

# COMBINED 2- $\mu\text{m}$ DIAL AND DOPPLER LIDAR: APPLICATION TO THE ATMOSPHERE OF EARTH OR MARS

UPENDRA N. SINGH, GRADY J. KOCH, SYED ISMAIL, MICHAEL J. KAVAYA, AND JIRONG YU

*NASA Langley Research Center, MS 468, Hampton, VA 23681, USA*

SIDNEY A. WOOD AND G. DAVID EMMITT

*Simpson Weather Associates, Inc., 809 E. Jefferson St. Charlottesville, VA, 22902 USA*

## ABSTRACT

A concept is explored for combining the Doppler and DIAL techniques into a single, multifunctional instrument. Wind, CO<sub>2</sub> concentration, and aerosol density can all be measured. Technology to build this instrument is described, including the demonstration of a prototype lidar. Applications are described for use in the Earth science. The atmosphere of Mars can also be studied, and results from a recently-develop simulation model of performance in the Martian atmosphere are presented.

## 1. Introduction

2- $\mu\text{m}$  lidar technology has been in use and under continued improvement for many years toward wind measurements. But the 2- $\mu\text{m}$  wavelength region is also rich in absorption lines of CO<sub>2</sub> (and H<sub>2</sub>O to a lesser extent) that can be exploited with the differential absorption lidar (DIAL) technique to make species concentration measurements.<sup>1</sup> A coherent detection receiver offers the possibility of making combined wind and DIAL measurements with wind derived from frequency shift of the backscatter spectrum and species concentration derived from power of the backscatter spectrum. A combined wind and CO<sub>2</sub> measurement capability is of interest for applications on both Earth and Mars.

## 2. Lidar Design

The lidar technology is based on advances in high-energy 2- $\mu\text{m}$  laser technology.<sup>2</sup> Progress has included demonstration of pulse energy as high as 1-J. A double-pulse format has been shown, useful for DIAL in which the wavelengths within the doublet are switched from on-line to off-line. Fine control of wavelength has been achieved in stabilizing the laser to absorption line center or the side of the absorption line.

A critical area specific to the use of solid-state lasers is the reliability and space qualification of the pump laser diodes (LD). An Independent Laser Review Panel, which was assembled by NASA to assess the status of lasers for space applications, recommended that NASA address this issue, which became an important objective of the NASA Laser Risk Reduction Program (LRRP). Under LRRP, a sophisticated LD characterization and lifetime testing facility was established. Measurements of existing and novel LDs have been performed, and new architectures for LDs have been conceived, fabricated and tested, leading to dramatic improvements in heat removal. This bodes well for longer

lifetime systems. Collaboration is ongoing with industry to ensure the availability of LDs for NASA space lidar missions.

A third technology asset is in the detector and receiver portion of the lidar system. Under LRRP, advancements in the detector/receiver subsystem have been made for coherent detection of light. Designs have been implemented of an integrated receiver package that offers higher SNR, elimination of wasted local oscillator laser power, and robustness of monolithic packaging.

A diagram of an implementation of the combined Doppler and DIAL system is shown in Figure 1. The heart of the lidar is a diode-pumped crystal of Ho:Tm:LuLiF in a ring resonator. A pair of continuous-wave (CW) lasers are alternated to serve as an injection seed source for the pulsed laser, a local oscillator for heterodyning, and as a frequency reference. Before being introduced to the pulsed laser cavity, the injection seed beam is passed through an acousto-optic modulator to create a frequency shift of 105 MHz. Such an offset sets an intermediate frequency between the local oscillator and pulsed laser output. To ensure a single-frequency pulsed output by the injection seeding process, the pulsed laser cavity is actively matched to the frequency of the injection seed by a ramp-and-fire technique.

DIAL requires alternating laser pulses at two different wavelengths, hence there are two CW lasers that are alternately switched into use. A fiber-coupled electro-optic switch is used to select the laser in use, with switching controlled by a logic signal. Switching is synchronized with double-pulse operation of the laser in which the laser is fired twice during one pumping cycle to create pulses separated by about 200  $\mu\text{s}$ . This doublet is repeated at a 5 Hz rate with the wavelength switched between pulses to create the first pulse on line and the second pulse off line. The on-line CW laser is actively locked to a line center by referencing to a sample of CO<sub>2</sub> in a gas cell by a frequency modulation technique.

The pulsed laser output is transmitted to the

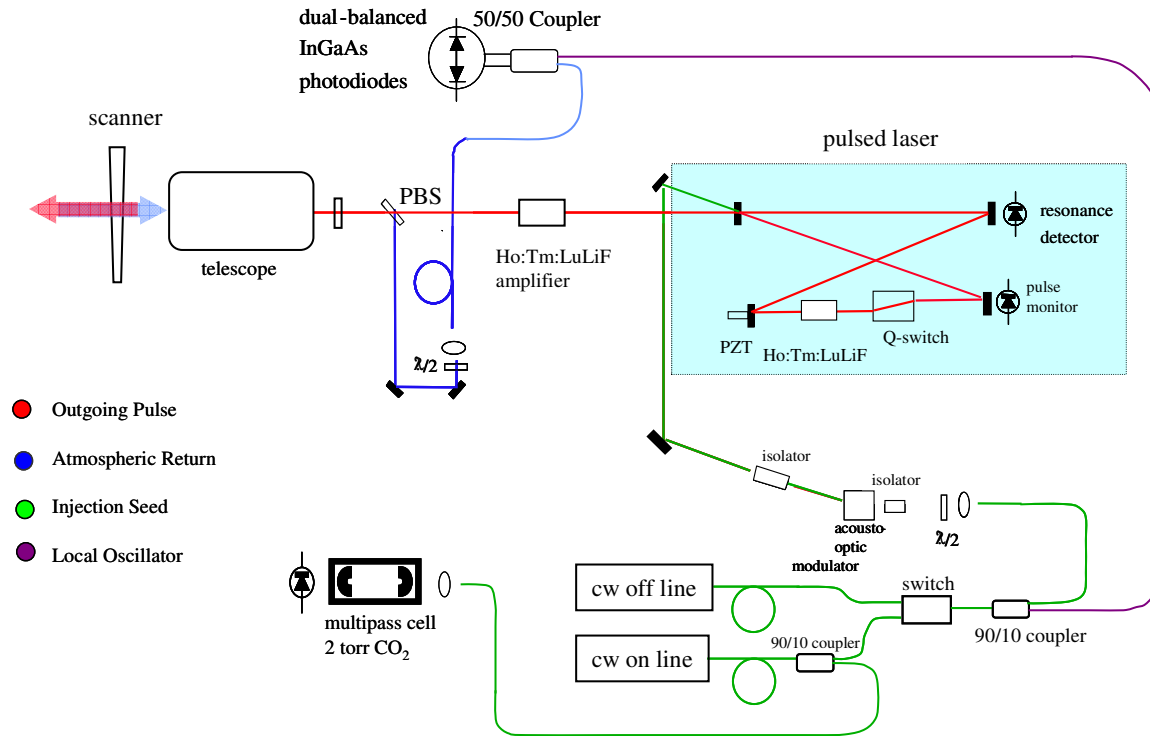


Figure 1 : Layout of combined DIAL/Doppler lidar. Curves paths involve optical fiber. For wind measurements the off-line CW laser is used.

atmosphere via an off-axis paraboloid telescope. After expansion by the telescope, the output laser beam can be pointed or scanned by a. The outgoing pulse and atmospheric backscatter are separated by a polarization relationship imposed by the combination of a quarter-wave plate and polarizing beam splitter. Heterodyne detection is provided by InGaAs photodiodes in a dual-balanced configuration.

### 3. Earth Applications

Global wind profile data will improve climate analysis and prediction because knowledge of the wind field is fundamental to understanding the role of greenhouse gases, the hydrologic cycle, heat and energy transport, radiative cloud processes, and the biogeochemical cycle. Wind profiles can be used in conjunction with data from passive microwave and infrared sounders to calculate the flux convergence of water vapor, and will enhance transport models, particularly those describing tropospheric and stratospheric flows of water vapor and pollutants. Current radiative models can be better evaluated and ultimately improved by provided knowledge of the global wind flow. The excitation, propagation, and dissipation of gravity waves, by which energy is transported to the upper atmosphere, could also be investigated.

Inadequate measurements of the global wind field likewise reduce the capability of numerical weather prediction (NWP) modeling efforts, on which NOAA relies to conduct its mission to advance weather forecasting and warnings to protect lives and property. Observing System Simulation Experiments (OSSEs) have shown that when

simulated global wind profile data are included in NWP models, they have a greater beneficial impact on forecast accuracy than the inclusion of other types of space-based data. OSSEs and other analyses have demonstrated that knowledge of wind profiles over the Pacific Ocean extends and improves the accuracy of weather forecasts over the United States. Development of an airborne lidar for wind measurement is currently on-going at NASA.<sup>3</sup>

Knowledge of the spatial and temporal distribution of CO<sub>2</sub> and an understanding of the causes of these variations are essential for predicting future levels of CO<sub>2</sub> and the impact of CO<sub>2</sub> on future climate change. A full understanding of the global atmospheric CO<sub>2</sub> cycle requires measurements of atmospheric CO<sub>2</sub> profiles on continental and global scales that are not currently available. The difficulty in making profile measurements arises from CO<sub>2</sub> exhibiting small variations in concentration over large spatial scales. Atmospheric gradients of CO<sub>2</sub> over continents are typically 2-10 ppmv. In order to attain the vertical and spatial measurements needed, a lidar system will have as requirements: 1) a profile measurement precision of 1.5 ppmv (0.5%) over 1=km vertical range intervals in the troposphere, and 2) column measurements with 1.5 ppmv precision. These requirements will allow the instrument to measure the influence of the land surface on CO<sub>2</sub> concentrations in the atmosphere, even where this influence is relatively weak. Observations made over time and space provide the basic data for determining the magnitude of atmosphere-biosphere fluxes, a principal objective of carbon cycle science. A lidar aimed at meeting these goals for CO<sub>2</sub> measurement is currently under

development at NASA.

While each of these measurement applications is being pursued individually, it is possible to make both wind and CO<sub>2</sub> measurements from the same lidar instrument. The pulsed laser transmitter is largely the same for either application, with the difference being the wavelength control for DIAL. With a coherent heterodyne receiver, the receiver design is also the same. Deriving wind or CO<sub>2</sub> data products is a matter of signal processing.

A breadboard prototype Doppler/DIAL, with the general design shown in Figure 1, has been built and tested in the atmosphere for performance in both wind and CO<sub>2</sub> measurement. Sample data is shown in Figures 2 and 3.<sup>5</sup>

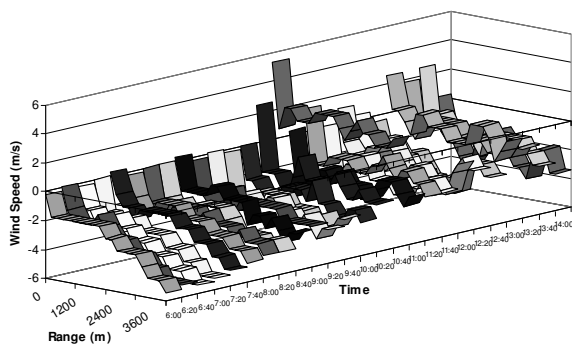


Figure 2: Line-of-sight wind measurements taken at the same time as the DIAL measurements of Figure 3. The off-line wavelength is used for wind measurements.

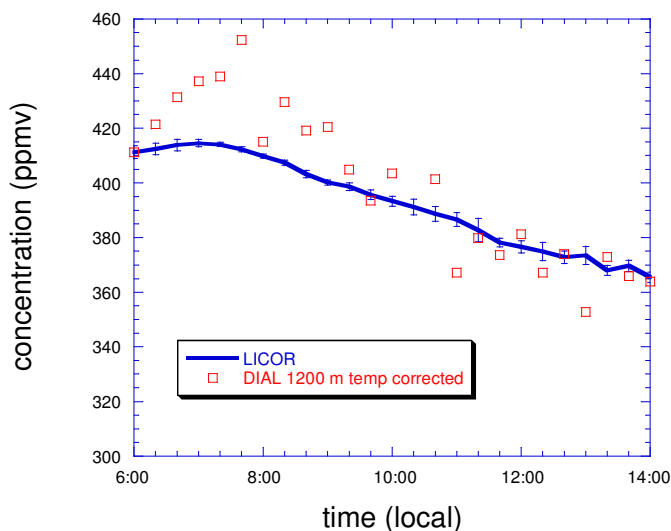


Figure 3: heterodyne DIAL measurements made in comparison with an in-situ sensor. Wind measurements of Figure 2 were derived from the same data.

#### 4. Mars Applications

The Martian atmosphere also presents wind and CO<sub>2</sub> measurement problems that could be met with a combined DIAL/Doppler lidar. CO<sub>2</sub> concentration in this scenario would be used to calculate variations in atmospheric density since the Martian atmosphere is composed of 95% CO<sub>2</sub>. Even with perfect entry conditions at the top of the atmosphere, landing location dispersions are on the order of 50 km due to uncertainty in middle atmosphere density and up to a kilometer due to low altitude winds while on parachute. Successful EDL design and operations requires knowledge of the seasonal, latitudinal, and diurnal variations in the global atmosphere as well as mesoscale and local weather conditions. Currently, uncertainties in the relevant nominal atmospheric density are as much as 25%. Furthermore, un-modeled, short spatial scale variations can have a significant effect on the success of the mission. At 100 km, where there is an extensive data set from aerobraking missions, density can double over horizontal distances of 20 km. Though smaller in relative amplitude, similar waves have been identified in the middle atmosphere during the EDL missions. Precision landing is particularly difficult with high, unexpected near surface winds due to the lack of control while on parachute. Finally, the atmosphere responds rapidly and dramatically to regional and global dust storms which can result in large density and wind variations throughout the entire atmosphere to 100 km and higher. Few of these phenomena are predicted by current atmosphere models and this lack of knowledge directly increases mission risk and reduces payload margins.

Systematic measurement of the Mars atmospheric density and winds will be required over several Mars years, supplemented with day-of-entry operational measurements. The precision and accuracy for application to Mars is not as stringent as Earth, but Mars does pose a challenge in needing a high level of wavelength stability and control in order to reference wavelength to the narrow linewidths found in the low atmospheric pressure of Mars.

NASA has initiated a study for a Mars Orbiting Lidar under a project for Laser/Lidar Technologies for Exploration for combined wind, CO<sub>2</sub>, and dust profiling. The primary thrust of the first phase of this study is to develop a model of lidar performance in the Martian atmosphere. Development of the Mars model, called the Mars Lidar Simulation Model, has taken an Earth lidar model as a starting point and replaced the Earth atmospheric parameters with those representative of Mars. A challenge in building this model has been the lack of observational data on properties such as dust density, dust distribution throughout the atmosphere, dust size and shape, atmospheric density, etc. We have used atmospheric models that offer the best estimates known on these parameters, primarily a climate database derived from the Mars Global Surveyor.

A simulation result for wind profiling is shown in Figure 4 using a standard background atmosphere. The dust levels encountered in this atmosphere provide sufficient backscatter for wind profiling up to 70-km altitude from a

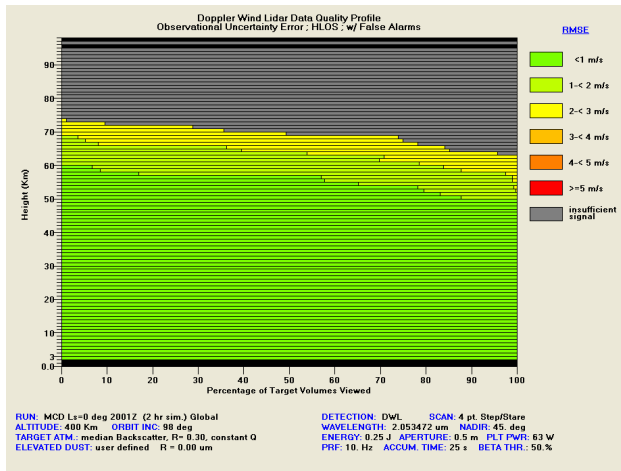


Figure 4 : Assessment of wind profiling capability of a typical Martian atmosphere. The high dust loading on Mars provides a high level of backscatter. Measurements are made to ground level, which in this case is 2-km above a topographical reference.

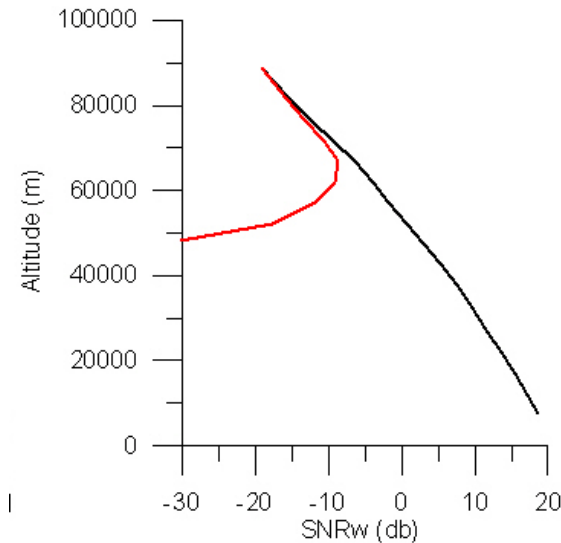


Figure 5 : Signal-to-noise ratio calculated for on-line (red) and off-line (black) wavelengths. The same lidar parameters used for the wind measurements of Figure 4 are used for this simulation, except the DIAL measurements are made nadir viewing.

relatively modest pulse energy of 250 mJ at 10 Hz repetition rate. The model includes a variety of options for dust loading in the atmosphere, including dust storms. In the case of a moderate dust storm, wind can be measured at altitudes above 90-km but the higher extinction prohibits measurements close to the ground.

The simulation for DIAL measurements is still under development, but a preliminary result is shown in Figure 5. The same atmosphere and lidar parameters used for the wind simulation of Figure 4 are taken here. While work is still progressing to determine the sensitivity and error associated with translating DIAL measurements to the calculation of density, the signal-to-noise ratios found with a 250-mJ lidar suggest a capability to make density measurement in the middle atmosphere. In order to make absolute calculation of density the temperature must also be known, and hence the lidar should be coupled to a temperature-measuring instrument.

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