

**Title of Investigation:**

**Atmospheric CO<sub>2</sub> Profiling Using Raman Lidar**



**Principal Investigator:**

**Dr. David N. Whiteman (Code 613.1)**

**External Collaborators:**

**Dr. Igor Veselovskii (University of Maryland-Baltimore County)**

**Initiation Year:**

**FY 2004**

**Aggregate Amount of Funding Authorized in FY 2003 and Earlier Years:**

**\$0**

**FY 2004 Authorized Funding:**

**\$30,000**

**Actual or Expected Expenditure of FY 2004 Funding:**

**Grant: \$30,000 to Dr. Igor Veselovskii**

**Status of Investigation at End of FY 2004:**

**Proposed for extension by Director's Discretionary Fund (DDF), but was not funded**

**Expected Completion Date:**

**Unfunded**

**Purpose of Investigation:**

Carbon is a fundamental component of life. Due to the combination of the use of carbon-based fuels and the reduction in photosynthesis due to the clearing of land, concentrations of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) are now higher than they have been for more than 100,000 years. These increases in "greenhouse gases" have important consequences for Earth's climate. Models now agree to the likelihood of global warming.

To understand atmospheric processes relating to CO<sub>2</sub>, new space-borne measurement systems are needed. However, as space-based systems are developed, it makes sense to pursue as well attractive ground-based technologies that can help improve our understanding of the carbon cycle. We can then use this understanding to validate space-borne measurements of CO<sub>2</sub> as they are developed.

Therefore, the purpose of this activity is to investigate the use of laser remote sensing to quantify the behavior of CO<sub>2</sub> in the atmosphere. In particular, we used a technique known as Raman lidar. With this technique, we use a laser to excite atmospheric molecules in a process known as Raman scattering. The signal is received by a telescope and processed by wavelength selective optics.

## FY 2004 Accomplishments:

During the first year of an intended 2-year research activity, we designed and procured detection optics and electronics required for the CO<sub>2</sub> Raman lidar measurements. A CO<sub>2</sub> Raman lidar system was constructed in the Code 613.1 Raman lidar laboratory using new components and other laboratory assets, including the laser and the telescope receiver. A series of measurements of CO<sub>2</sub> mixing-ratio measurements were performed using this setup. Figure 1 shows the comparison of model predictions of Raman lidar profiles of atmospheric molecular nitrogen and CO<sub>2</sub> and actual measurements performed on September 3, 2004. The averaging time was 20 minutes for these measurements. The measurements agree with the model predictions above the altitude of approximately 3 km, where the lidar overlap function, which is not properly simulated by the model, influences the data. The model's agreement and the actual measurement in the far field confirm the model predictions that 1 parts per million (ppm) measurements are possible in the lower troposphere using extended averaging.

Figure 1. A comparison of model predictions of molecular nitrogen and carbon dioxide with measurements of these quantities performed on September 3, 2004 from the Code 912 Raman lidar laboratory in the Earth Sciences Building. The agreement of the model predictions and the measurements in the far field validate the model predictions. The near-field disagreement is due to an incorrect specification of the lidar overlap function in the numerical model.

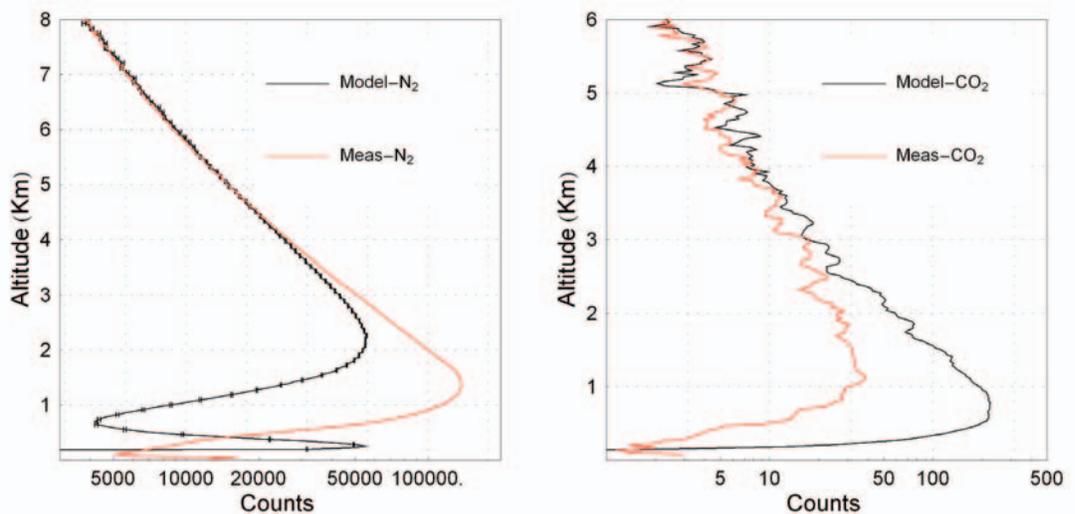
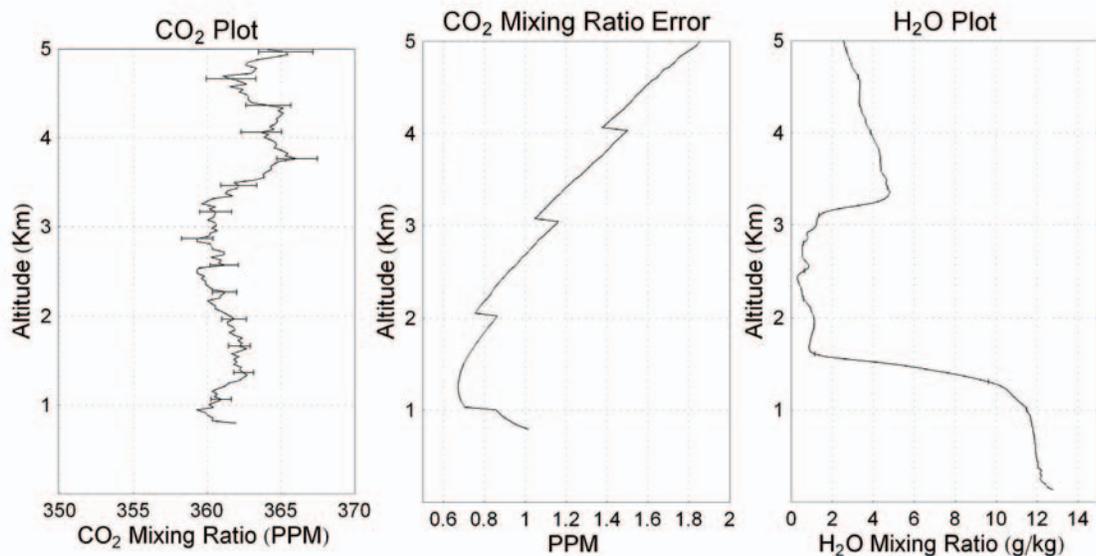


Figure 2. (Left) CO<sub>2</sub> mixing-ratio profile made over a 3-hour period on the night of September 19, 2004. The calibration has been chosen so that mean values in the lower troposphere were ~360 ppm. (Middle) Assessment of the random error of the CO<sub>2</sub> mixing-ratio measurement indicating that measurements even into the free troposphere are possible with precision less than 2 ppm using a 3-hour average. (Right) The simultaneously measured water vapor-mixing ratio profile. Note the positive correlation of CO<sub>2</sub> and H<sub>2</sub>O above 3 km. The cause of this is unknown.



After successfully demonstrating agreement between the model predictions and the measurements, we took 3 hours of Raman lidar measurements on September 19, 2004. Simultaneous measurements of CO<sub>2</sub> and H<sub>2</sub>O mixing ratios were acquired. The plot of these measurements is shown in figure 2.

The calibration constant for the CO<sub>2</sub> measurements shown in the figure was chosen to yield ~360 ppm near the top of the boundary layer. These measurements, therefore, are useful only for gauging the precision that is possible with a Raman lidar measurement. The middle panel shows that with a 3-hour average, the precision of the measurements is less than 1 ppm up to nearly 3 km and less than 2 ppm to 5 km. The third panel shows the simultaneous measurement of water vapor-mixing ratio using the same Raman lidar system. This constitutes what we believe to be the first simultaneous active remote-sensing measurements of CO<sub>2</sub> and water vapor-mixing ratio. The precision of the CO<sub>2</sub> validates the model predictions and justifies that further research be performed to assess the error sources of the measurements and perform a proper calibration of the measurement. This is the work that was proposed as a second-year extension of this activity.

### **Planned Future Work:**

The research proposed to extend this activity is designed to assess the full-error budget of the Raman lidar CO<sub>2</sub> measurement capability. To accomplish this, systematic error sources need to be quantified and their influence on the total-error budget of the measurement quantified. Systematic errors due to possible interference from several sources have been identified including: 1) rotational Raman lines from molecular oxygen; 2) fluorescence of optics or atmospheric aerosols; and 3) the lidar system overlap function. A full-error propagation will be performed to quantify the magnitude of any systematic error sources that are found to be significant and experimental techniques will be developed to minimize their influence. Following development of an optimized measurement technique, the full-error budget of the actual measurements will be assessed.

### **Criterion for Success:**

The criterion for success of this project is the demonstration of a fully calibrated measurement of CO<sub>2</sub> including an assessment of all systematic errors with total error budget in the range of 1-2 ppm. We have only demonstrated that the Raman lidar technique has sufficient precision to meet the error-budget requirement. The work that remains is the more difficult assessment of all remaining potential error sources. What makes this project risky is the possibility that one of these sources of systematic error will cause the total error budget to exceed acceptable levels.

### **Summary:**

We have validated the predictions of a numerical model, which indicate that Raman lidar can measure atmospheric CO<sub>2</sub> with sufficient precision to quantify CO<sub>2</sub>. NASA has major activities in the retrieval of CO<sub>2</sub> from such sensors as the AIRS (Atmospheric Infrared Sounder) instrument on Aqua. Also, other instruments for quantifying CO<sub>2</sub> from space are currently under development. Ground-based systems are both closer to the source of CO<sub>2</sub> variation and quicker to develop. They are, therefore, useful for improving CO<sub>2</sub> modeling and validating space-borne CO<sub>2</sub> measurements when they are available. Therefore, the Raman lidar capability shown in this study can be used to address these NASA needs.