CHARACTERIZATION OF ERROR SOURCES FOR AIRBORNE AND SPACE-BASED CO$_2$ DIAL MEASUREMENTS

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ABSTRACT

Modeled Differential Absorption Lidar (DIAL) measurements of carbon dioxide (CO$_2$) column optical depths were used to evaluate error sources for airborne and space-based CO$_2$ measurements. Measurement errors associated with uncertainties in DIAL wavelengths, atmospheric temperature profiles, and atmospheric water vapor profiles were evaluated for a selected CO$_2$ line to assist in optimizing future airborne and space-based CO$_2$ measurements.

1. INTRODUCTION

The increase in anthropogenic CO$_2$ in the atmosphere is a matter of record and will most likely continue. Although CO$_2$ is widely recognized as a major contributor to global climate change, it is not easy to measure because the variations above background levels are very small [1]. This makes it extremely difficult to detect temporal and spatial trends, and yet that is what is needed on a global scale to gain a better understanding of the sources and sinks regulating the amount of CO$_2$ in the atmosphere. Global column CO$_2$ measurements from a space-based DIAL instrument have been proposed as a way to address this need. A measurement precision of about 1 part per million by volume (ppmv) or about 0.3% has been indicated as the requirement for such an instrument to measure CO$_2$ sources and sinks [2]. The DIAL measurement of CO$_2$ is sensitive to many potential errors including: the knowledge of CO$_2$ line parameters (line strength, half width, and pressure shift); knowledge of DIAL laser wavelengths; knowledge of water vapor in determining dry air density; and knowledge of temperature in determining CO$_2$ absorption cross sections [2]. Since the uncertainties in the CO$_2$ absorption line parameters can be addressed with high precision spectroscopic methods in the laboratory and are a determinable physical parameter, they are not the subject of this analysis. This paper addresses the CO$_2$ DIAL measurement errors associated with the uncertainties in the knowledge of DIAL laser wavelengths and water vapor and temperature profiles. These error sources are evaluated over a range of nominal laser wavelengths for a selected CO$_2$ absorption line by calculating mixing ratio errors using the modeled CO$_2$ optical depth variations.

2. CO2 LINE CHARACTERISTICS AND OPTICAL DEPTHS

We have tentatively selected the R24 CO$_2$ line at 15711.1110 nm (6364.9225 cm-1) as suitable for airborne and space-based DIAL measurements based on a combination of criteria including: line strength, relative insensitivity to temperature variations, and minimal absorption interference from other gases or from adjacent CO$_2$ lines [2]. Table 1 gives the parameters used in calculating the Voigt approximation to the CO$_2$ absorption line shape. All parameters are from the HITRAN 2004 database except the line strength which is from recent high-precision laboratory measurements [private communication, Chris Benner]. Because the air broadened half width for this line is 0.0698 cm-1, or 17.38 pm, we assume an off-line position of +50 pm, or more than two half widths away from the line center.

Table 1. Absorption Line Parameters

Wavelength, nm	1571.1110
Molecular line strength, cm^{-1}/molec./cm^2	1.3549e-23
Air broadened half width, cm^{-1}	0.0698
Temperature dependence coefficient	0.78
Lower-level energy E", cm^{-1}	234.0883

A weak CO$_2$ absorption line is located about –37 pm from the line center of the selected CO$_2$ line. The line

strength of the secondary line is 23 times weaker than that of the primary line, and its absorption can be accounted for by adding its wavelength-dependent cross section to that of the primary line. If this secondary line were not accounted for and an off-line DIAL wavelength were placed at -50 pm, an error of about 1.3% or 5 ppmv would result. This error would increase with even larger negative shifts from line center. As a result, operation on the positive side of the primary line avoids this problem.
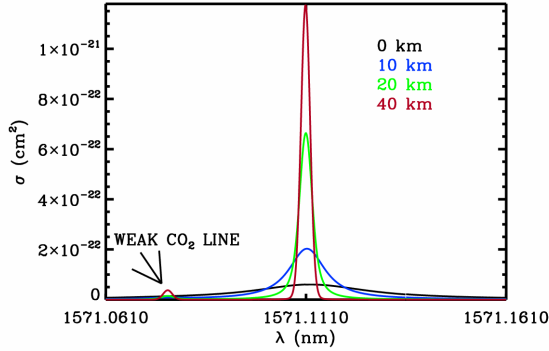

Figure 1. Absorption cross section for altitudes up to 40 km and offsets ±50 pm about line center for the primary line at 1571.1110 nm and the nearby weak line at 1571.0740 nm.

The pressure-induced absorption line shift and linewidth broadening for the primary absorption line are illustrated in Figure 2. The pressure shift is defined as the shift in the wavelength of the absorption peak when going from a vacuum to one atmosphere pressure. The impact of the pressure shift on DIAL measurements has been discussed previously [5]. We have used the HITRAN 2004 value of 1.4 pm shift per atmosphere for this primary absorption line in our calculations.
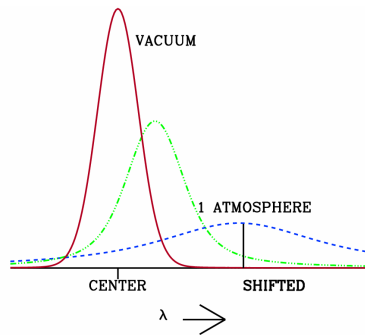

Figure 2. Concept of absorption line pressure-induced wavelength shift and line broadening when going from vacuum to 1 atmosphere pressure. Note that the line width and pressure shift are not to scale.

The absorption cross section profiles for the selected line at line center and several side-line positions are shown in the top of Figure 3, and their corresponding optical depth weighting functions from Eq. (1) are shown at the bottom. The weighting functions show the altitude-

dependent sensitivity of the column optical depth measurements. We compute the differential optical depth weighting function as

$$W = \delta\tau_{on\,/\,off} / \delta z \qquad (1)$$

where $\delta\tau_{on/off}$ denotes the net optical depth between on and off-line absorption across a vertical bin size of δz. For relative comparison purposes, W is then normalized to 1.0 at its maximum value to give W' for the normalized weighting function at any given wavelength. The mid-latitude summer model atmosphere from the AFGL profiles of temperature and pressure from 0 – 120 km [3] is used in these calculations. The line center has a broad weighting function with most of the column optical depth coming from the surface to about 20 km, while the side-line measurements at +10 and +20 pm offsets have the most sensitivity in the lower troposphere.
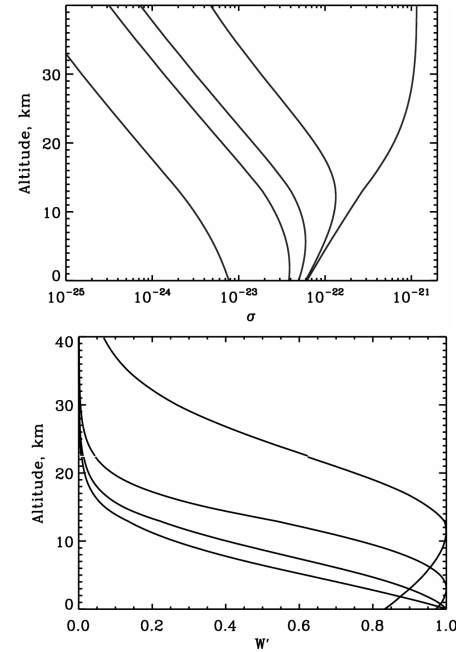

Figure 3. The top graph shows absorption cross section profiles and the bottom graph shows the normalized altitude-dependent, differential optical depth weighting functions (W') that were calculated from the difference cross sections between on- and off-line absorption and assuming a constant 375 ppmv CO_2 mixing ratio. From right to left the profiles are for line center at low pressure (LC), +5, +10, and +20 pm offsets from LC and the leftmost cross section in the top graph is for the off-line at +50 pm.

3. EVALUATION OF ERROR SOURCES

Unless otherwise specified, the US standard atmosphere AFGL profiles of temperature and pressure from 0 – 120

km [3] were used to compute the absorption cross sections and the model CO_2 profile. The latter is represented as a constant fraction of the molecular number density based on 375 ppmv. The total 1-way optical depth of CO_2 is calculated as

$$\tau = \int_{z0}^{z} \alpha(z) n_{co2}(z) \delta z \qquad (2)$$

where $\alpha(z)$ is the absorption cross section, n_{co2} (z) is CO_2 number density, and δz is the vertical bin size. In the error analysis the fractional change in the total 1-way optical depth is multiplied by the assumed CO_2 mixing ratio to estimate the error in the CO_2 mixing ratio (ppmv). We use these simulated optical depths from either airborne or spaced-based platform altitudes to evaluate the previously listed error sources.

3.1 Wavelength knowledge

To evaluated the impact of laser wavelength uncertainties on the CO2 measurement errors, we compared the change in optical depth associated with a desired laser wavelength with the optical depth associate with the actual laser wavelength which is shifted from the desired wavelength by the uncertainty in the wavelength knowledge or stability. We use the optical depth at a given wavelength and one calculated at a small shift from that wavelength to evaluate the error caused by the uncertainty in wavelength knowledge or stability. Figure 4 shows the errors generated by wavelength uncertainties of different amounts at different wavelength positions across the candidate primary absorption line. We see that the impact of wavelength uncertainty is at a minimum near line center, but it is the largest when only slightly off line center by about 5 pm. For example, a 0.01 pm error in the wavelength, when at 5 pm from line center, gives about 0.5 ppmv relative error in the DIAL column measurement. As can be seen in the figure, these errors only decrease slowly at larger offset wavelengths.
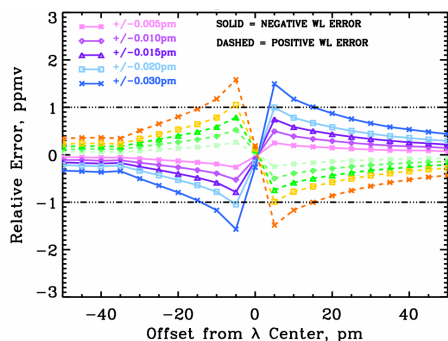

Figure 4. Error in DIAL column CO_2 for wavelength uncertainties of 0.005 to 0.03 pm. Note slight asymmetry due to pressure shift.

3.2 CO_2 mixing ratio dependence on water vapor knowledge

Knowledge of the amount of water vapor in the column is required to derive the desired dry CO_2 mixing ratio. To determine the error that would result from not including humidity information, we use radiosonde profiles from a relatively moist (RH about 40% above 2 km) and a dry (RH about 20% above 2 km) case and calculate the error from using total molecular density instead of dry molecular density when simulating the DIAL CO_2 from an aircraft altitude of 12 km. As seen in Table 2, the moist case produced significant errors for all wavelengths, while the dry case errors are small at the center line and grow more significant using side-line measurements. This source of error can be reduced by an order of magnitude by obtaining water vapor information with an accuracy of 10% or by deriving the dry air density directly using other methods.

Table 2. Relative mixing ratio errors (ppmv) due to lack of humidity information for a moist and dry case

Wavelength	Center	5 pm	10 pm	15 pm
Moist	1.64	1.57	2.13	1.78
Dry	0.23	0.31	0.52	0.87

3.3 Temperature sensitivity

In the DIAL measurement of CO_2 it is necessary to choose absorption lines that are relatively insensitive to variations in atmospheric temperature. This is done so that uncertainty in the knowledge of the local temperature will not produce significant errors in the DIAL measurement. Browell et. al. [4] showed that this error can be estimated from the percent change in the absorption cross sections due to a 1-K difference in temperature at a given altitude. For the line center position near the surface, this gives a 1-K temperature sensitivity for the CO_2 number density of 0.15% or 0.56 ppmv. To evaluate the impact of the temperature measurement uncertainty on the column CO_2 measurements, we obtained a set of temperature profiles based on NWP analysis and forecast fields for three latitude regions (polar, mid-latitude, and tropical) where each latitude region contained a truth profile and an ensemble set of perturbed profiles. The perturbations represent the error characteristics of space-based retrievals for that latitude region. Figure 5 shows the average temperature profile for each latitude region with the perturbations represented by the average standard deviation given in 5-km altitude bins.
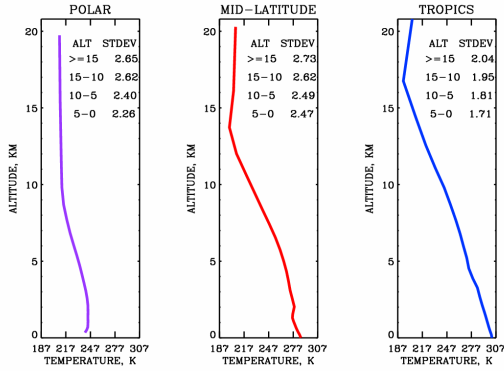
Figure 5. The average temperature profile for each latitude region with the perturbations represented by the average standard deviation given in 5-km altitude bins.

The optical depths for the true and perturbed temperature profiles were calculated, and the standard deviation of the optical depths for the perturbed temperature profiles was calculated for each region. The standard deviation of these optical depths was converted to an equivalent error in the CO_2 measurement using the relationship $(\sigma_{\tau perturbed}/\tau_{truth})*375$. As seen in Figure 6, for this particular CO_2 absorption line the on-line optical depths show the error is least at about 10 pm offset from line center for all latitude regions.
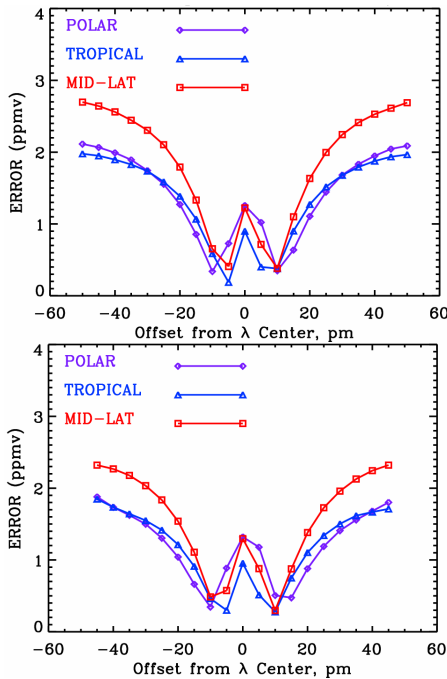

Figure 6. Relative temperature errors in CO_2 measurements for on-line wavelength only (top) and for combination of DIAL wavelengths (off-line constant at +50 pm) (bottom) for three latitude regions.

4. DISCUSSION

This paper discussed the background for the modeling of CO_2 column measurements from airborne and space-based platforms and the sensitivity of those measurements to errors in the knowledge of laser wavelengths, atmospheric water vapor, and atmospheric temperature. These results can be used to help estimate the error budget for high sensitivity DIAL column measurements from aircraft and space and to help optimize the various trade-offs associated with the development of such a system.

5. REFERENCES

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