Development of Laser, Detector, and Receiver Systems for an Atmospheric CO_2 Lidar Profiling System

Syed Ismail[1], Grady Koch[2], Nurul Abedin[3], Tamer Refaat[4], Manuel Rubio[5], and Upendra Singh[6]
[1,2,3,5,6]NASA Langley Research Center, Hampton, VA 23681
[1]757-864-2719; Syed.Ismail-1@nasa.gov
[2]757-864-3850; Grady.j.Koch@nasa.gov
[3]757-864-4814;m.n.abedin@ nasa.gov
[5]757-864-2338; Manuel.a.rubio@nasa.gov
[6]757-864-1570;Upendra.n.singh@nasa.gov
[4]Old Dominion University, Norfolk, VA 23529
[4]757-218-0608; trefaat@jlab.org

Abstract—A ground-based Differential Absorption Lidar (DIAL) is being developed with the capability to measure range-resolved and column amounts of atmospheric CO_2. This system is also capable of providing high-resolution aerosol profiles and cloud distributions. It is being developed as part of the NASA Earth Science Technology Office's Instrument Incubator Program. This three year program involves the design, development, evaluation, and fielding of a ground-based CO_2 profiling system. At the end of a three-year development this instrument is expected to be capable of making measurements in the lower troposphere and boundary layer where the sources and sinks of CO_2 are located. It will be a valuable tool in the validation of NASA Orbiting Carbon Observatory (OCO) measurements of column CO_2 and suitable for deployment in the North American Carbon Program (NACP) regional intensive field campaigns. The system can also be used as a test-bed for the evaluation of lidar technologies for space-application. [1] [2]

This DIAL system leverages 2-µm laser technology developed under a number of NASA programs to develop new solid-state laser technology that provides high pulse energy, tunable, wavelength-stabilized, and double-pulsed lasers that are operable over pre-selected temperature insensitive strong CO_2 absorption lines suitable for profiling of lower tropospheric CO_2. It also incorporates new high quantum efficiency, high gain, and relatively low noise phototransistors, and a new receiver/signal processor system to achieve high precision DIAL measurements.

Atmospheric tests of the laser have been conducted by operating it locked to the CO_2 absorption line center, with off-set locking in the side-line mode, and in the off-line position. The reference laser is locked to center of absorption line within 390 kHz. This improves the level of stabilization by factor of 10 compared to earlier configuration. The detector has been characterized in the laboratory and by conducting atmospheric tests at The National Center of Atmospheric Research (NCAR), Boulder, Colorado. The receiver uses an F2.2 all aluminum 40 cm diameter telescope and the system is designed to focus light onto a 200 µm size detector. Subsystem level integration and testing has been completed in the second year. System level testing is planned in the third year along with validation in the late spring of 2008 that involves comparisons with ground-based and aircraft in situ CO_2 sensors.

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1. INTRODUCTION

The atmospheric burden of CO_2 is increasing in response to widespread anthropogenic combustion of fossil fuels. Roughly half of the emitted CO_2 is absorbed by the Earth's oceans and terrestrial ecosystems [1]. This uptake [2] varies annually from 1 to 6 PgC/yr. Understanding source/sink processes and the geographic patterns of carbon fluxes are primary goals of carbon cycle science. Uncertainty in predictions of the carbon cycle is one of the leading sources of uncertainty in projections of future climate [3]. A double-pulsed DIAL system operating in the 2.05-micron band of CO_2 is being developed for profiling CO_2 in the low-to-mid troposphere. There are several advantages of this system over passive remote sensing systems including day/night operation, reduction or elimination of interference from clouds and aerosols, and direct and straight forward

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inversion that leads to better quality data and faster retrievals with few assumptions. A ground-based lidar profiling system with ability to delineate atmospheric boundary layer (ABL) CO_2 from the free tropospheric CO_2 is needed that can operate during day or night. CO_2 distributions in the troposphere are linked to transport and dynamical processes in the atmosphere and are associated with near-surface sources and sinks. Annually averaged, inter-hemispheric, and continental to marine boundary layer CO_2 mixing ratio differences are on the order of 1 to 3 ppm [4]. Thus 0.2 ppm has long been a benchmark for required instrumental precision. Achieving this level of precision is difficult with remote sensors. Much larger mixing ratio differences emerge, however, at smaller spatial and temporal scales. In many instances exchange of ABL CO_2 with the free troposphere takes place through convective activity and passage of weather fronts. Hurwitz et al. [5], describe several synoptic passages and document 10 to 20 ppm mixing ratio changes that result from frontal passages. Thouret et al. [6], have shown that there is a high probability of observing more than one layered structure above the boundary layer at any time. Airborne sampling shows that the majority of the vertical structures in CO_2 mixing ratios are found within the lowest 5 km of the troposphere [4]. Thus, the requirements of this DIAL system development are: 0.5% (1.5 ppm) precision for vertical differences in the 30 minute mean mixing ratio resolved every 1 km from 0.5 to 5 km above ground.

Progress during the last two years in the design, development, atmospheric testing, and performance modeling associated with the development of this DIAL system is presented in this paper. Field evaluation of the DIAL will be conducted in the third year of the project in coordination with field observations of the North American Carbon Plan (NACP) and OCO pre-validation activities.

2. THE CARBON DIOXIDE DIAL PROFILING SYSTEM

The DIAL system incorporates a high pulse energy, tunable, wavelength-stabilized, and double-pulsed laser that operates over a pre-selected temperature insensitive strong CO_2 absorption line in the 2.05-µm band. It incorporates a newly developed low noise and high gain InGaAsSb/AlGaAsSb (AstroPower) infrared heterojunction phototransistor (HPT) with a 200 µm sensitive area diameter. It is planned to operate it in the direct detection mode by taking advantage of a large 40 cm diameter telescope, which increases the photons collection at the detector by a factor of 16 over our previous system [7] in order to make CO_2 measurements above the boundary layer. The key lidar system parameters are given in Table 1. The Ho:Tm:LuLiF tunable laser is configured to operate at the 2053.204 nm CO_2 absorption line. Later, the laser is planned to operate on the more temperature insensitive line [8] at 2050.967 nm using the Ho:Tm:YLF configuration. The CO_2 line will be fully characterized using a tunable high-resolution (New Focus Model #6335) laser diode at the Jet Propulsion Laboratory [9]. Accurate spectroscopic parameters will be derived that are critical to realizing ground-based CO_2 lidar detection strategy. The low-pressure line position is known to an uncertainty less than 6×10^{-5} cm^{-1} [9]. The ambient temperature line strength will be determined to 2%, the line width to 3%, and the atmospheric pressure shift to 5×10^{-4} cm^{-1} using a multispectral fitting technique.

TABLE I: Lidar parameters

Parameters	Value	Unit
Pulse Energy	90	mJ
Pulse Width	180	nsec
Pulse Repetition Rate, doublet	5	Hz
Spectrum	Single Frequency	---
On-line Wavelength	2050.967	Nm
Off-line Wavelength	2051.017	Nm
Beam Quality	< 1.3× Diffraction Limit	---
Long Term Stability	<2 (1 hr)	MHz
Telescope Diameter	40	cm
Detector	AlGaAsSb/InGaAsSb Phototransistor	---

3. LASER DEVELOPMENT AND TESTING

Recent improvements in performance of the laser transmitter include double-pulse operation as demonstrated in the past with other DIAL systems. The double-pulse is injection seeded with different on/off wavelength for each pulse of the doublet. The wavelength switching is accomplished by having two injection seed lasers that can be rapidly (in order of 1 µs) switched by an electro-optic device controlled by a simple logic signal. One of the seed lasers is tuned to the CO_2 line and the second is tuned to off line. The on-line laser is referenced to a CO_2 absorption cell at low pressure, and recent work has improved the performance of the wavelength locking to a level within 390 kHz standard deviation over hour-long time periods. This level of stabilization to line center reflects a factor of 10 improvements over our previous implementation, realized by converting to an external frequency modulation technique rather than wavelength dithering of the laser cavity length. An option now exists for tuning the on-line laser to the side of the line rather than the center of the line. By using the side of the absorption line, the optical depth of the DIAL measurement can be tailored for optimal performance. The side line reference is made by locking one seed laser onto line center and referencing a second laser to the center-line by monitoring the heterodyne beat signal between the two. A feedback loop has been implemented to lock the side-line laser to the center-line laser. A block diagram of the laser system is shown in Figure 1. Electronic control holds an offset from center-line locked laser. Offset can be electronically programmed and laboratory tests have assessed quality of offset lock set up to 2.8 GHz (37.3 pm). Atmospheric tests were conducted in a zenith-pointing mode at NASA Langley Research Center (LaRC) during the summer of 2006 using the heterodyne detection system to test the ability to operate in the side-line mode. Figure 2 shows the results of measurements of differential optical thickness as a function of altitude. The side-line was used as on-line and 3 different side-line positions were used that were offset by 24, 31, and 38 pm from line center. These results indicate the ability to operate the laser in the sideline mode to optimize performance by tuning the sideline to desired absorption. More quantitative CO_2 measurements in the atmosphere were made in March, 2007 in the boundary layer using the Ho:Tm:LuLiF laser and the existing heterodyne detection system. These DIAL measurements were compared with in situ gas analyzer (LI-COR 6252, [10]) and initial results indicate that the two sensors show the same trend and occurrence of CO_2 perturbations. The DIAL data show excellent precision.

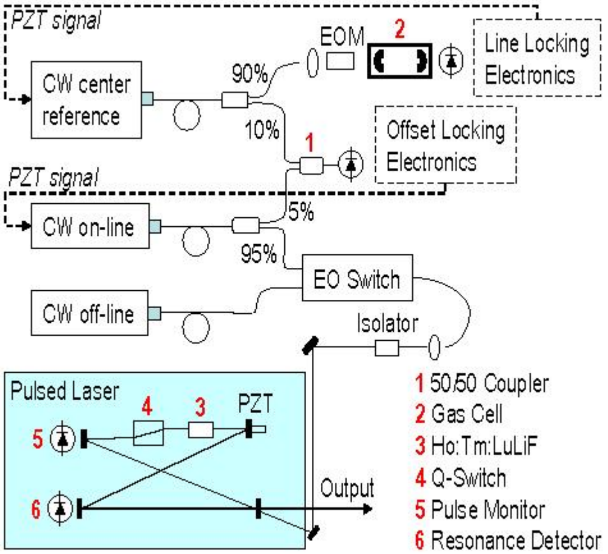

Figure 1. Block diagram of injection seeded Ho:Tm:LuLiF laser. Injection seeding setup, with line center locked to the CO_2 line, side-line with offset locking with reference to the line and an off-line away from the absorbing line, is shown in the upper portion of the figure.

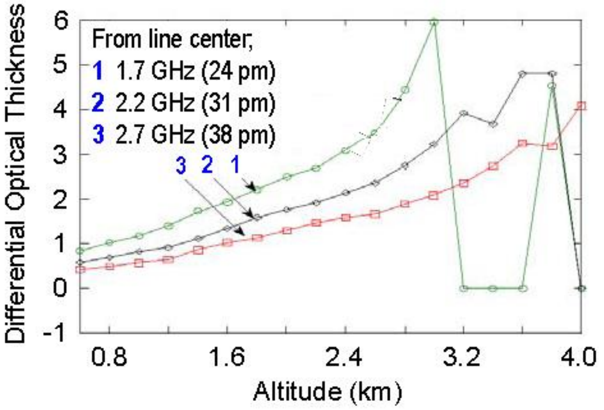

Figure 2. Atmospheric tests for measuring the differential optical depths using changing side-line tuning.

4. DETECTOR SYSTEM INTEGRATION AND ATMOSPHERIC TESTS

There are no detectors available commercially that can meet the requirements of the DIAL system under development. An ideal detector would be an APD with high quantum efficiency (~70%), high gain (~100) with low noise-equivalent-power (NEP ~ 2×10^{-14} $W/Hz^{1/2}$) and low excess noise factor (< 2), high bandwidth (> 1 MHz), and fast settling time (1-3 µs to reach 1% signal level). A newly developed InGaAsSb/AlGaAsSb heterojunction phototransistor (HPT), with a 200 µm sensitive area diameter, was used as the detector of choice [11]. The advantages of the phototransistor include high gain (> 3000), lower NEP, and higher quantum efficiency (~70%) compared to the traditional extended wavelength PIN photodiodes. These phototransistors are sensitive over the wavelength region 1.0 to 2.3 µm with peak performance near 2.0 µm. Characterization of these detectors showed the capability to provide high gain with lower bandwidth and longer recovery times. To capture rapid variations of signals in the lower troposphere, a low gain setting for the phototransistor will be required for the near field and a high gain setting for the far field. Post detector electronic circuit was developed that consists of analog and digital circuit elements. Figure 3 shows the configuration of the detection system analog electronics. The main features of detection system electronics includes computer controlled detector bias; temperature control electronics; trans-impedance amplifier with dark current compensation; voltage amplifier with offset and gain adjustments; and state-of-the-art waveform 24-bit digitizer (National Instruments PXI-5922).

The capability of the detection system and its applicability to this program could not be demonstrated at LaRC (while the receiver system was still under development). High sensitivity aerosol scanning lidar (REAL: Raman-shifted Eye-safe Aerosol Lidar)) system [12] of NCAR, was used for atmospheric testing by integrating the newly developed HPT into the system. REAL has a 40 cm telescope, two 200 µm diameter InGaAs APD detector channels, and operates at 1.543 µm wavelength. Atmospheric tests of the detection system were conducted at NCAR initially in June 2006 and later in December 2006 to test the HPT. The 200-µm HPT was used instead of one of the APD channels and the other

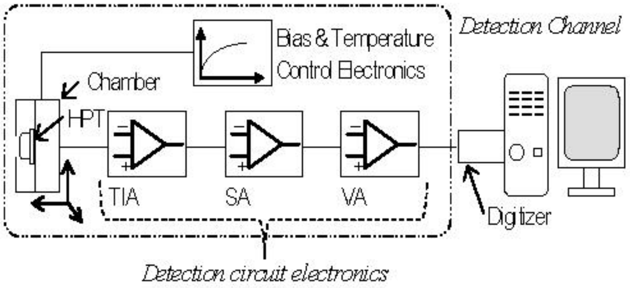

Figure 3. Block diagram of HPT detection system electronics.

APD was used as a reference. While the HPT detector is not optimum for 1.543-µm, still, the first atmospheric tests in June 2006 indicated that it has sensitivity to detect atmospheric features (cloud and aerosol layers) to altitudes > 5 km. This was the first demonstration of a HPT in a lidar system [13]. These tests showed that the HPT could resolve atmospheric features ~100 m in size (HPT operating with a 3 V at 20 °C). However, the HPT detection system showed signal overshoot effects during recovery from a high signal that obscured measurements up to 3 km. Since the HPT in itself had not shown an overshoot during its characterization, the amplifier circuit following the HPT was a suspect.

Electronic trouble-shooting was performed to the TIA circuit at LaRC. This investigation indicated that the detector's bias node required a large capacitance to stabilize the bias junction. An improved circuit with a stabilizing capacitor was rebuilt. Figure 4 compares the results of overshoot (blue) and the improved performance (pink) using the new circuit. When a 1 mW optical pulse was applied to the phototransistor without the proper capacitance, a long undershoot occurs (70 µs), which in a lidar system will cause masking of measurements up to about 10 km. Using the new circuit, the problem was corrected for the second trip to NCAR. Figures 5 and 6 compare the measurements obtained with the HPT and REAL APD at 1.543-µm wavelength for a near-filed boundary layer and far-field cloud layer. The overshoot problem is eliminated and the layers features are recovered compared to the measurements during the period of June 2006. However, lower bandwidth and slower recovery problems cause systematic effects in the data from the HPT system compared to the APD system as illustrated in the figures.

To minimize systematic effects due to the bandwidth and slow recovery and to retrieve atmospheric lidar data from the HPT channel further lab characterization was conducted at NCAR including impulse response tests using short (0.1 µs) pulse laser and dynamic linearity tests using simulated lidar signal profiles [14]. Data from the impulse response tests were used to deconvolve the measurements from the HPT channel. An iterative deconvolution technique was employed that is a modification of the earlier van Cittert technique [15]. In such technique, the detection system transfer function, represented by the impulse response, is convolved with the data. The resulted signal is then used with the original data to define an error function that is applied to correct the original data in an iterative procedure. The iteration sequence is repeated until meeting a certain condition. In the presented analysis, the condition was set to minimize the difference between two successive iterations.

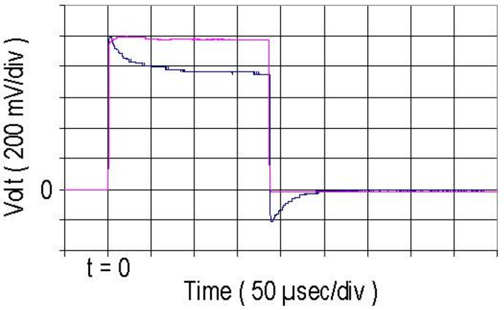

Figure 4. Improved performance of circuit with the addition of a large capacitor (pink trace) compared with performance during tests at NCAR (blue trace).

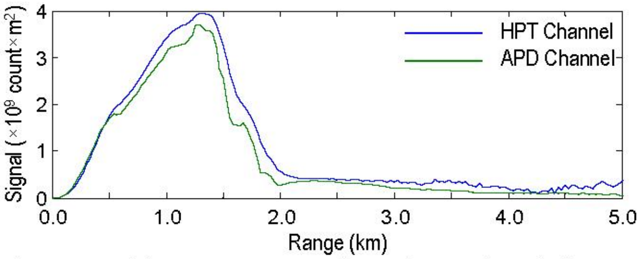

Figure 5. Lidar measurements from the test (HPT) detector compared with results from APD detector system. The lidar was pointing with an elevation angle of 20 degrees.

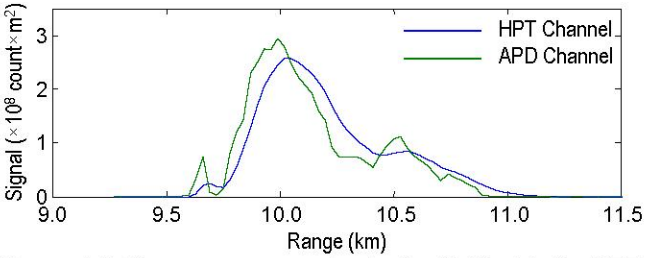

Figure 6. Lidar measurements in the far field with the HPT and APD detector systems. Lidar was pointing in the zenith direction.

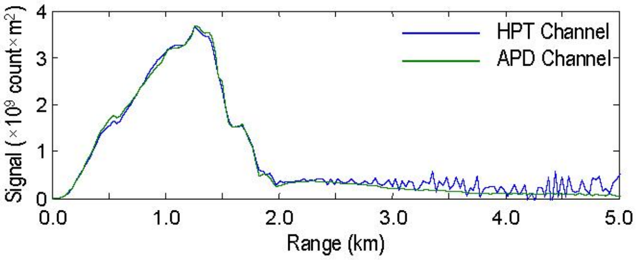

Figure 7. Comparison of data from HPT and APD channels after deconvolution of the near field data.

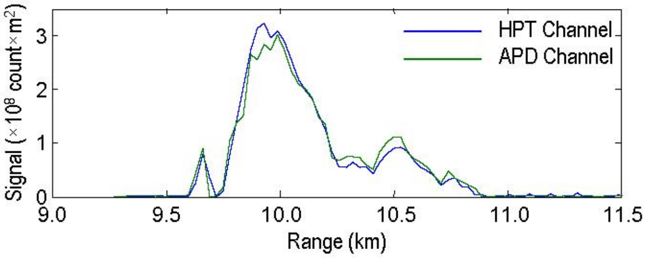

Figure 8. Comparison of data from HPT and APD channels after deconvolution of the far field data. (Compare results with Figure 6).

Advantages of this iterative deconvolution includes resolution recovery and linearity enhancement while controlling the noise deterioration. Besides, this deconvolution scheme depends on much stable and well defined convolution process leading to easier solution conversion. Results of deconvolution using this procedure are shown in Figures 7 and 8 for both HPT and APD channels. It is clear from the figures that the deconvolution process increased the resolution, and minimized phase delay between HPT and APD data. The deconvolution procedure was implemented for the whole series of measurements with consistent results [14]. Some degradation of signal-to-noise (S/N) in the low S/N regions was observed.

5. RECEIVER SYSTEM

Two receiver channels are planned to capture the full dynamic range of signals in the near (within the boundary layer 0.5 to 2.0 km range) and far field (above the boundary layer >1 km). The optical receiver uses a 40 cm diameter F/2.2 all aluminum telescope to minimize thermal effects. The optical schematic of the receiver is shown in Figure 9. The incident radiation is focused by the two mirrors of Cassegrain telescope through the pinhole and coupled into a fiber optic. The receiver optics includes a collimating lens, narrowband interference filter, focusing lenses, and protective window. A beam splitter is used to divide the radiation into optical paths leading to two HPT detectors in two channels. The optical design includes focusing the optical signal onto the 200-µm diameter detector.

Finally, the collimating and focusing lenses are of a triplet (3 lenses) design and fabricated from SF11 optical glass. These are custom coated for use at 2-µm wavelength. Off-the-shelf interference filters and beam splitters are used in the design. The custom designed telescope was manufactured by Welch Mechanical Design, Baltimore, MD. One of the specifications for this telescope was to have a small (45 µm diameter) focus area (blur spot size). The laser beam is transmitted into the atmosphere co-axially after a 20× beam expansion to limit the transmitted field of view to 85 µ-radians. The receiver FOV is set to 350 µ-radians using the pinhole at the focus of the telescope. Light from the telescope focus spot is coupled to the collimating lens of the aft.-optics system by a multimode optical fiber. The telescope, aft.-optics, detectors, and other components are placed inside an all-Aluminum enclosure box to limit stray light from the laser. This box also provides optical baffling and overall structural support.

6. SUMMARY

An atmospheric CO_2, ground-based, DIAL system is being developed at NASA LaRC. The system capabilities include measuring range-resolved and column amounts of CO_2 with high-resolution, while profiling aerosol and cloud distributions. High pulse energy, tunable, wavelength-stabilized, and double-pulsed 2-µm laser is used as the transmitter. The laser is operable over pre-selected temperature insensitive strong CO_2 absorption lines. All-aluminum Cassegrain telescope is used in the receiver. The receiver optics focuses the radiation onto newly developed phototransistors. Accompanied with state-of-the-art electronics and digitizer, system fine-tuning and testing is in progress.

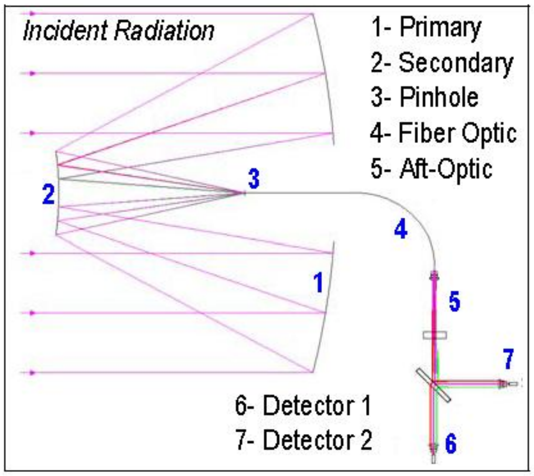

Figure 9. Schematic diagram of the optical design of the receiver system.

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BIOGRAPHY

Syed Ismail *received his PhD in Space Physics from the University of Calgary, Canada in 1979. He is a Senior Research Scientist in the Science directorate at NASA Langley, and he is internationally recognized for his research using Differential Absorption Lidar (DIAL) systems. He has led algorithm development, modeling of lidar systems, lidar system development, and atmospheric measurements with advanced ground-based, airborne, and space-based lidar systems. Dr. Ismail has led investigations of water vapor, aerosols, and clouds using the Lidar Atmospheric Sensing Experiment (LASE) system operating from the ER-2, P-3 and DC-8 and studies of future DIAL aircraft and space missions. He is currently involved in the development of DIAL systems to measure atmospheric carbon dioxide. Dr. Ismail was awarded NASA's Exceptional Achievement Medal for his work on LASE in 1996. He was the Chairman of the Program Committee of the 19th International Laser Radar Conference held in Annapolis, MD in 1998. He has Chaired/Co-chaired in a number of scientific/technical conferences and presented a number of invited talks at several international conferences. Dr. Ismail is a member of the American Geophysical Union and American Meteorological Society's Committee on Laser Atmospheric Studies (1995–1997).*

Grady J. Koch *received as B.S. in electrical engineering in 1991 from Virginia Tech, an M.S. in electrical engineering in 1995 from the University of Illinois at Urbana-Champaign, and a Ph.D. in electrical engineering in 2001 from Old Dominion University. In 1987 he began work at NASA Langley Research Center as a cooperative education student, taking regular employment there in 1991. His research interests include coherent lidar, differential absorption lidar, solid-state lasers and diode lasers*

M. Nurul Abedin *with NASA since 1999, and industry/university since 1989, received his PhD in solid state physics from Rensselaer Polytechnic Institute in 1989. He is the Lead Electro-Optics Sensor Technologist of the Remote Sensing Flight Systems Branch where he plans, directs, and coordinates research and technology development programs dealing with detectors, lasers, optics, and active remote sensing instruments applicable to the earth and space science missions and also planetary exploration systems. With over twenty two years experience in electro-optics devices, materials characterization, and active remote sensing, Dr. Abedin's research and development activities include studies of quantum wells, superlattices, superconductor, CCDs, HgCdTe FPAs, InGaAsSb pn/SAM APD, phototransistors, two-color and multi-color devices, modeling of infrared detectors, and Raman/Laser Induced Fluorescence/Lidar multi-sensor instrument. Dr. Abedin is a member of the AIAA, IEEE, OSA, and SPIE; Langley's representative on the AIAA Sensor Systems Technical Committee; Associate Editor 2nd term & member of editorial board on IEEE Sensors Journal. He is the Editor-in-Chief in IEEE Sensors Council Newsletter.*

Tamer F. Refaat *is a Senior Research Scientist at the Applied Research Center, Old Dominion University, working at NASA Langley Research Center, Hampton, Virginia. He received his BS (with honors) and MS degrees in electrical engineering in 1991 and 1995, respectively, from Alexandria University, Alexandria, Egypt, and PhD in 2000 from Old Dominion University, Norfolk, Virginia. His research interests includes optical and radiation detectors development, modeling and characterization and its application to lidar instruments. He has been involved in lidar receiver's design and implementation for profiling atmospheric constituents such as aerosol, water vapor, ozone and carbon dioxide. Dr Refaat is a member of IEEE and SPIE.*

Manuel A. Rubio *is an Optical Systems Engineer working at NASA Langley Research Center, located in Hampton, VA. He received his M.S. and B.S. in Optical Sciences from the University of Arizona in 2001 and 1996, respectively. He will complete his Optical Sciences Ph.D. in 2008 from the same institute. From 1997 through 2001, he was a NASA Graduate Student Researchers Program Fellowship recipient. He preformed research on advancing laser-radar instrument performances by improving their optical designs. His interests are the research and development of next-generation ground-based, airborne, and space-based optical instruments.*

Upendra N. Singh *received his PhD in physics from University of Pierre and Marie Curie, Paris, France in 1985, and D.E.A. (Diplo ˆme d'Etude Approfondis) from University of Franche`-Compte´, Besanc¸on, France in 1982. In India, he earned degrees in MPhil in physics, MSc in applied physics, and BSc (Honors) degree in physics during 1979, 1980, and 1974, respectively. He is the Chief Technologist at Systems Engineering Compentency of NASA Langley Research Center, Hampton, VA. Currently, he is the Principal Investigator of the NASA's Laser Risk Reduction Program, a multi-center NASA Program dedicated towards developing an endto- end lidar capability leading to space-based remote sensing. He has authored or coauthored more than 150 research papers. In the last seven years, he has chaired 20 international conferences/ symposium in the area of active and passive remote sensing of the Earth's atmosphere. He is a Fellow of SPIE and member of OSA and IEEE. He is also serving on the SPIE Symposia Committee and is on the Board of Editors, Journal of Optics and Lasers in Engineering, Elsevier Science Ltd., England. He has received numerous awards including NASA Outstanding Leadership Medal in 2001 for ''Significant contributions and distinguished, internationally recognized, scientific and technical leadership of NASA programs in the area of active and passive remote sensing of the atmosphere.''*