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LIDAR TEMPERATURE PROFILING: PERFORMANCE SIMULATIONS
OF MASON'S METHOD

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Several methods of using lasers to measure atmospheric temperature profiles
have been described.[1-4] Mason's suggestion[1] is analyzed here to assess its capa-
bilities for various lidar configurations. Temperatures are inferred from a mea-
sure of the Boltzmann distribution of rotational states in one of the vibrational
bands of O_2. Differential absorption is measured using three tunable, narrowband
pulsed lasers. The outputs of two are tuned to wavelengths at the centers of
absorption lines at either end of a particular branch in the band. The third wave-
length is in a region of no absorption; its lidar return measures only the atmo-
spheric backscatter, and therefore allows one to calculate the absorption coef-
ficients at the other two wavelengths as a function of altitude. From the ratio
of the two line absorption coefficients plus a priori knowledge of the line para-
meters, one can calculate the temperature-altitude profile.

We made computer simulations of various lidar configurations, using different
line pairs in the "atmospheric bands" of O_2. These bands ($\sim$ 630, 690, 760 nm) are
likely candidates because the line strengths are sufficient for optimum absorption
in the troposphere and stratosphere. Also, tunable lasers and photomultipliers
for the near IR have improved rapidly in recent years. Results described here
are based on the O_2 line pair giving the best performance in each situation.

We refer the reader to Schotland[5] for a discussion of differential absorption
lidar, and to Mason[1] and Heaton[4] for the expressions relating the ratio of the
absorption cross-sections to the standard line parameters:

$$\sigma_1/\sigma_2 = A_1 \exp(-A_2/T) \tag{1}$$

where $A_1 = (B_1/B_2)[(2J_1+1)/(2J_2+1)](\nu_1\gamma_2/\nu_2\gamma_1)$, and

$$A_2 = (B_o hc/k)[J_1(J_1+1) - J_2(J_2+1)].$$

The B_i are the Einstein absorption coefficients, J_i the rotational quantum numbers, and ν_i the line center frequencies; the half widths γ_i are assumed, to first order, to all have the same temperature dependence.[6] B_o is the rotational constant, h Planck's constant, c the speed of light, and k Boltzmann's constant. The ratio of cross-sections is obtained from the lidar return signals as

$$\frac{\sigma_1(\overline{R})}{\sigma_2(\overline{R})} = \frac{\ln[P_o(R)P_1(R+\Delta R)/P_o(R+\Delta R)P_1(R)]}{\ln[P_o(R)P_2(R+\Delta R)/P_o(R+\Delta R)P_2(R)]}, \tag{2}$$

where the P_o are the off-line returns and P_1 and P_2 are the on-line returns evaluated at distances R and R+ΔR. The range $\overline{R}$, at which the average cross-sections σ_i are determined, is simply $R+\frac{\Delta R}{2}$ under the usual assumptions[5] for differential absorption lidar. Note that Eq. (2) does not depend on the number density of the absorbing species; this is an important feature of this method. The number density may be obtained from one of the on-line signals once the temperature profile is known.

To estimate the sensitivity of the technique and estimate the errors and noise in a temperature profile measurement, we solve Eq. (1) for temperature,

$$T = A_2[\ln A_1 - \ln(\sigma_1/\sigma_2)], \tag{3}$$

and differentiate Eq. (3) about each variable that could contribute significant errors.

Sources of noise considered were photon statistics, background light, and a 1% signal-processing error. Photon noise was usually the major error source in the temperature determination. Only nighttime measurements are considered here because the daytime background in a practical bandwidth of 1 nm is too high for

an acceptable signal-to-noise ratio. All of the parameters in the factor A_1 in Eq. (1) are constants; therefore, any uncertainties in these parameters contribute systematically rather than randomly. This uncertainty would be less if the constants were known better, or if one were to use a simultaneous calibration of each lidar signal pulse, similar to that recently employed in a water vapor lidar.[7] Alternatively, a systematic correction could be made to the temperature profile by measuring the temperature in situ somewhere along the line-of-sight. We assumed that the variance in A_1 was 10^{-3}, an optimistic value based on what we considered would be the best obtainable values in a careful measurement of the parameters in A_1. Present data would give a variance of about 10^{-2}.

While this analysis is for a Lorentz profile(and, strictly speaking, the O_2 lines have a Voigt profile) it provides sufficient accuracy for assessing the errors and practical applications of the method, especially in the troposphere where the lineshape is nearly Lorentzian. The technique is fairly sensitive to temperature. Defining $U \equiv \sigma_1/\sigma_2$ and differentiating Eq. (1), we see that the fractional change in the ratio of the cross-sections varies with small changes in temperature as

$$\Delta U/U = (A_2/T)\ (\Delta T/T).$$

Using the $J = 1$ and $J = 19$ lines in the P Branch, B Band, and $T = 288K$, then $\Delta U/U = .0094\ \Delta T$, about a 1% change per degree. However, performing a similar calculation on Eq. (2), we find that the measurement is very sensitive to noise in the on-line signals. A 1% noise level on each signal gives $\sim 10\%$ error in the cross-section ratio as calculated from lidar returns.

The parameters used here describe realistic lidar systems, leaning towards the optimistic to allow for technological improvements that are currently underway. The transmitting laser(s) is capable of emitting 300mJ/pulse, simultaneously in each of three wavelengths, two of them narrowband to $\approx .01\ cm^{-1}$. The receiver

consists of a 1 M^2 collecting telescope and a GaAs photomultiplier. Overall efficiency of the optics is 50%, and the range resolution of the measurements is ~~determined~~ 0.5 - 2.0 km. The atmospheric model is a clear mid-latitude summer model.[8] O_2 data were taken from Babcock and Herzberg,[9] Burch and Gryvnak,[10] and Miller, Boese, and Giver.[11-13]

The first lidar configuration considered was ground-based. Errors in the temperature profile measurement are given in Figure 1 as a histogram to show each vertical range element along the profile. Shot noise (dashed line) is the major contributor to the total random error (solid line). At short range, the 1% signal-processing noise (not shown separately) limits the accuracy. This could be improved with quieter, more accurate electronics and finer digitization. Systematic errors from the uncertainty in A_1 (dotted line) may introduce a fairly constant offset of 2-3K. The optimum line pair for lower troposphere profiling from the ground up is (J = 1, J = 19) in the P Branch of the B Band ($\sim$ 690 nm). Measurement accuracy of $\pm$ 1K up to 6 km altitude with 0.5 km resolution is possible when 300 laser pulses are averaged. This is equivalent to about a 30 sec measurement for a large laser system, or 300 sec for a system more typical of the present day.

Another useful lidar platform would be an aircraft or balloon for profiling the troposphere and lower stratosphere (Figure 2). Using the same wave lengths as before, one can profile the troposphere with reasonable accuracy and vertical resolution from an aircraft at 10 km altitude, and an aircraft at 20 km can profile the lower stratosphere. Alternatively, the entire 20 km could be mapped from 20 km by utilizing weaker absorption lines in the O_2-γ Band. The laser signals are not attenuated as rapidly; hence greater penetration depth is possible, with a concomitant loss in vertical resolution and/or temperature accuracy. The receiver collecting area is decreased 10x for the 20 km platform, to simulate what a smaller aircraft such as a U-2 would be able to accommodate.

For Space Shuttle experiments, we observe an "error well", typical of satellite lidar simulations, as seen in Figure 3. Errors are large at high altitudes owing to lack of sufficient scattering and absorption to obtain strong signals and detectable absorption. As the number of scatterers and the absorption increase, the errors become smaller at lower altitudes, until the attenuation of the on-line signals becomes so great that the errors increase rapidly again. The location of this "error well" is a strong function of the absorption line strength. The choice of stronger lines goes with measuring at higher altitudes, and weaker lines with lower altitudes. Figure 3 shows what can be done using both less and more laser energy than in Figures 1-2, for the B Band measurements. For this case, improvements in accuracy by increasing laser energy come with great difficulty. Also depicted are the errors in a tropospheric profile using the γ Band and the increased laser energy, and a simulation for the A Band, which gives rather poor results in this case.

This study shows that temperature profiles using Mason's method applied to the red O_2 bands would be rather coarse when measured from a Space Shuttle lidar, given present expectations for orbital lidar systems. On the other hand, quite adequate temperature profiling in the troposphere and lower stratosphere can be carried out using reasonable lidar systems from ground-based and aircraft/balloon platforms. Recently a new O_2-based lidar method has been proposed for temperature[14] and pressure[15] profiling which holds promise for improved Shuttle measurements.

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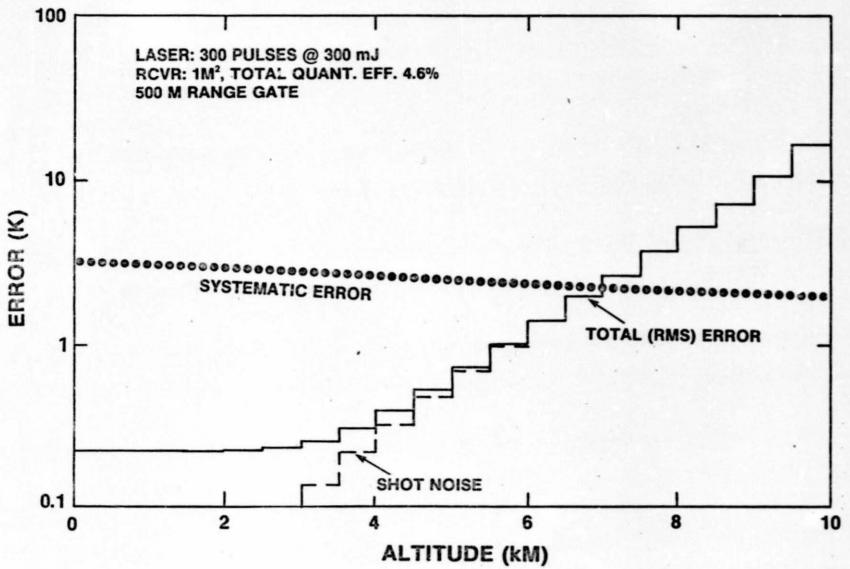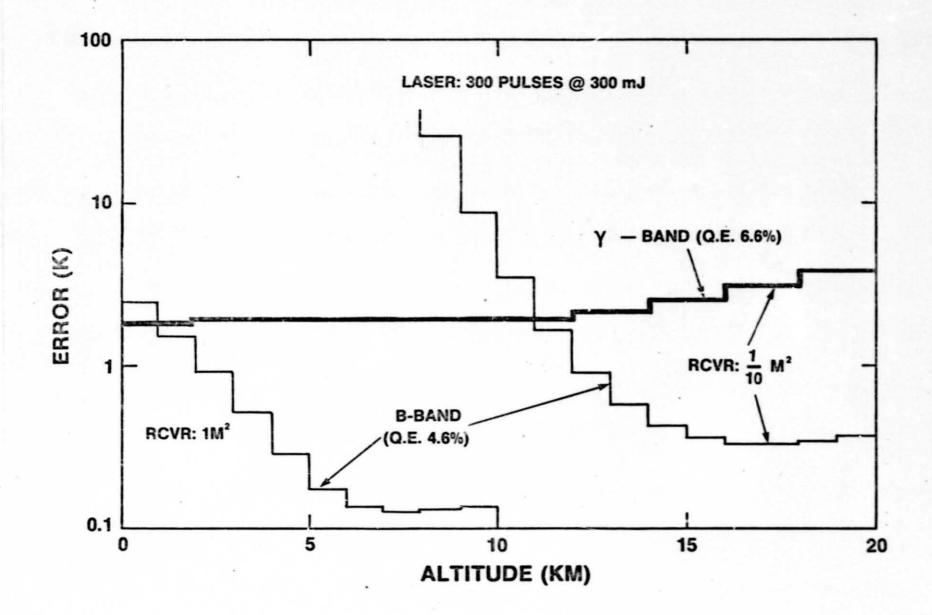
Figure Captions (Schwemmer & Wilkerson)

Figure 1.   Errors in the lidar temperature profile measured from the
                 ground, using lines J=1 and 19 in the P-branch of the O_2
                 B-band.

Figure 2.   Errors in the O_2 temperature profile measured with
                 nadir-viewing lidar in aircraft. B-band profiling
                 from 10 and 20 km (light lines) employs 1 km vertical range
                 resolution and the J=(1,19) line pair in the P-branch.
                 γ-band errors (J=1 and 17) are also shown from the air-
                 craft at 20 km (dark line).

Figure 3.   Errors in lidar temperature profiles measured from Space
                 Shuttle. The altitude of optimum accuracy increases with
                 O_2 band strength. Line pairs in the P-branch of each band
                 are J=(1,21)A; (1,19)B; (1,17)γ. A ten-fold decrease in
                 B-band accuracy is shown for a hundred-fold decrease in
                 total laser energy.

LASER: 300 PULSES @ 300 mJ
RCVR: 1M^2, TOTAL QUANT. EFF. 4.6%
500 M RANGE GATE

SYSTEMATIC ERROR

TOTAL (RMS) ERROR

SHOT NOISE

ERROR (K)

ALTITUDE (kM)

LASER: 300 PULSES @ 300 mJ

γ — BAND (Q.E. 6.6%)

RCVR: $\frac{1}{10}$ M²

B-BAND
(Q.E. 4.6%)

RCVR: 1M²

ERROR (K)

ALTITUDE (KM)