting temperature measurements [2, 5].

The hyperfine features of the Na Doppler-free spectrum at both $D_{2a}$ peak and crossover frequencies can be resolved [5] to a precision of better than 2 MHz. The values of the Na 3s and 3p energy levels are known to an accuracy of better than 1 MHz [5, 6]. Experiments to simultaneously record [7] the Doppler-free fluorescence spectra of our reference Na cell at different laser power illuminations and the transmission functions of a temperature-stabilized interferometer with known free spectral range (~75 MHz) were made recently. The measured fluorescence spectra, when compared with the accurately known energy levels, have permitted us to determine the locations of the sharpest features [5] of the $D_{2a}$ and crossover resonances to be $-652.0$ MHz and $188.0$ MHz, respectively. The details of these measurements and the process of determining the frequency of resonance features will be prepared for a future publication.

Taking these values as the lidar operational frequencies, $v_a$ and $v_c$, and using the measured laser lineshape function, a revised lidar temperature calibration curve may be calculated. When it is compared with the calibration curve using the previous frequencies, $-656.7$ MHz and $203.9$ MHz, the calculated temperatures are lowered by about 2–3 K. The calibration curves using the old and newly determined lidar frequencies for $v_a$ and $v_c$ are compared in Fig. 1a. Following the work of the Illinois group, in particular Bills and Gardner [3], we have also refined our data analysis procedure to detect, at the onset, occasionally incorrect photocount files due to mistuning of the laser which escaped from the attention of the operator. To facilitate data processing, the incorrect files are replaced and some of the missing files due to short-term (a few minutes up to 30 min) cloud coverage are inserted by files interpolated from the neighboring legitimate files; however, the data points that are affected by these files are later deleted from the final result. In addition to applying spatial and temporal filtering with Hamming windows, typically 15 min and 2 km, to reduce the high-frequency noise contamination, the effect of Na extinction are accounted for in the calculation of temperature as well as Na density in the refined procedure. Since Na extinction is more pronounced at the $D_{2a}$ peak frequency $v_a$, its inclusion tends to produce a lower calculated temperature in the refined analysis. An example illustrating this effect is shown in Fig. 1b, where the calculated temperature profiles using the same measured data, with and without accounting for the Na extinction properly, are compared. Since in high resolution, the fluorescence cross section is temperature dependent, the temperature and Na density are inter-related [5]. This gives rise to different Na column abundances, respectively, $2.01 \times 10^9$ cm$^{-2}$ and $1.97 \times 10^9$ cm$^{-2}$ for the temperature profiles shown in Fig. 1b. When Na extinction is accounted for, the calculated temperature is lowered by as much as 5 K. Thus, depending on altitudes, the effects of Na extinction

![Fig. 1](image-url)

**Fig. 1.** a) Comparison of the calibration curves (intensity ratio vs temperature) of a Na temperature lidar between the use of old and newly determined peak and crossover frequencies, ($-656.7$ MHz, $203.9$ MHz) and ($-652.0$ MHz, $188.0$ MHz), respectively; b) A calculated nightly averaged temperature profile (Feb. 15, 1992) with Na extinction disregarded from the expression for intensity ratio is compared to that with Na extinction fully accounted for. The newly determined lidar frequencies were used for both calculations; c) A nightly averaged profile of photocounts per bin is shown with the corresponding Na density profile. The criterion of 5% Na density (thin horizontal bars) is seen to admit more range bins into the layer than the criterion of 50/25 photocounts (coarse horizontal bars) for the case of 40 photocounts per laser pulse in this night of Feb. 26, 1991.