END-TO-END TESTBED FOR RAPID ANALYSIS OF LASER REMOTE SENSING DATA AND APPLICATION TO FLIGHT DATA IN PREPARATION FOR ASCENDS

T. Scott Zaccheo*, Hilary E. Snell*, Jeremy Dobler†, Michael Dobbs†, Edward Browell+
and Berrien Moore‡

**AER, Inc, Lexington, MA 02421-3126, †ITT Corporation, Fort Wayne, Indiana 46801, +NASA Langley Research Center, Hampton, Virginia 23681, ‡Climate Central, Inc., Princeton, New Jersey 08542*

1. INTRODUCTION

This work describes the design and use of an extensible testbed developed to provide end-to-end simulation and analysis of laser-based remote sensing systems. This testbed provides a graphical user interface (GUI) based set of tools for simulating mission performance, and a modular framework that facilitates the comparison of measured data from prototype/operational instruments with other measurements and modeled results. This framework provides standardized interface approaches for combining community line-by-line radiative transfer (RT) models with atmospheric state information obtained from historical databases and *in situ* measurements. In the examples presented in this work, the line-by-line RT model LBLRTM was integrated with profiles obtained from historical databases and balloon and aircraft-based measurements. Using a comprehensive RT modeling approach not only provides information about the primary absorption feature, but also the impact of other trace gases on the measurements.

Our presentation focuses on the utility of the testbed in the analysis of aircraft flight data acquired using a fiber laser-based instrument designed and developed jointly by ITT and NASA Langley Research Center (LaRC) to measure carbon dioxide (CO_2) column amounts. Surface/atmospheric temperature, moisture and pressure information was obtained from rawin/radiosonde launched in conjunction with the flight campaigns or as part of national/international networks. In addition, CO_2 profile data were obtained from coincident *in situ* measurements collected by LaRC. Using this data we present measured differential optical depths for several configurations of the instrument and the corresponding model results. We also illustrate how our analysis tools allow for error estimation due to uncertainties in the atmospheric state and an assessment of a first-order correction designed to minimize the differences between measurements and modeled results. This correction is used to account for terms such as instrument calibration biases and uncertainties in spectral knowledge.

2. OVERALL DESIGN

The testbed is designed to provide a single user-configurable software architecture that can be used during the design, development and implementation lifecycle of an atmospheric remote sensing system. We have applied this general technology to the development of several applications for assessing the performance of remote sensing systems currently under development including those designed to measure a variety of trace gases such as mapping global CO_2 concentrations. The general flow for this testbed is illustrated in Figures 1 and 2. Figure 1 illustrates the simulation processing stream and Figure 2 shows the aircraft flight analysis testbed process flow. The two processing streams are incorporated into a single user application which contains many common modules that are employed by both processes.

2.1. Simulation Design

In simulation mode, the input atmospheric profiles can be selected from various sets generated using numerical weather prediction (NWP) data, the Thermodynamic Initial Guess Retrieval, version 3 (TIGR-3) dataset or European Centre for Medium-Range Weather Forecasting (ECMWF) profiles. These atmospheric state profiles are created using a process that employs a covariance matrix computed from long-term statistical differences between cloud-free NWP analysis and 6-hour forecast profiles. The intent is to capture the correlations associated with the uncertainty in the atmospheric state. A test profile set is constructed by specifying a mean or set of mean profiles. These profiles are then perturbed by adding correlated errors derived from the

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[1] *Corresponding author address:* T. Scott Zaccheo, AER, Inc., Lexington, MA 02421-3126; e-mail: szaccheo@aer.com

covariance matrices to constrain the atmospheric variability in a physically consistent manner. This gives a realistic measure of the profile variability for the specified variance. Note that the number of profiles used for any given simulation is a trade-off between the overall variability and required calculation time.

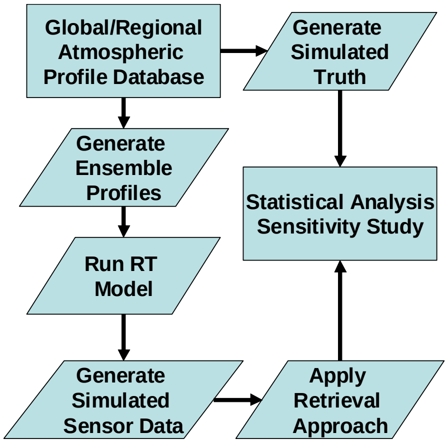

Figure 1: **Flow diagram of a sensor simulation testbed that combines simulation-based performance assessment tools with analysis of pre-flight test data**.

In the standard simulation mode, the selected profiles are used in conjunction with radiative transfer (RT) modeling techniques. Currently the testbed uses LBLRTM (Clough, 2005) for calculation of monochromatic optical depths (OD) on a per-layer basis, to compute the path transmittances. The use of layer ODs over a relatively wide spectral region provides flexibility (and computational savings) for variations in sensor geometry parameters including view angle and aircraft/ground pressure altitude, and sensor wavelengths without having to re-compute the ODs.

These simulations can be used directly to provide sensitivity analyses of potential sensor configurations or in conjunction with other satellite orbit simulation tools such as those designed to assess the impact of global cloud cover on an operational instrument or the impact of such measurements on regional modeling of CO_2 dynamics (Zaccheo, 2008).

2.2. Instrument Analysis Design

In the instrument assessment mode, *in situ* upper air data are ingested from program specific rawin/radiosondes or automatically obtained from NOAA and other sources via standard network protocols. These atmospheric state data are then combined with *in situ* measurements of the vertical CO_2 concentration obtained in flight to provide a vertically consistent view of the atmospheric temperature, moisture and CO_2 concentrations over the targeted flight track. Using aircraft position information to determine sensor pointing, this set of vertical profiles is used to compute a set of user-defined error assumptions via the RT modeling tools described above. The result is an ensemble simulation of potential observed radiances and/or measured ODs for a given flight track or flight track segment.

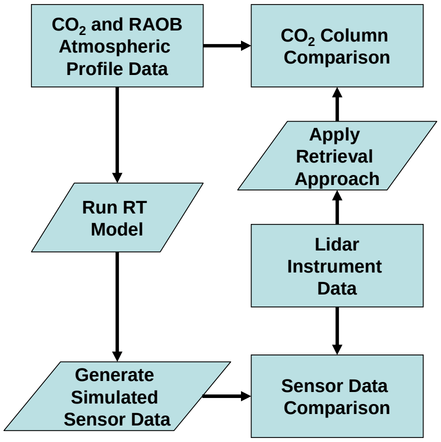

Figure 2: Flow diagram of a measurement analysis testbed that combines RT-based simulation tools and *in situ* measurements to provide performance assessment of flight test data.

The resulting simulated values can then be directly compared to differential laser absorption measurements and used in the retrieval algorithm to estimate and compare simulated retrieved CO_2 column amounts with those derived from the directly measured CO_2 concentrations. As part of this simulation process, the user may specify a set of error terms that enables not only the computation of average or most-likely RT-based estimates of differences in OD given the aircraft location and a sampled atmospheric state, but also an estimate of the error bounds on these mean values. The current testbed enables the user to specify uncertainties in vertical CO_2 concentrations, wavelength knowledge and observation path length. Errors in vertical CO_2 concentrations describe natural variation across the flight path as well as uncertainties between the lowest measurement level and the surface. Wavelength uncertainties represent differences between measured laser wavelengths and actual operating frequencies. Variations in wavelength at the peak or trough of an absorption feature have only a nominal impact on the measurement difference. However, variations in wavelength for channels along the side of an absorption feature may have a significant impact on differential absorption. Errors in path length caused by knowledge of viewing angle and changes in topography are emulated via changes in surface pressure. In this analysis environment, the path length is specified as a function of atmospheric pressure at the observer, the surface pressure and an estimate of viewing angle.

3. APPLICATION

The tools described above were designed, developed and used to perform preliminary analyses of a CO_2 laser system for channel selection as well as the analysis of aircraft instrument performance. In the example described below, data from an ITT-developed multi-channel trace gas laser absorption system (Dobbs and Dobler, 2008), a commercial laser altimeter and GPS instrumentation, were ingested into the testbed framework, via custom interfaces, temporally collocated with each other and with both model results based on aircraft GPS/altimeter information and collocated *in situ* vertical temperature, moisture and CO_2 concentration information. The coincident vertical temperature and moisture data were obtained from rawin/radiosondes launched from ground sites during the flight, and the vertical CO_2 concentration measurements were obtained via planned spiral maneuvers during flight. This process not only provides an integrated method for analyzing field data, but also compares the measured values with collocated *in situ* measurements and model-based expectation.

The flight data described in this work was acquired during 11 flights in September and October of 2008. These flights consisted of approximately 100 segments over various terrain including both land and coastal waters in and around the Suffolk, VA area. The data shown in Figures 3, 4 and 5 illustrate typical RT calculations and comparisons between *in situ* measurements, laser measurement data and model results developed using the testbed described above. Figure 3 shows a collection of RT-based OD estimates computed from local upper air data and two independent *in situ* CO_2 profiles acquired during a typical flight. The toolbox performs multiple RT calculations for each flight segment depending on aircraft GPS altitude and instrument viewing geometry. The curves shown in Figure 3 denote the modeled ODs for the 1.0 cm^{-1} region centered around 5365.0 cm^{-1} for every 1 meter variation in aircraft-to-ground path length. After computing this set of OD curves, the testbed constructs a differential OD estimate for user selectable time intervals along a selected flight path. In the example shown in the figures below, the nominal wavelength sample positions are indicated by the vertical lines labeled 0-2. These lines show the position of the laser center-line position (line 0), the secondary off-line position (line 1) and the primary off-line position (line 2). A typical set of resulting measurement channel differences is shown in Figure 4. The solid blue lines are the modeled primary off-line minus center line OD differences constructed from data in Figure 3, while the red line shows the measured differences of the selected flight segment. The dotted blue lines show the possible estimated extremes given user defined uncertainties in knowledge of surface CO_2 concentrations, laser wavelength and surface height.

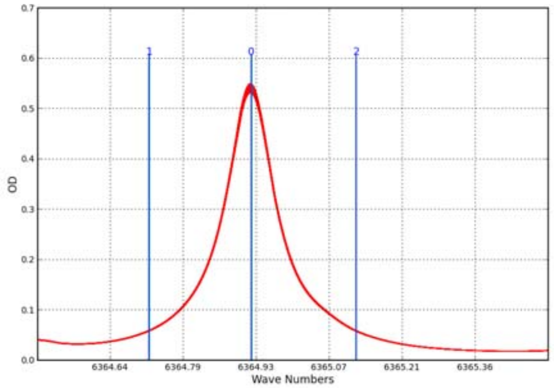

Figure 3: **Sample RT calculations for various altitudes and atmospheric conditions along a sample flight segment. Vertical lines denote nominal wavenumber values for each of the three laser channels. 0) Line center position, 1) Primary off-line position and 2) Secondary off-line position.**

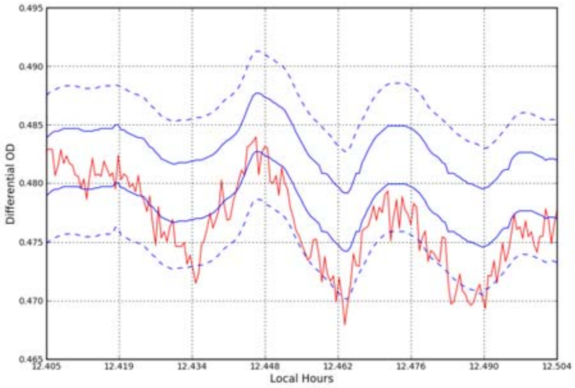

Figure 4: **Measured and modeled OD differences between primary off- and center-line. Red line shows the measurements, and solid blue lines denote the modeled OD differences for two independent *in situ* measurements of CO_2 column amount. Dotted blue lines show possible min/max extremes due to uncertainities in surface CO_2 values, wavelength knowledge and terrain height.**

In these examples a ±2ppm error in surface CO_2, a ±0.4 pm error in wavelength knowledge (within instrument measurement error) and ±2 mbar error in surface pressure (equivalent to ~30m change in vertical path length) was used to construct the error bars. The most notable features demonstrated in this figure is that the measured values fall within the modeled extremes and the modeled values track the measured variations in ODs due to changes in aircraft altitude both in amplitude and periodicity.

In addition to differential ODs, the CO_2 and dry air number densities for the column between the surface and the aircraft are also estimated as part of this testbed modeling calculation. These values were then used in combination with the measured differential ODs to estimate column CO_2 using a standard approach (Zhao, 2000) and modified for the case of a total column measurement. The CO_2 column estimates for the example flight sections are shown in Figure 5 along with the corresponding error estimates and the column values derived from the *in situ* data. There is little or no variation in derived *in situ* column amounts since both are computed from spatially invariant profiles whose column values vary only slightly if at all as a function of aircraft altitude, i.e. CO_2 is well mixed. The measurement estimates nominally fall within the measured values and vary as expected as a function of aircraft latitude/longitude position.

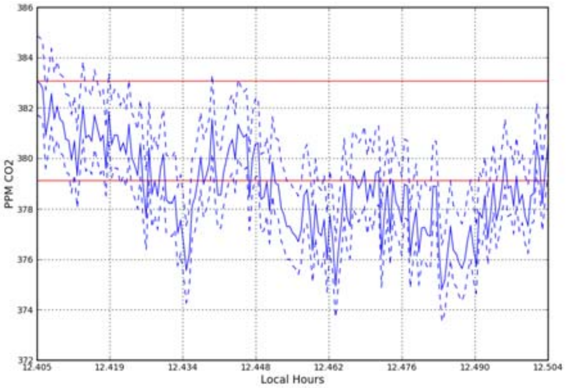

Figure 5: Measured and retrieved column CO_2 in ppms for a sample flight segment. Solid red lines show the CO_2 column amounts computed from *in situ* measurements. The solid blue lines denote retrieved values from laser absorption measurements, and the dashed blue lines illustrate potential min/max estimated from uncertainties in laser wavelength.

4. SUMMARY

In this paper we have outlined the design and use of an extensible testbed for simulation and analysis of laser-based remote sensing data. This testbed uses standard interfaces to enable the addition of modules as more complex simulations are required as part of the sensor design or data analysis process. We have demonstrated the utility of this system through its application to the development of a laser-based system for the measurement of column CO_2 in support of concept studies for ASCENDS (http://decadal.gsfc.nasa.gov/ascends.html).

5. REFERENCES

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