

Development of an Airborne Triple-Pulse 2- μm Integrated Path Differential Absorption Lidar (IPDA) for Simultaneous Airborne Column Measurements of Carbon Dioxide and Water Vapor in the Atmosphere

Upendra N. Singh(a), Mulugeta Petros(b), Tamer F. Refaat(b),
Jirong Yu(b), Charles W. Antill(b) and Ruben Remus(b)

(a) NASA Engineering and Safety Center,
NASA Langley Research Center, Hampton, VA 23681

(b) Remote Sensing Branch, MS 468,
NASA Langley Research Center, Hampton, VA 23681
Upendra.N.Singh@nasa.gov

Abstract: This presentation will provide status and details of an airborne 2- μm triple-pulse integrated path differential absorption (IPDA) lidar being developed at NASA Langley Research Center with support from NASA ESTO Instrument Incubator Program. The development of this active optical remote sensing IPDA instrument is targeted for measuring both atmospheric carbon dioxide and water vapor in the atmosphere from an airborne platform. This presentation will focus on the advancement of the 2-micron triple-pulse IPDA lidar development. Updates on the state-of-the-art triple-pulse laser transmitter will be presented including the status of seed laser locking, wavelength control, receiver and detector upgrades, laser packaging and lidar integration. Future plan for IPDA lidar system for ground integration, testing and flight validation will also be presented.

Keywords: Active Remote Sensing, Carbon Dioxide, Water Vapor, DIAL, IPDA Lidar, Triple-Pulse Laser

1. Introduction

Through the continual support from NASA Earth Science Technology Office (ESTO), current efforts at NASA Langley Research Center (LaRC) are focused on developing a 2- μm triple-pulse integrated path differential absorption (IPDA) lidar instrument for independent and simultaneous monitoring of carbon dioxide (CO_2) and water vapor (H_2O) in the atmosphere [1]. Triple-pulse IPDA lidar instrument design, development and integration is based on the knowledge gathered through the successful demonstration of the 2- μm double-pulse IPDA lidar for atmospheric CO_2 measurements [2]. Several enhancements and updates of the triple-pulse instrument over the double-pulse instrument included in both the transmitter and the receiver systems [3]. Transmitter updates include the ability of generating three successive pulses, instead of two, with high-energy and high-repetition rate using a single pump pulse. The wavelength control and locking scheme is extend, up to 35 GHz away from the R30 CO_2 line, to accommodate H_2O sensing. In the receiver, detection systems and data acquisition hardware are updated for better performance in terms of detection sensitivity and random error reduction. Real-time data analysis and processing implementation would expedite science data production to further extend instrument testing and validation. These enhancements are detailed in the following subsections.

2. Triple-Pulse IPDA Remote Sensing Technique

The 2 μm wavelength region offers many suitable absorption features for CO_2 as well as H_2O . For CO_2 sensing, the R30 line, located at 2050.9670 nm, provides an attractive absorption cross section with unique characteristics. These include low temperature sensitivity and low interference from higher abundant H_2O molecules. This is indicated in figure 1, which compares the composite absorption spectra for CO_2 and H_2O

derived using the HITRAN database for line parameters, assuming Voigt line profile at two altitudes. The H₂O absorption peak located at 2050.5322 nm coincides close to CO₂ absorption minima, between R30 and R32 lines and away from the R32 peak. The IPDA laser transmitter generates three successive pulses locked to three different wavelengths, as shown schematically in figure 2. A single pump pulse produces three successive 2- μ m laser pulses, 150 μ sec apart. Using an enhanced wavelength control scheme, each of these pulses can be tuned and locked at different wavelength, as marked in figure 1. The principle of wavelength selection for this IPDA instrument is demonstrated in the same figure. The CO₂ on and off-line wavelengths are selected around the R30 line, so that both would have similar H₂O absorption to minimize H₂O interference on CO₂ measurements. Similarly, H₂O on- and off-line are selected around the absorption peak such that CO₂ interference is minimized on the H₂O measurement. However, both CO₂ on-line and H₂O off-line measurements share the same wavelength, which achieves simultaneous measurement of both molecules with triple pulses rather than quadruple pulses almost independently while avoiding interference from each other.

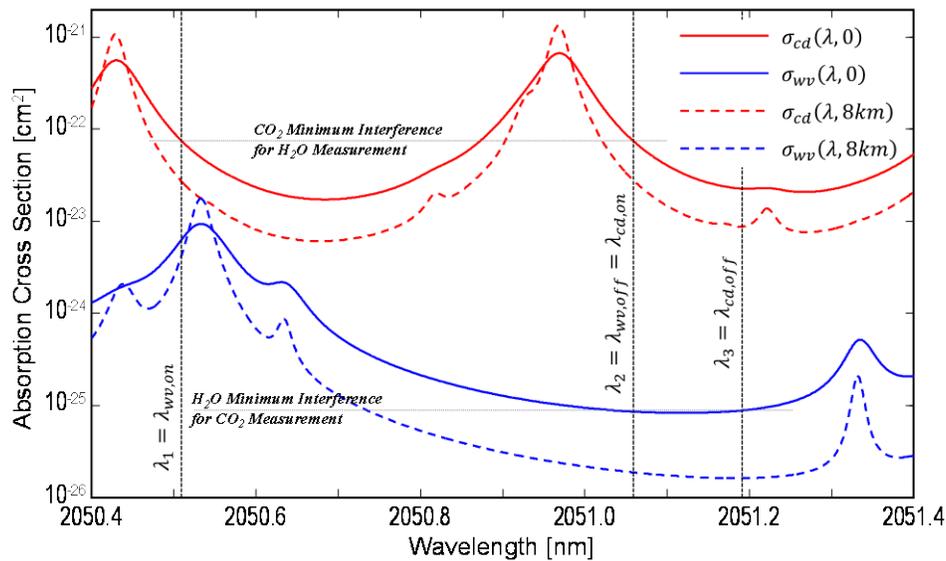


Figure 1. Absorption cross-section spectra of H₂O and CO₂, σ_{wv} and σ_{cd} , respectively at two altitudes.

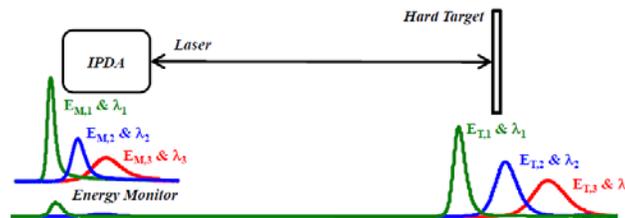


Figure 2. 2- μ m triple-pulse IPDA lidar principle of operation.

3. Triple-Pulse IPDA Transmitter

The triple-pulse IPDA laser transmitters is based on the Ho:Tm:YLF high-energy 2- μ m pulsed laser technology, with end pumping using 792 nm AlGaAs diode arrays [4]. Relative to the pump pulse, Q-switch triple-trigger produces three successive laser pulses with relatively controlled energies and pulse-widths are separated by approximately 200 μ sec. Thermal analysis conducted for proper heat dissipation out of the laser crystal, which is a critical issue that can result in crystal damage. As a proof of concept, a prototype

oscillator with triple pulsing capability was demonstrated, as shown in figure 3. Final laser configuration including thermal analysis and alignment optimization is currently on going to achieve higher energies.



Figure 3. Oscilloscope record for the successful triple-pulse operation.

The exact wavelengths of the pulsed laser transmitter are controlled by a wavelength control unit within 1 MHz. The unique wavelength control of the triple pulses uses a single semiconductor laser (JPL) and provides three seeds of any frequency setting within 35 GHz offset from the locked CO₂ R30 line center reference. This unit includes several optical and electro-optic components which were acquired and characterized. Integration of a prototype wavelength controller demonstrated technological challenges handling high bandwidth signals which was managed by proper RF designs and implementations.

4. Triple-Pulse IPDA Receiver

Similar to the double-pulse IPDA, the 2- μ m triple-pulse IPDA lidar receiver consists of a 0.4 m Newtonian telescope that focuses the radiation onto 300 μ m diameter spot. The telescope secondary mirror is a two surface dichroic flat that turns the return radiation 90° to the side integrated aft-optics from one surface. The opposite surface is used to transmit the expanded laser beam coaxially with the telescope. A single automated mount is used for bore-sight alignment. The telescope focused radiation is collimated, filtered then applied to a 90%-10% beam splitter. The 90% channel is an exact replica of the double-pulsed lidar. The 10% channel is planned to be used with an e-APD detector. These e-APD devices are space-qualifiable and were validated for airborne lidar operation at 1.6- μ m at NASA Goddard Space Flight Center (GSFC). In co-ordination with ESTO, LaRC is collaborating with GSFC to integrate this detector into the 2- μ m IPDA. The IPDA hard target return signals are digitized and stored through a data acquisition unit. The data acquisition unit is based on two similar 2-channels, 1 GS/s high-performance digitizers (Agilent; U5303A) that are triggered from the laser Q-switch. One digitizer is dedicated to the IPDA return signals, with a variable record length of about 70k samples, while the other is dedicated to the laser energy monitors, with a fixed record length of 10k.

5. Triple-Pulse IPDA Integration

A trailer was prepared as a mobile lidar laboratory for IPDA ground testing at NASA LaRC and ground-based field validation campaigns. This trailer will be used for the triple-pulse IPDA initial integration and ground testing. Once complete, airborne integration would start by transferring the instrument to the NASA B-200 aircraft. The IPDA instrument size, weight and power consumption were restricted to the payload requirements for such small aircraft to be easily adopted in any larger airborne research platform for future missions. Other housekeeping instruments will be integrated into the B-200 aircraft as well, which will include a LiCor in-situ sensor for CO₂ and H₂O mixing ratio measurement, GPS for global timing, aircraft position, altitude and angles measurements and video recorder for target identification. Besides, aircraft built-in sensors provide altitude, pressure, temperature and relative humidity sampling at flight position.

6. Triple-Pulse IPDA Validation Plans

The 2- μm IPDA lidar validation is important to assess both CO_2 and H_2O atmospheric measurements. Instrument validation will start on ground after instrument integration in the mobile laboratory. The mobile laboratory enables IPDA lidar horizontal measurement using a set calibrated hard targets and vertical measurements using clouds as hard target. Ground validation objectives are to check IPDA operational readiness before aircraft deployment, obtain IPDA signals and noise to evaluate instrument systematic and random errors, compare instrument errors to IPDA models and compare CO_2 and H_2O measurements against correlative in-situ instruments. Other long term objectives include transferring the laboratory with the instrument to different tall tower sites, such as WLEF tall tower in Park Falls, Wisconsin, and the Southern Great Plains ARM site in Lamont, Oklahoma.

For airborne validation, initial engineering flights would focus on instrument operation and comparing airborne and ground performance. Once proven success, the objective would focus on comparing CO_2 and H_2O measurements against correlative in-situ sensors and models. The validation will rely on onboard sensors as well as coordinating and collaborate with science community for other independent sensors, such as NOAA air-sampling and Pennsylvania State University passive sensors. Airborne validation will be planned to target different conditions such as different surface reflectivity, day and night background, clear, cloudy and broken cloud conditions, variable surface elevation and urban pollution and plume detection. The validation may also cover different location such as the Upper Midwest summer, where strong vertical and horizontal spatial gradients in CO_2 occurs due to agricultural fluxes and urban deployment in winter, where flight around isolated urban centers could identify a clear atmospheric boundary layer CO_2 plume. 2- μm triple-pulse validation activities might have the potential to coordinate with ACT-America flights.

7. Conclusion

A 2- μm triple-pulse IPDA lidar instrument is being developed at NASA LaRC. This active remote sensing IPDA instrument targets and measures both atmospheric CO_2 and H_2O . Wavelength selection and laser transmitter operation allows measuring both species independently and simultaneously. This is the first demonstration of measuring two different atmospheric molecules with a single instrument. Instrument design is based on knowledge gathered through the previously successful 2- μm double-pulse IPDA. Critical transmitter and receiver enhancements were implemented in the new triple-pulse design that significantly advance the technology. In the transmitter, modifications include triple-pulse operation of the laser and wavelength control design. In the receiver, updates includes additional high performance e-APD detector and advanced data acquisition system. The e-APD detector supplied by NASA GSFC, is a state-of-art, space qualifiable device that was validated for lidar applications. Work progress of the 2- μm triple-pulse IPDA program is on schedule. Instrument validation plans are under discussions to collaborate with different institutes with similar interests.

8. References

- [1] T. Refaat, U. Singh, J. Yu, M. Petros, S. Ismail, M. Kavaya, and K. Davis, "Evaluation of an airborne triple-pulsed 2- μm IPDA lidar for simultaneous and independent atmospheric water vapor and carbon dioxide measurements", *Applied Optics* 54, 1387-1398, 2015.
- [2] T. Refaat, U. Singh, J. Yu, M. Petros, R. Remus and Syed Ismail, "Double-pulse 2- μm integrated path differential absorption lidar airborne validation for atmospheric carbon dioxide measurement", *Applied Optics* 55, 4232-4246, 2016.
- [3] U. Singh, M. Petros, T. Refaat and J. Yu, "2-micron triple-pulse integrated path differential absorption lidar development for simultaneous airborne column measurements of carbon dioxide and water vapor in the atmosphere", *Proc. of SPIE* 9879, 987902, 2016.
- [4] U. Singh, B. Walsh, J. Yu, M. Petros, M. Kavaya, T. Refaat, and N. Barnes, "Twenty years of Tm:Ho:YLF and LuLiF laser development for global wind and carbon dioxide active remote sensing", *Optical Materials Express*, 5, 827, 2015.