29th Review of Atmospheric Transmission Models Meeting

13-14 June 2007
Museum of Our National Heritage
Lexington Massachusetts

Session 2: LIDAR

Invited Presentation ...

Chemical Species Measurements in the Atmosphere Using Lidar Techniques

Philbrick, C.R. (Slides & Paper)

White Light Lidar (WLL) Simulation and Measurements of Atmospheric Constituents

Brown, D.M., P.S. Edwards, Z. Liu and C.R. Philbrick (Slide Presentation)

Supercontinuum LIDAR Measurements of Atmospheric Constituents

Brown, D.M., P.S. Edwards, K. Shi, Z. Liu, and C.R. Philbrick (Paper)

Multistatic Lidar Measurements of Aerosol Multiple Scattering

Park, J.H., C.R. Philbrick and G. Roy
(Slides & Paper)

Supercontinuum LIDAR Measurements of Atmospheric Constituents

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Abstract - **Optical transmission and radiance models such as MODTRAN^{TM} 4 have provided the framework for the conceptual design of many remote sensing systems spanning the commercial, military, and academic arenas. Our application of MODTRAN^{TM} 5 has allowed us to design and test a supercontinuum absorption lidar (SAL) system capable of measuring concentrations of various atmospheric constituents at background levels through a long path absorption. Our white light lidar systems utilize femtosecond or nanosecond supercontinuum lasers and free space or fiber optic coupling options for the transceiver systems. Prototype designs are currently being used to demonstrate the capability of these techniques to measure open path atmospheric concentrations of H_2O, O_2, and other species across the Penn State University Park campus. The purpose of this study is to demonstrate the capability of this technology to accurately quantify atmospheric species concentrations through broadband absorption of a supercontinuum source. By controlling the source of broadband radiation, the approach is able to remove uncertainties inherent in hyper-spectral remote sensing systems that use sunlight as a source. Analysis of Differential Absorption Spectroscopic (DAS) data collected through the SAL requires the use of various multi-wavelength algorithms to determine concentration path length. Even though these algorithmic approaches are still under development, preliminary trade studies and performance estimates are possible through the use of the MODTRAN^{TM}5 model. Preliminary examples are discussed.**

I. INTRODUCTION

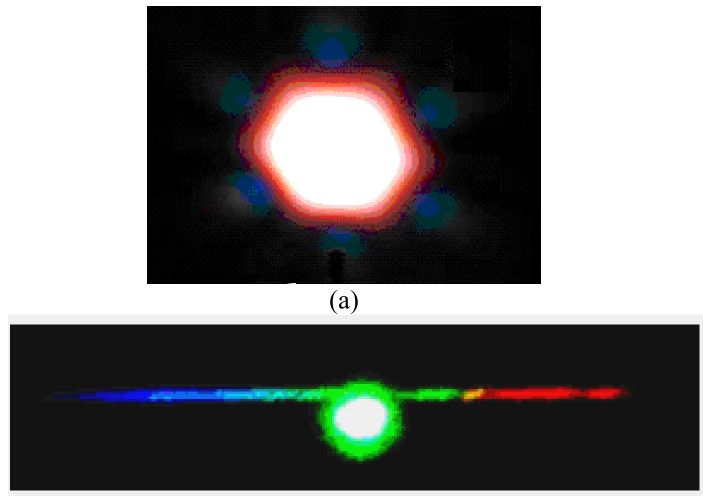
Recent research conducted in the Department of Electrical Engineering at Penn State has focused on a new DIfferential Absorption Lidar (DIAL) technique that utilizes low power supercontinuum sources to make accurate and robust measurements of atmospheric constituents. The MODTRAN^{TM} models have been used as a reference for comparisons with the measured spectra and for investigating the path concentration of species [1]. By using the broad spectral band of a coherent supercontinuum laser [2], differential absorption measurements at many spectral features can be exploited. Development of the Supercontinuum Absorption Lidar (SAL) extends our previously reported investigations to "real world" outdoor measurements of atmospheric species of interest. An additional focus minimizes the transmitted power without compromising the spectral mapping capability of the SAL measurements. By employing the long path absorption approach we have greatly reduced the power requirements necessary to measure concentrations for a host of atmospheric species. When comparing to the supercontinuum absorption data reported by Kasperian et.al. [3] and Rodriguez et.al [4] from the Teramobile project, our technique makes similar absorption measurements with 15 orders less power transmission. With greatly reduced power and cost requirements, we ultimately envision urban pollution monitoring and/or emergency response mapping of chemical species using the SAL. When the approach is coupled with remotely deployed retroreflectors or hard targets, the versatility of such a system is clearly realizable for a range of topologies both in the commercial and military sectors. Additionally, we suggest that highly accurate trace species measurements can be achieved with LPA geometry from ground to space. Measurements to date have been limited to the ultraviolet, visible, and near IR spectral regions, however, we are working on a source that will extend the measurement range into the mid-IR region.

II. SUPERCONTINUUM ABSORPTION LIDAR DEVELOPMENT

The ultra high spatial coherence and low temporal coherence of the supercontinuum white light makes it possible to generate a nearly perfect temporally incoherent point light source. It is the broad bandwidth and high spatial coherence characteristics of the supercontinuum laser source that are particularly useful for remote sensing applications. The systems utilize very short laser pulses (typically in the nanosecond or femtosecond regime) coupled into highly nonlinear photonic crystal fibers to create the broadband spectrum ranging from hundreds to thousands of nanometers. The result of spreading the power across this large wavelength band is typically referred to as a "white light laser," see Figure 1(a). If the collimated supercontinuum white light is then passed through a prism, a rainbow is formed as shown in Figure 1(b).

In addition to the broad bandwidth of the supercontinuum source, wavelength stability as a function of output power is critical when performing differential absorption measurements. This is particularly important for highly structured spectra like that of oxygen in the NIR. Unfortunately, the high peak power of the femtosecond laser, soliton propagation dynamics, and the small ~1 μm core diameter of the PCF used for supercontinuum generation lead to significant high frequency fluctuations in the spectrally broadened pulse. These variations are particularly apparent when observing regions of the spectrum in high resolution, which is a necessity when performing differential absorption comparisons of highly structured species. At low resolution, a scan of the same supercontinuum region may appear to be smooth, broad, and void of high frequency fluctuations; however, a scan at increased resolution typically exhibits large fluctuations, sometimes on the order of the differential absorption intended to be observed in the experimental case.

The first series of indoor white light supercontinuum laser experiments at Penn State utilized femtosecond pulses (average power ~ 500 mW, repetition rate ~ 88MHz, pulse width ~ 64 fs) coupled from a mode locked Ti:Sapphire laser (KM Labs) into a 7 cm photonic crystal fiber (PCF) [2] (NL-2.0-770, Crystal Fibre) to generate the supercontinuum spectrum. Although the high frequency interferents were present in the transmitted spectrum of this source, the variations were not very detrimental to overall success of the measurement. This was mainly due to the large absorption strength of the water vapor band being examined. However, recent work in the same wavelength band has included measurements using an alternate supercontinuum source with notably less output power. The goal of this system is to demonstrate the system capability with further reduced operating requirements while trading off increased susceptibility to noise sources. To combat the more prominent concern of noise levels, secondary goals using this revised approach were to reduce the high frequency wavelength instabilities in the supercontinuum spectrum. By using a pumping laser in the nanosecond regime and changing the supercontinuum generation engine to four-wave mixing, simply increasing the PCF size and length yields notable advantages in the stability of the generated spectral response. The layout of the instrument with the nanosecond pumped supercontinuum source integrated into the transceiver is shown in Fig. 2.



(a)

(b)

Figure 1. (a) The far field pattern of the supercontinuum white light generated from a photonic crystal fiber. (b) The rainbow observed after the collimated white light passes through a prism.

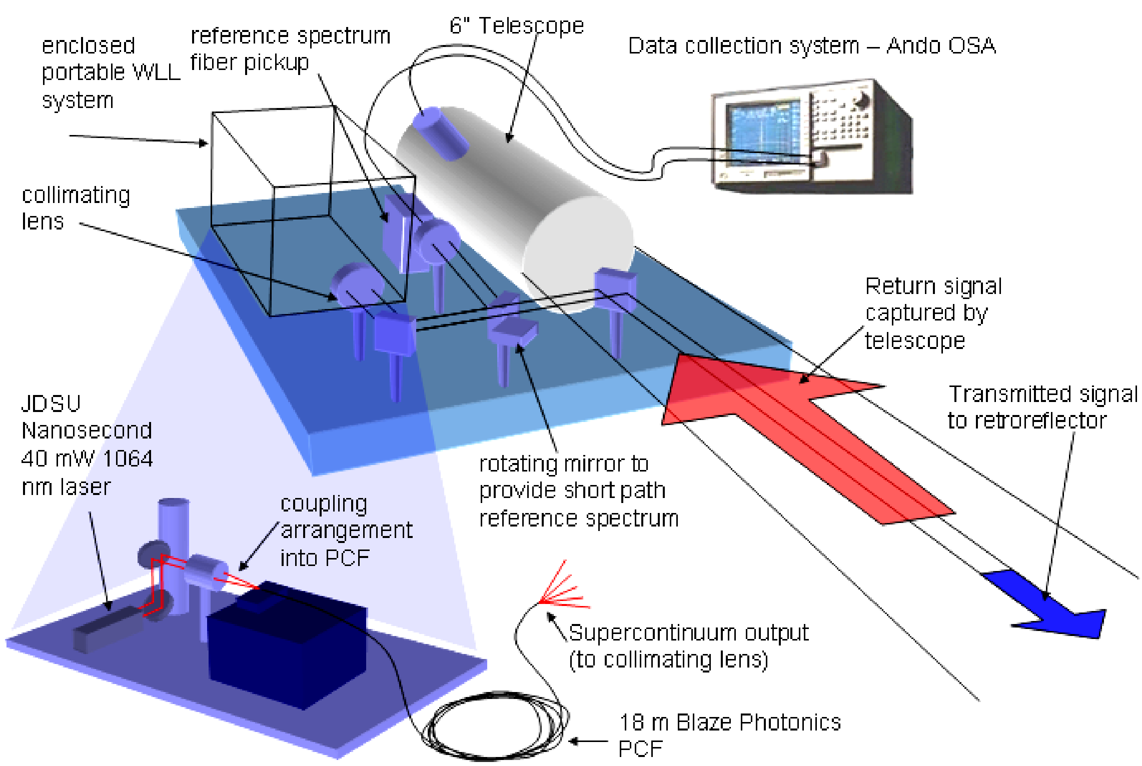


Figure 2. Supercontinuum absorption LIDAR using a low power supercontinuum source at site of remote transceiver system.

The supercontinuum white light can be generated by coupling sub-nanosecond laser pulses from a passively Q-switched microchip laser (JDSU NP-10620-100, wavelength at 1064 nm, average power ~ 100 mW) into a 18 m photonic crystal fiber (Blaze Photonics SC-5.0-1040). The nanosecond pumped supercontinuum source is the heart of the more recently developed SAL transmitter used at the Penn State University Park campus for outdoor measurements. Fig. 2 shows the optical setup used to monostatically transmit and receive the supercontinuum signal. Various broadband mirrors are used to fold the transmitted beam into the center of the FOV of the 4" Newtonian collection telescope for the long path measurement. To normalize low frequency variations in the collected long path spectral return from the retroreflector target, a short path reference spectrum is created via flip mounted optics. The detector used for the entire spectral range of both the reference and signal paths is an Ando AQ6315E optical spectrum analyzer. Fig. 3 is an image of the scattered component of the supercontinuum returned from a retroreflector 150 m away. Fig. 4 shows the broadening of the 1064 nm pump wavelength over a range of wavelengths in the visible part of the spectrum through various nonlinear optical processes (primarily self phase modulation).

Figure 3. Reflection of UV-NIR supercontinuum source off a 6" retroreflector ~150 m away

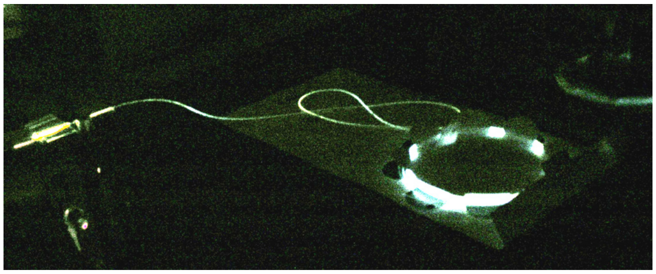


Figure 4. When properly tuned for maximum output power, the wavelength spread of the supercontinuum light due to self phase modulation can be observed in the PCF.

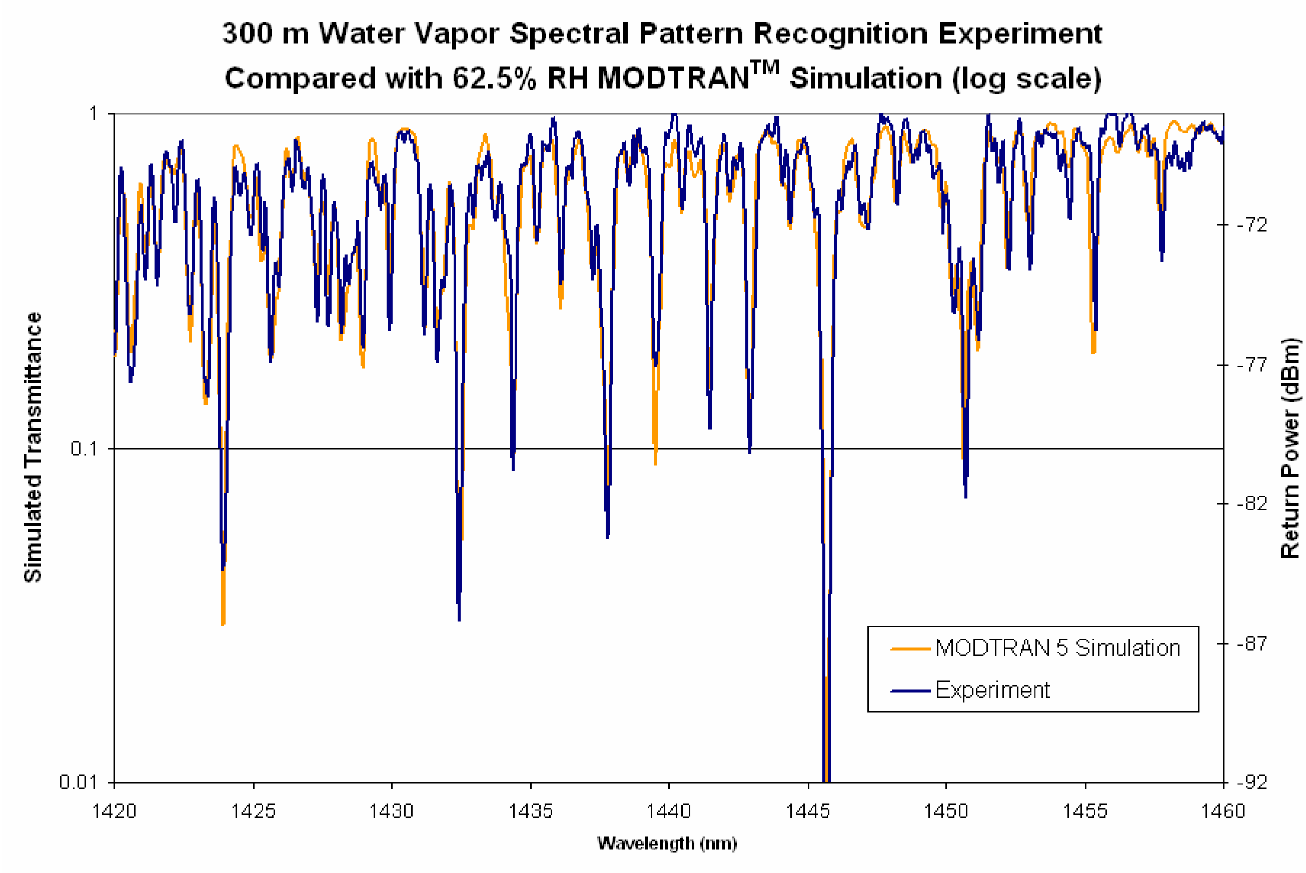


Figure 5. Spectral scan of the 1420 to 1460 nm band in the infrared; notice the strong water vapor absorption features.

Integrating the supercontinuum source into a lidar transceiver allowed collection of measurements over a 300 meter atmospheric path. The absorption spectra of various background species can be readily observable. A prominent region of these absorption features is the water vapor band in the 1350 to 1440 nm wavelength region. When transmitting an approximate total power of only 8 mW, the system was capable of capturing enough backscattered laser radiation over a wide spectral range that returned from a retroreflector target to provide adequate signal level for the Ando OSA to detect water vapor absorption. Fig. 5 shows the normalization of this signal for the wavelength band of interest compared to a MODTRAN™ simulation result. The striking agreement between the experimental and simulated results led into a more in depth confirmation of the water vapor concentration through a least squares fitting algorithm. Previously, in the laboratory environment, the 1380 to 1420 nm region was chosen for verification studies because it is the wavelength location of strong absorption features. However, the large absorption on some spectral lines in this range led to false results due to complete absorption of the corresponding supercontinuum wavelengths. Instead, the region from 1434 to 1439 nm shown in Fig. 6, was chosen for quantitative studies. Although the overall magnitude of absorption is smaller in this range, the longer 300 m path provides enough differential absorption to provide a robust spectral signal of the water vapor absorption structure.

A least square fitting algorithm is used to quantitatively determine water vapor concentration by simulating various water vapor concentrations for a 300 m path using the MODTRAN™ transmission code. These datasets were then compared to differential absorption calculations to find the best matching simulation. With such a large number of different wavelength features available for differential absorption comparisons, ratio matrices are created to quickly compare the data samples. Following the formation of the matrices through random sampling of wavelengths, the sum total difference of ratio matrices for the simulated values and experimental data were evaluated to find the best matching result. When comparing the MODTRAN™ simulation values with the experimental data through this approach, a best match of 62.5% RH is found, see Fig. 7. This compares well with measurements by a MET station deployed nearby on the University Park campus at the times the experiment was performed.

III. SUPERCONTINUUM ABSORPTION LIDAR TOPOLOGY 2: MEASUREMENTS OF ATMOSPHERIC OXYGEN

The differential absorption technique capitalizes on detecting miniscule differences between on-line and off-line wavelengths and is therefore most proficient with stable, low noise measurements at specified wavelengths. When performing many differential absorption calculations with the supercontinuum absorption lidar data, a stable continuous spectrum will naturally generate the most reliable resultant in calculating the concentration path length. The differential absorption effect is best realized when taking a reference spectrum to remove instrument function imposed in the collected dataset by the experimental hardware and the background atmosphere. However, the interest in this study is to determine the atmospheric background concentration of various constituents. A wavelength normalization for the full path reference spectrum would remove the exact differential absorption signature we may wish to analyze.

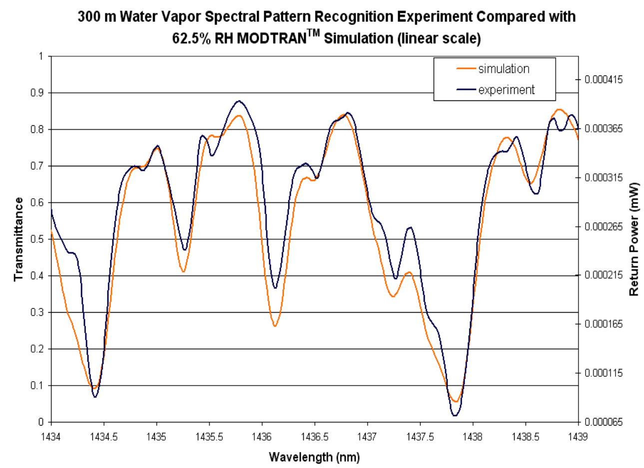


Figure 6. A subset of the collected spectra was used for quantitative calculations.

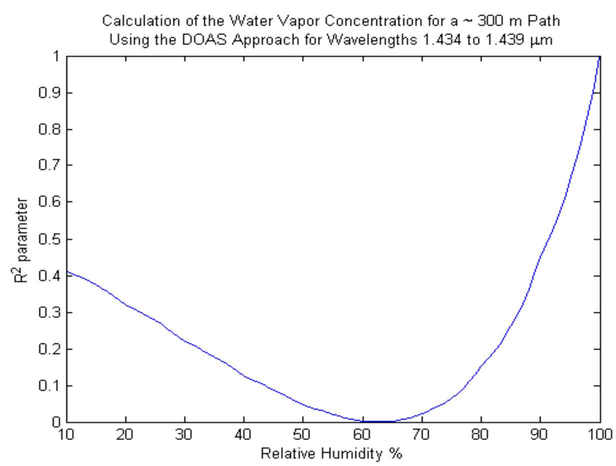


Figure 7. Using a least squares detection approach, an arrived water vapor relative humidity of 62.5 % is realized. This compares well with what was measured by a MET station deployed nearby.

Short path reference spectra have been evaluated to study the long path experimental results with limited success. When receiving the return signal from different distances in the far field (whether it is over a short reference path or any longer path), the coupling geometry to the return fiber changes dramatically due to the variability in the near field focus quality of the scattered signal. Additional wavelength distortion is introduced in the collected signal due to the chromatic aberration in the fiber optic focusing optics themselves. Together these effects combine to vary the coupling efficiency as a function of wavelength. When this effect is present in both the transmitting and receiving sides of the system, as is used in this arrangement, the differential absorption effect due to oxygen in the NIR range is scarcely observable. Fig. 8 indicates the long fiber path from the basement to the roof of the three-story building.

To combat the problems introduced by coupling the supercontinuum light into fiber, we must examine the dynamics of broadband laser propagation in a multimode fiber. Through experimentation in the laboratory it has been determined that high frequency wavelength fluctuations are due to high order mode interference at different wavelengths. We know of two possible ways to reduce the wavelength effects of these higher order propagating modes on the collected signal spectra;

1. Use fibers that only permit single mode operation in an attempt to avoid high order mode interference from corrupting the differential absorption data, and/or
2. Restrict or filter the high order modes on the transmitting and receiving sides of the system.

If the goal of the SAL project was only to utilize specific widely spaced wavelengths provided by the supercontinuum laser source, individual fibers with high transmission for each of these wavelengths would optimize system performance. The obvious limitation to this approach however, is that the differential absorption comparisons are restricted to the fiber cutoff frequency choices. System tunability is hence compromised when using this approach. Alternatively, standard broadband telecom fibers can be used. By simply bending the transmit and receive fibers in a host of geometries, the high order modes 'leak' from the surface of the fiber at the steep incident angles with the core-cladding interface. Experimentally, this effect was verified by bending the transmit fiber for a series of radii and observing the illumination of the fiber walls, while the output approaches that expected for single mode performance.

SAL is used for high sensitivity measurements of highly structured or low concentration species of interest. The high sensitivity is obtained with a research grade liquid nitrogen cooled PI/Acton spectrograph serving as the broadband detector. An easy target, oxygen, was selected to test operation using this high sensitivity approach. For the initial measurements, the absorption band in the 762 nm range was chosen due to the strong absorption bands and high supercontinuum power levels achieved there. By extending the outdoor path to 600 m, and mode filtering the transmitted and received signals, the oxygen signature is clearly observable in the raw data, see Fig. 9. When performing a polynomial fit and subsequent average for multiple spectral scans, we arrive at the conclusion for oxygen absorption spectra in the NIR shown in Fig. 10 (blue line). After making the necessary adjustments to the MODTRAN™ 5 simulation (orange line) so that the wavelength resolution matches that used on the spectrograph, the results are shown to match well. Further improvements to the quality of the optical absorption spectrum are expected after mode filtering apparatuses are integrated into both the transmitting and receiving sides of the SAL instrument. Following this upgrade to the instrument, measurements will be obtained to evaluate previously developed data processing algorithms to extract concentration path length (CPL) of the signals from oxygen, water vapor and other atmospheric constituents that have small absorption features in the spectral range of the supercontinuum laser source.

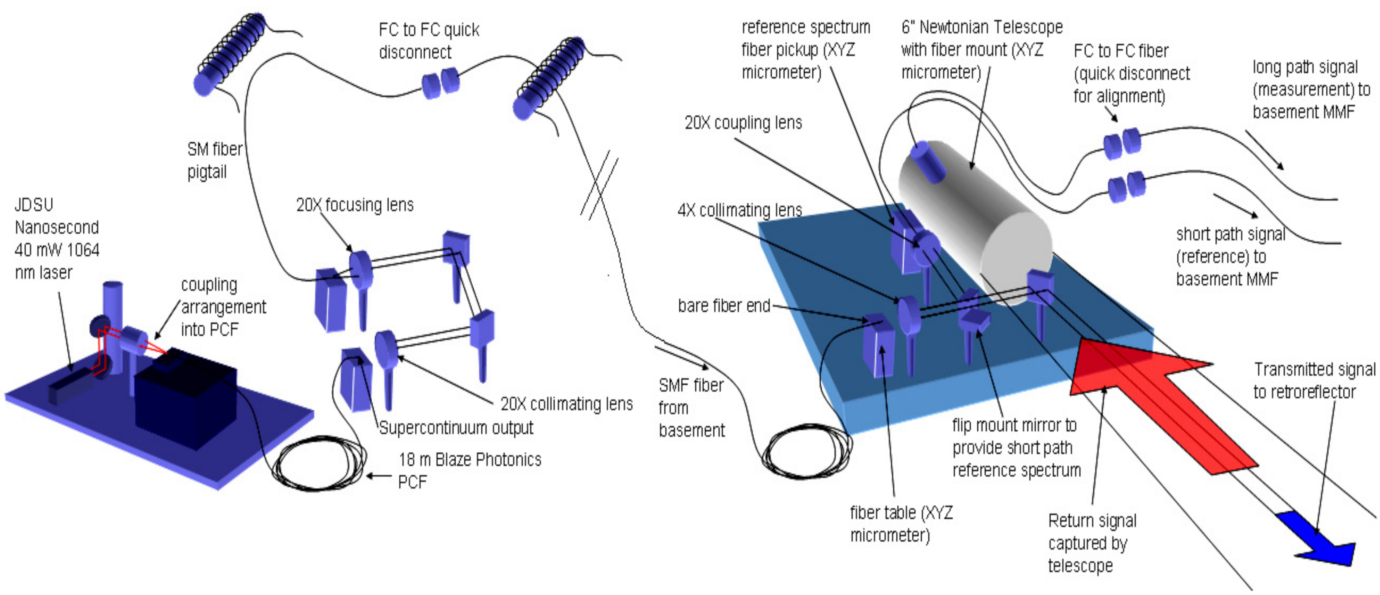


Figure 8. Supercontinuum absorption lidar using a low power supercontinuum source and detector that are fiber optically coupled to rooftop mounted transceiver system.

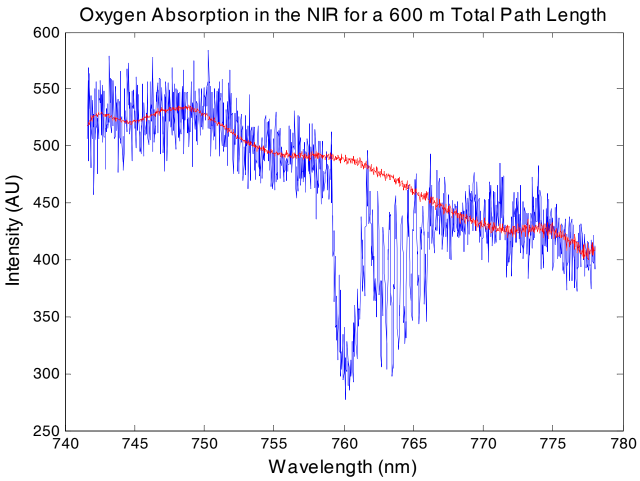


Figure 9. Raw data collected for 600 m atmospheric path, oxygen absorption target. Red line is normalization polynomial fit.

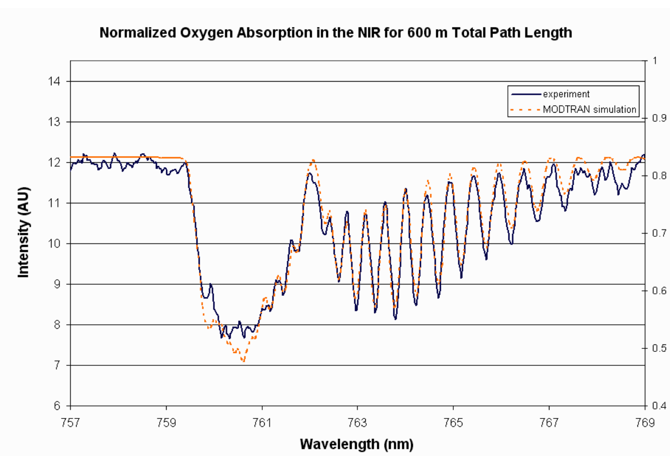


Figure 10. Final processed results for 600 m open atmospheric path of oxygen absorption compared to MODTRAN™ simulation result.

IV. CORRECTION OF MODTRAN™ WAVELENGTHS FROM VACCUUM TO AIR

All MODTRAN™ simulations performed in this study were found to be offset from experimental results by roughly 0.2 to 0.3 nm. At the 2007 AFRL Transmission Meeting it was suggested that this deviation could be due to the lack of the conversion of MODTRAN™ output wavelengths from vacuum conditions to those expected in air. When then applying the standard conversion (1) to the MODTRAN™ outputs, excellent agreement is realized (Figs. 11 and 12) [5].

$$\lambda_{air} = \frac{\lambda_{vac}}{1.0 + 2.735182\times10^{-4} + \dfrac{131.4182}{\lambda_{vac}^{2}} + \dfrac{2.76249\times10^{8}}{\lambda_{vac}^{4}}} \quad (1)$$

Equation 1 units are in Angstroms.

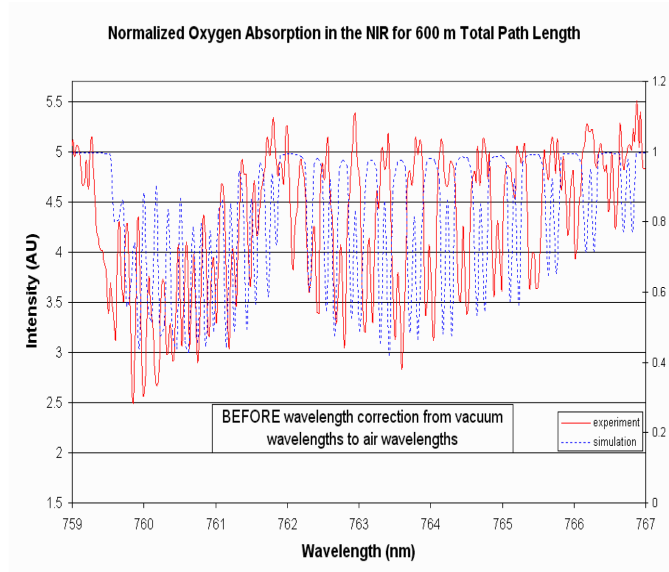


Figure 11. Uncorrected MODTRAN™ simulation result compared to raw experimental data.

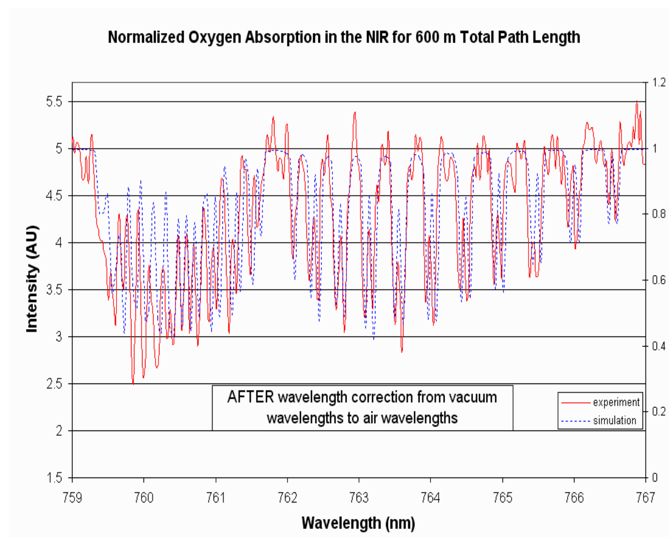


Figure 12. Corrected MODTRAN™ simulation result compared to raw experimental data.

V. CONCLUSIONS

The high spatial coherence of supercontinuum sources allow them to be operated much like a laser, and lend themselves well to operations traversing long atmospheric paths. While the research is still under development for midwave infrared (MWIR) supercontinuum sources, current results have demonstrated the long path absorption technique using near infrared (NIR), visible and ultraviolet (UV) supercontinuum sources. This study has presented the results of two of these measurements, namely results for atmospheric concentrations of water vapor and oxygen. Our conclusions from multiple measurements using three system designs, and in making revisions required to achieve these results suggest that measurements of additional atmospheric species and several trace species are realizable using the presented approach. Data collection, processing, and interpretation steps depend on system configuration and the target species of interest; therefore it is critical to develop a host of algorithmic approaches for processing and interpreting the collected data. Lastly, our experimental results when compared to the MODTRAN™ 5 transmission code confirm the 0.2 to 0.3 nm ambiguity in the region of the 762 nm oxygen absorption, as discussed at the AFRL 29th Review of Atmospheric Transmission Models in Lexington, MA, 13-14 June, 2007.

ACKNOWLEDGEMENT

The authors would like to thank all the members of the Ultrafast Optics Laboratory in the Department of Electrical Engineering at Penn State for their expertise, support, and readiness to always be ready to discuss the problems and successes of both our collaborative and individual projects. We also gratefully acknowledge the contributions of Drs. Gail Anderson and John Selby, as well as the many researchers responsible for development of the MODTRAN™ model that is currently available. The questions related to wavelength corrections for the MODTRAN™ data were described by Dr. John Selby in a paper for the 29th annual AFRL Transmission Meeting, 13-14 June, 2007.

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