S1-2 A High Spectral Resolution Lidar at 532nm for Simultaneous Measurement of Atmospheric State and Aerosol Profiles using Iodine Vapor Filters

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Abstract

A brief literature history leading to a High Spectral Resolution Lidar (HSRL) to simultaneously measure vertical profiles of atmospheric state and aerosol parameters is described. This working HSRL system uses a narrow band (~ 74 MHz) pulsed double YAG transmitting laser operated at 532 nm. Two iodine vapor filters are used as narrowband blocking filters in the detection system to spectrally separate the much narrower Mie (aerosol) scattering from the Doppler broadened Rayleigh-Brillouin (molecular) scattering, allowing the spectral width of the molecular scattering and atmospheric temperature to be determined. A total scattering channel that includes both the Mie and Rayleigh-Brillouin scattering is also used to determine aerosol backscatter ratio simultaneously. Using a fairly modest transmitter and receiver (Power/Aperture Product = 0.19 Wm^2) along with temperature and pressure input provided at one altitude and one time, this system could measure temperature profiles up to 15 km. Based on 12 nights of field data taken between Jan and Jun 1998, we demonstrate temperature measurement with rms variation of ~2 K over an altitude range of 2 - 5 km for a spatial resolution of 300 m and integration time of 1 hr. A brief discussion of future prospect of HSRL is also given.

Introduction

After successful measurements of aerosol distribution in the troposphere with lidars, the need for measuring aerosol and atmospheric parameters, such as temperature, was generally recognized [Shimizu et al., 1983]. Fiocco et al. [1971] demonstrated the feasibility of using a Fabry-Perot interferometer to reject aerosol scattering and of measuring temperature and backscatter ratio in the troposphere via Rayleigh-Mie scattering. Due to the strict requirement in transmitter spectral purity, a single-mode c.w. argon-ion laser was used, yielding such measurements without spatial resolution. With wide spectral separation from Rayleigh-Mie scattering, vibrational Raman scattering can be used for temperature profiling nominally with little aerosol interference [Keckhut et al., 1990]. This method however suffers 3 orders of magnitude reduction in scattering efficiency. Despite of its difficulty in separating aerosol (Mie) scattering from molecular (Rayleigh) scattering spectrally, the use of Rayleigh scattering for the retrieval of atmospheric temperatures is still very attractive. Schwiesow and Lading [1981] have attempted to reject Mie scattering with a Michelson interferometer and to measure temperature profile by Rayleigh scattering without a practical success. Rotational Raman scattering, which is ~ 2.5% efficient as compared to Rayleigh scattering but requires a moderate laser spectral purity, has also been proposed [Cooney, 1991] and applied [Cooney, 1984; Nedeljkovic et al., 1993] for temperature measurements. This technique still suffers from weak signal and from an inability to reject a large amount of aerosol scattering. Temperature measurements via Rayleigh scattering enjoyed an earlier success in the stratosphere and mesosphere where it is free from aerosol interference. In this case, a broadband laser is used to probe the profile of molecular density, from which atmospheric temperatures are calculated assuming local thermal equilibrium and hydrostatic equilibrium [Kent and Wright, 1970; Hauchecorne, and Chanin, 1980]. By monitoring both transmission and reflection signals from a Fabry-Perot interferometer tuned to reflect most of Mie scattering, the Wisconsin group was able to measure the profiles of backscatter ratio successfully [Shipley et al., 1983] and coined the name High Spectral Resolution Lidar [HSRL]. Their inability to reject all aerosol scattering in the molecular channel made temperature measurements very difficult if not impossible. The used an iodine absorption cell later improved their measurement considerably [Piironen and Eloranta, 1993].

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Our own involvement in tropospheric temperature measurements was prompted by the realization of the difficulty in optical alignment and in complete rejection of aerosol scattering using interferometers, Michelson and/or Fabry-Perot. We thus proposed the use of an atomic vapor filter that can reject aerosol scattering in excess of 30 dB without the need of critical optical alignment [Shimizu et al., 1983]. Using this concept with a barium filter, we successfully measured the backscatter ratio profile soon after such a lidar system at 554 nm was installed [Alvarez et al., 1990]. Temperature profiling proved to be much more difficult. Our implementation of a working HSRL based on atomic or molecular filter proceeded in stages as described below. Implementation of a lead filter for HSRL [Voss et al., 1994] unfortunately did not lead to an instrument for temperature measurements.

Our first stage temperature and backscatter ratios were measured using two barium atomic vapor filters in the receiver and a pulsed dye amplified single frequency dye laser tuned to 554 nm [She et al., 1992]. Although this system developed by Alvarez et al. [1993] had temperature uncertainties as large as 10 K, the potential of a HSRL for measuring atmospheric and aerosol parameters was fully demonstrated. There are several factors that led to the quoted large temperature uncertainty, the main one is attributable to the fluctuations and lack of stability in the vapor filter transmission resulting from a high operating temperatures (~700-800 K) needed to provide the necessary extinction and sensitivity to air temperature. Other problems of secondary importance resulted from manually tunig the laser frequency to the barium transition without an automatic locking mechanism, thus degrading the system stability, and the detection of un-wanted Rotational Raman scattering, thus degrading the measurement sensitivity. To improve temperature measurements over the barium system in our intermediate stage of development, Caldwell [1995] developed a prototype system at 589 nm that used one iodine vapor filter which could be controlled at a lower temperatures with better stability. He also employed Doppler-free spectroscopy to lock and tune the laser to the two preset iodine hyperfine transition lines, and inserted a Daystar filter with 100 GHz bandwidth in the receiving system to reject rotational Raman signal all together. With this system, Caldwell achieved temperature accuracy better than 5 K at 1 km with a 375 m and 82 min resolution. The main uncertainty, photon counting statistics, was the result of using a photo-multiplier that had relatively low maximum linear count rates, which limited the amount of usable transmitted laser power to no more than 20 mW without creating pulse pile-up in the receiving system for low altitudes. This gives rise to a photon-noise temperature uncertainty of 3 K at 1 km. Unlike the barium system, the measurements were not limited by the vapor filters. Both the barium system at 554 nm and iodine vapor filter system at 589 nm were operated at wavelengths that required a dye oscillator and a pulsed dye amplifier to provide the narrow bandwidth necessary for temperature measurements.

In order to complete the research that resulted in a working HSRL, we had setup and characterized a solid state transmitter operating at 532 nm for the HSRL, by determining its tuning range, tuning rate, and spectral lineshape. An all solid state laser system provides a more robust and compact transmitter that is both transportable and easier to operate for a longer time. With the new transmitter operated at 532 nm, we then measured and characterized the iodine vapor transmission properties near this wavelength, and assessed how iodine resonant absorption lines could be used to spectrally separate the molecular and aerosol backscattered signals and to measure atmospheric temperatures with good sensitivity. After both the transmitter and the receiving absorption cell were characterized as a complete system, we performed HSRL measurements in the field.

The HSRL system AT 532 nm

Since the lidar system uses the spectral information from the scattered returns and should be capable of tuning to an iodine absorption line, the laser transmitter must have high spectral resolution (~100 MHz) and be tunable over ~10 GHz. Our current lidar setup, as shown in figure 1, consists of a Lightwave model 142 cw dual wavelength laser having 50 mW of both 1064 nm and 532 nm light. The 1064 nm light is used to seed a pulsed doubled Spectra Physics YAG laser (model DCR-3A) producing the transmitted laser beam, which is tunable with near Fourier transform limited lineshape. The cw seed laser is frequency locked to an iodine Doppler-free saturated absorption line [Arie et al., 1992], with an active feedback control loop to provide an absolute frequency reference. The laser transmitter properties are summarized in Table 1. Unlike the prototype system at 589 nm that used one iodine filter and two transmitter frequencies, this system uses two iodine filters and one transmitter frequency because the YAG laser can not be rapidly frequency tuned. Therefore, an additional iodine cell and temperature controlled housing were constructed. The lidar system measures the temperature and aerosol profiles in the troposphere, thus requiring the system to handle a large dynamic range in the collected signal. The previous system required improved photon counting statistics to achieve 1 K temperature accuracy at 1 km. The new lidar system improves the maximum linear count rates to utilize all the laser power that is available (~6 W), considerably higher than that used in the system at 589 nm. More than a factor of 10 in linear photocount rate was received without saturation, allowing the photon counting errors to be significantly reduced. New photomultiplier tubes (PMT) that have a higher maximum linear count rate, along with a biaxial transmitter beam were incorporated to reduce the counts at lower altitudes and provide more counts in higher altitudes.

The detection system uses a relatively small 8-inch Cassegrain telescope, giving rise to a Power/Aperture product of 0.19 Wm^2. A Daystar filter with a FWHM of 130 GHz has been added to the system to eliminate rotational and vibrational Raman scattered light from the return signal, avoiding the need to include them in data analysis. In addition, this narrower bandwidth also allows measurements to be made at dusk and dawn. The signal is then split into three channels. Two molecular scattering channels have iodine vapor filters, along with an unfiltered channel which measures the total Rayleigh-Mie scattering are shown in figure 1. The iodine filter transmission functions have been measured, frequency scaled, and characterized for the lidar inversion to be discussed below. The two iodine filters operated at cell temperatures ~82° C and ~57° C have different transmission as a function of frequency giving two independently filtered molecular scattering signals. Even though the filters have complicated spectra, the extinction at line center is greater than 34 dB for a filter width of ~2 GHz, in the same order as the Rayleigh scattering spectral width. The laser frequency was locked to a Doppler-free feature in [Arie et al., 1992] the 1108 iodine absorption line.

The selection of the laser frequency was made from a range of frequencies that were accessible to the Lightwave 142 laser. The particular range of 10 GHz near 18787.322 cm^{-1} used in the current setup is special in that there are two absorption bands (1107 and 1108) that overlap for temperatures near the hotter iodine filter. This allows the filter width of the hotter filter to be nearly twice as wide (~ 4 GHz) as a single absorption line. This turns out to be very significant considering that it is difficult to get a single line wider than ~2 GHz in width without going to much higher cell temperature. This leads to a high measurement sensitivity of 0.42 %/K, a key factor for success of this lidar. In comparison, the measurement sensitivities for the 554 nm and 589 nm systems were, respectively, 0.26 %/K and 0.24 %/K.

HSRL Inversion Method

In response to a narrowband single frequency laser beam tuned to an absorption line of molecular iodine, the collected backscattered light is composed of several components: Rayleigh scattering, rotational and vibrational Raman scattering, and aerosol (Mie) scattering. Since the aerosols are much more massive than the molecules, the spectral broadening of the Mie scattering (~10 MHz) is much smaller than the Rayleigh (molecular) scattering (width ~2 GHz). The rotational Raman scattering spectrum is separated from the laser frequency by more than 150 GHz and is filtered by a narrow bandpass Daystar filter (130 GHz FWHM) and therefore not considered in equations below. The total scattering return, both the aerosol and molecular scattering, can be expressed as equation 1, where β_m and β_a denote the molecular and aerosol volume backscatter coefficients respectively, and where ξ, E, A, α, are the channel efficiency (including telescope overlap), total outgoing energy, telescope area, and the total extinction coefficient, respectively.

(1) $$N_t = \xi_t \frac{E}{h\nu} \frac{A}{z^2} \Delta z \left[\beta_m^{\pi} + \beta_a^{\pi}\right] e^{-2\int_0^z \alpha dz'}$$

$$N_{m,i} = \xi_{m,i} \frac{E}{h\nu} \frac{A}{z^2} \Delta z \tag{2}$$
$$\bullet \left[\beta_m^{\pi} \; f_{m,i}(T,P) \right] \; e^{-2\int_0^z \alpha(z')dz'}$$

$$\beta^{\pi} = n(T,P) \left. \frac{d\sigma}{d\Omega} \right|^{\pi} \quad \text{and} \tag{3}$$

$$f_{m,i}(T,P) = \int_{-\infty}^{\infty} R(\nu - \nu_o, T, P)\, F_i(\nu) d\nu$$

$$\frac{N_{m,1}}{N_{m,2}} = \frac{\xi_{m,1}}{\xi_{m,2}} \frac{f_{m,1}(T,P)}{f_{m,2}(T,P)} \tag{4}$$

$$\frac{N_t}{N_{m,i}} = \frac{\xi_t}{\xi_{m,i}} \left[\frac{\beta_m^{\pi} + \beta_a^{\pi}}{\beta_m^{\pi}} \right] \frac{1}{f_{m,i}(T,P)} \tag{5}$$

To obtain atmospheric state parameters, we use the iodine vapor filters as band stop filters to remove the aerosol scattering signal which is centered at the laser frequency. Equation 2 shows the lidar equation with the aerosol scattering signal removed using the iodine filter transmission function, $F_i(\nu)$. The part of Rayleigh scattering signal passed through the iodine filters is determined by $f_{m,i}$ in equation 3, where i represents two independent filters at different cell temperatures and m denotes molecular scattering. The Rayleigh scattering function, centered at the laser frequency ν_0, $R(T,P,\nu-\nu_0)$, can be determined from the model of Tenti et al. [1974] where T and P are the air temperature and pressure, respectively. Here, β_m is the product of n(T,P), the air density, and $d\sigma/d\Omega$, the differential Rayleigh scattering cross section. After filtering the aerosol signal and knowing the transmission of the iodine filters one can invert for the temperature and pressure profiles using the measured ratio of $N_{m,1}/N_{m,2}$ from the two independent molecular channels. With pressure given at one initial altitude, equation 4 determines the temperature from the measured signal ratio and density from the ideal gas law for that altitude. Then assuming hydrostatic equilibrium allows one to obtain pressure and temperature at next altitude. The iterative process propagates along the altitude axis for the determination of the profile of atmospheric state parameters. In addition, once the temperature and pressure profiles are determined, the total extinction can be deduced from equation 2 by taking the spatial derivative of the signal of one of the filtered channels. In addition, the total scattering and one molecular channel form a ratio giving the backscatter ratio as shown in equation 5. This forms a self consistent inversion method to calculate the state parameters, backscatter ratio, and extinction coefficients.

Field Measurement Results

Twelve nights of data were taken between Jan - Jun 1998 at Christman Field, Ft. Collins, CO (40.6°N, 105°W, 1569m above sea level). Most of the data taken is in the evening hours, with some nights running till sunrise. Most of the data can be compared to local Denver and/or Ft. Collins balloon sounding to assess the temperature measurement accuracy and uncertainty of our working HSRL.

A major shortcoming of the current system is the existence in the lidar temperatures of an offset of 10 K or less when compared to the sounding results, which requires a multiplicative adjustment on relative efficiencies between the two molecular channels for its correction. Though annoying, the difficulty of accurate efficiency measurement is well known and often requires calibration for its resolution in lidar data analysis and retrieval. For example, in rotational Raman lidar (Nedeljkovic et al., 1993) an entire temperature profile over the range of a balloon sounding is needed for system calibration. The needed calibration constant in our case can be determined merely by a reference (temperature) measurement at one altitude and one time during the entire night of data acquisition. That such an offset exists can be seen in Fig. 2a, where a 5 hour, 300 m averaged temperature profile measured on June 19, 1998 is shown. The fact the lidar temperature profiles with and without a calibration adjustment are nearly parallel to one another suggests that only one adjusting constant is needed. Indeed, the multiplicative factor can be determined by matching the lidar temperature and balloon temperature at one altitude. The use of this factor so determined will make the two profiles fall on the top of one another within the statistical experimental error bars as shown in figure 2b.

Table 2 gives a list of nights that HSRL data were taken. The filter transmission curves were taken periodically to ensure that they remain the same. Any time the filter cell temperatures had changed, new transmission curves were measured. All nights used three channels of data, allowing calculations of both the state parameters and the backscatter ratios. All lidar rawdata profiles collected were initially summed over three minute intervals and have 75 m range resolution. Data were later processed at different averaging times and range resolutions. Also given are the duration of the data set and whether balloon data from Denver and Ft. Collins were available for comparison. All nights have Denver balloon data and some nights also have Ft. Collins balloon data taken at Christman Field in support of these measurements. The temperature offset, which is 10 K or less, may be positive or negative. Notice that the night of April 19, our lidar temperatures are in agreement with the results of balloon sounding without needing adjustment. Obviously, the relative efficiency problem also exists between molecular and the total scattering channels. Since most nights had fairly clear weather, an estimate of the backscatter ratio offset was made by assuming unity backscatter ratio at high altitude (not within a cloud).

Both Denver and Ft. Collins balloon data are plotted for comparison. The Ft. Collins balloon was launched about one hour after the lidar data was initiated. Independent of the offset, as shown in Fig.2a, the lapse rates of the balloon and HSRL data matche well. The measured lapse rates between 5 and 10 km are 8.0 K/km and 7.9 K/km for the Ft. Collins balloon and the HSRL, respectively. That the lapse rate and tropopause altitudes are in agreement despite of offset, is true for all nights we have data, suggesting that our lidar is a working system for HSRL measurements.

Conclusion and Discussion

We have presented a brief account of our development of a HSRL at 532 nm capable of measuring vertical profiles of atmospheric state parameters (temperature, pressure and density) and optical aerosol parameters (backscatter ratio and aerosol extinction coefficient). This is made possible by the use of iodine vapor filter operating at a temperature that the absorption lines 1107 and 1108 overlap, leading to high measurement sensitivity of 0.42%/K.

Though the PA product of this working system is only 0.19 Wm^2, the HSRL can measure a temperature profile up to 15 km (resolution 300 m) with 1 hour of integration. Due a slow system instability that still exist, an additional calibration constant is needed to adjust the relative efficiencies between the two molecular channels and to obtain absolute temperatures with photon noise limited accuracy. In practice, the needed calibration constant may be provided by inputting temperature and pressure values at one altitude and one time (by independent measurement from a collocated weather tower perhaps) for one night of observation.

Further improvements on the spectral purity of the transmitting laser source and the system stability, one can hope to eliminate the need for this additional calibration and approach the theoretical HSRL performance. Since the offset problem lies in the variation of relative efficiency between two channels, it may be possible to develop a frequency agile system using an GHz acousto-optic modulator [She and Yu, 1994] so that required molecular scattering ratio for the determination of temperature may be obtained with one iodine filter. This approach, however, like in the 589 nm system, would necessarily reduce the lidar duty cycle by a factor of two, reducing the signal to noise of the measurement. Another problem that reduces the effective use of laser power is the continuum absorption that exists in iodine vapor under high operating temperatures [Hair, 1998]. Creative ways to increase iodine absorption linewidth (by pressure broadening with buffer gas, for example) without increasing filter temperature should be explored.

In addition to mean temperature profiles, our lidar was able to detect inversion layers as well as aerosol dynamical motions during the course of data acquisition. Due to the length of this article, we are unable to describe the details in experimental results, in iodine filter principle and operation, or methods of improvements. For more information, the reader should consult a recent Ph.D. thesis by J. W. Hair [1998].

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Table 1 System parameters for transmitter and receiver.

PULSED DCR-3D	
Average Power	6 Watts at 532 nm
Pulse Duration	5 ns
Divergence	0.5 mrad full angle
Pulse Repetition Rate	20 Hz
Linewidth	60 MHz

CW LIGHTWAVE MODEL 142	
Average Power	50 mW at 532 nm 50 mW at 1064 mW
Linewidth	< 10 kHz
Tuning Range	> 10 GHz
Locking Accuracy	2 MHz

DETECTION SYSTEM	
Telescope	8 inch diameter Cassegrain
PMT's	H5783P Hamamatsu
Iodine Filters (57°C, 82°C)	3.0 GHz, 4.3 GHz
Daystar Filter	1.3 angstrom FWHM
Counting Board Interface	Optech 700 MHz Multichannel Scalar Ave.

Table 2 Summary of HSRL lidar measurements.

Date (UT)	Time (UT)	Ft. Collins Balloon(#) Denver Balloon(#)	Temperature Offset (K), %	Backscatter Ratio offset %
01/14/98	5:55 - 10:32	0,2	+7K, 2.9%	-5%
01/15/98	2:30 - 11:05	0,2	+12K, 4.9%	0%
02/07/98	3:07 - 4:22	0,2	+10K, 4.1%	-2%
02/12/98	1:07 - 14:11	0,2	+6K, 2.5%	-5 %
04/01/98	3:08 - 14:11	0,2	0K, 0.0%	+5%
04/11/98	2:07 - 10:17	0,2	-9K,3.7%	0%
04/19/98	3:17 - 10:42	0,2	0K, 0.0%	-5%
04/30/98	2:28 - 8:28	0,2	+9K. 3.7%	-5%
05/14/98	2:39 - 11:31	2,2	+2K, 0.8%	<1%
06/19/98	4:17 - 10:32	1,2	-10K, 4.1%	+<1%
06/20/98	2:48 - 9:53	1,2	-7K, 2.9%	+5%

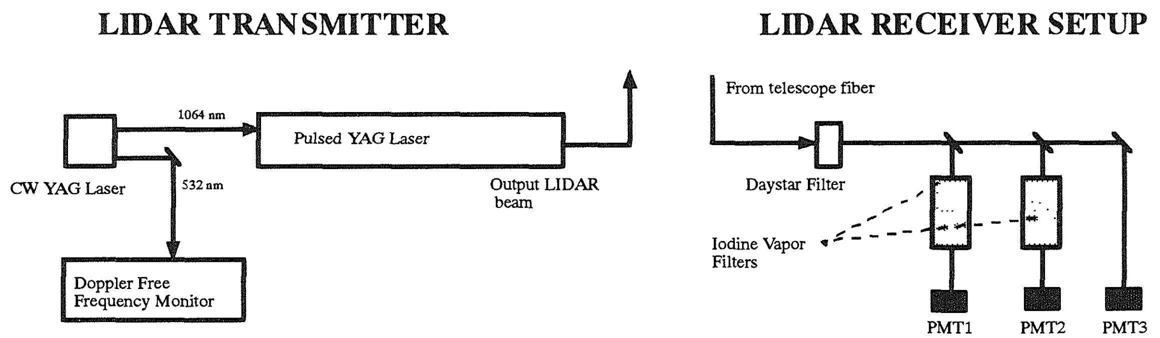

Figure 1. Schematic of the HSRL system. The transmitter system consists of a seeded pulsed YAG laser of 74 MHz linewidth. The receiver consists of two molecular and one total scattering channels.

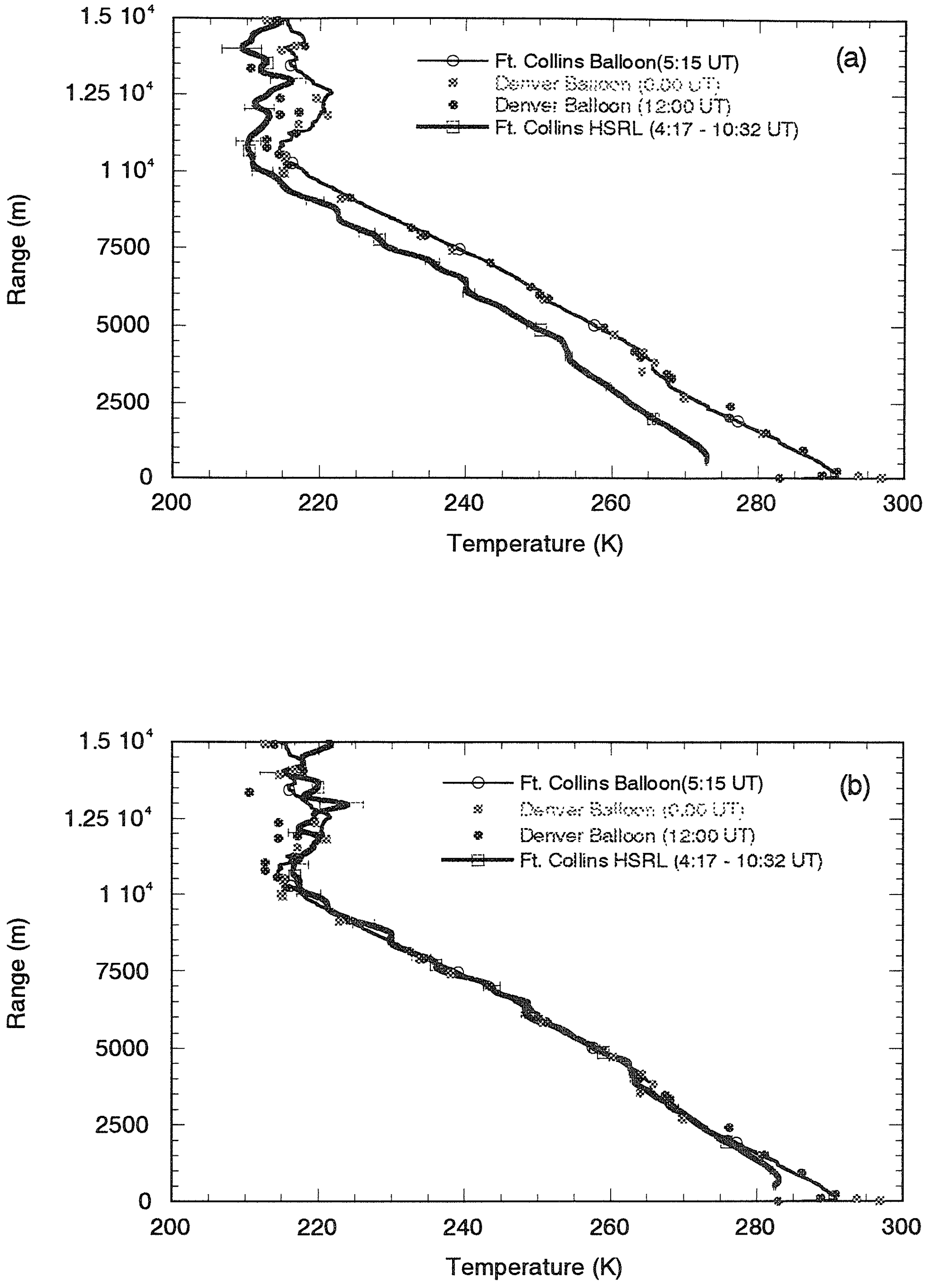

Figure 2 The HSRL 5 hour, 300 m averaged temperature profile for June 19, 1998, plotted with the Ft. Collins and Denver Balloon sondes. The error bars give the photon counting error at 1 km intervals for the HSRL data. (a). Lidar temperature profile is offset from balloon sounding. (b). If an ajustment factor is determined by matching the lidar temperature to the Fort Collins balloon temperature at one altitude and used in the data retrieval, the two profiles fall on the top of one another within the statistical experimental error bars indicated.