Laser Absorption Spectrometer Measurements of Atmospheric O_2 in the 1.27 µm Band

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***Abstract* – This paper discusses the development of a Laser Absorption Spectrometer (LAS) instrument for measuring atmospheric O_2 in support of the future space mission, Active Sensing of CO_2 Emissions over Nights Days and Seasons (ASCENDS), put forth in the National Research Council's Decadal Survey, 2007 [1]. Over the past year a transmitter capable of emitting 1.8 watts of average power with < 3 MHz linewidth at the desired wavelength of 1271 nm has been developed. This transmitter is based on stimulated Raman amplification in a P_2O_5 doped fiber, designed to minimize Stimulated Brillion Scattering (SBS) while maintaining high Raman gain. The transmitter has been integrated into an ITT Engineering Development Unit (EDU) and has made preliminary measurements of O_2 at ITT's lidar ground test facility. The measurement approach is based on ITT's flight validated EDU for measuring atmospheric CO_2. This technique takes advantage of the high sensitivity measurement method known as lock-in amplification to allow multiple wavelengths to be simultaneously transmitted and received on a single detector, even in the presence of significant background noise. The wavelengths are separated in post processing, normalized and their ratios taken to yield the differential absorption between the transmitted wavelengths. The differential absorption is then combined with other measurements such as range to the target, temperature and altitude to determine the atmospheric pressure. A Line-By-Line Radiative Transfer Model (LBLRTM), utilizing local weather station data is being used for comparisons with the lidar measurements. An Overview of the ITT EDU, details of the amplifier development to date, methodology of the measurement and retrieval methodology are covered in the following sections.**

LAS INSTRUMENT OVERVIEW

The architecture for ITT's CO_2 LAS EDU for ASCENDS is illustrated in Figure 1. The all-fiber-coupled transmitter consists of a set of distributed feedback lasers (DFB's), each paired with a modulator or semi conductor amplifier (SOA), and one or more erbium doped fiber amplifiers. Each continuous wave (CW) laser wavelength is amplitude-modulated with its own RF frequency and all are transmitted simultaneously. A lock-in method is used to separate the wavelengths in the return measurement signal as well as the transmitted energy reference signal.

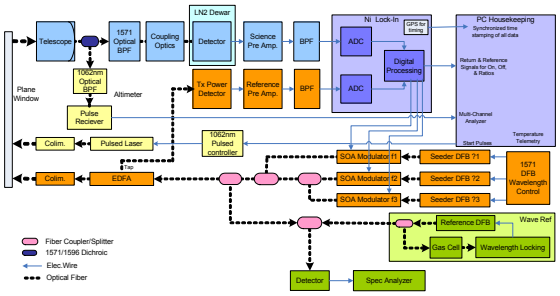

Figure 1. ITT's CO2 LAS has been operationally validated via extensive ground and aircraft campaigns.

This instrument has undergone multiple ground and airborne field tests in cooperation with NASA Langley Research Center (LaRC), since 2004. The instrument was built largely with off-the-shelf components and uses high reliability telecom components, including lasers, modulators and fiber amplifiers in the transmitter. All wavelengths are transmitted simultaneously from a single fiber collimator and the return signal is collected by a simple 8" telescope fiber coupled to a HgCdTe APD. This eliminates sensitivity to common electronics noise and highly varying surface reflectance, and also minimizes the effects of atmospheric turbulence and speckle by making them common mode. The analog signal is sampled with a high resolution scope card housed in a National Instruments PXI chassis and the digitized signal is passed through our custom-built software-based lock-in processing system which allows separation of the signals from the individual wavelengths. The separated signals are then used in the standard DIfferential Absorption Lidar (DIAL) relations to determine the integrated column differential optical depth.

The additional components for the O_2 function for ASCENDS are conceptually shown in Fig. 2. The architecture for the transmitter subsystem for the O_2 LAS instrument for ASCENDS is the same as the CO_2 instrument and shares the complete receiver including detector, electronics and signal processing.

The main difference from the CO_2 transmitter is that the O_2 module uses a fiber Raman amplifier which is pumped by a Yb fiber laser, rather than the Erbium Doped Fiber Amplifier (EDFA) used for the CO_2 system.

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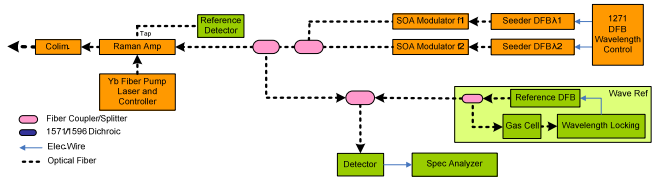

Figure 2. O2 specific components that will be added to the existing CO2 LAS

More detailed information regarding the CO_2 instrument and validation efforts can be found in references [2-6].

O_2 LAS TRANSMITTER OVERVIEW

While the current state of rare-earth doped fiber amplifiers that operate near 1270 nm is limited, fiber Raman amplifiers (FRAs) offer a viable alternative to rare-earth laser amplifiers for achieving amplification in wavelengths where direct transitions are not available, such as the measurement of atmospheric O_2 for the ASCENDS mission [7]. Raman amplification in optical fiber is based on the non-parametric nonlinear process of stimulated Raman scattering (SRS) as has been discussed extensively in the literature over the past 25 years [8, 9].

Until recently, FRAs have been limited in their application due to their lower output power because of the relatively low gain for SRS as compared with other competing nonlinear processes. In particular, stimulated Brillouin scattering (SBS) is the most problematic [10], and as such, numerous techniques for suppressing SBS in optical fiber have been suggested.

Methods such as increasing the fiber core size (large mode area or LMA fibers) [11] or shortening the fiber length as employed in rare earth doped fiber amplifiers do not readily work for FRAs since both are prohibitive to Raman gain [12]. In addition, increasing the spectral linewidth of the amplifier seed will reduce SBS [10] but is not desirable for remote sensing and spectroscopy applications. Instead, alternative techniques have been and are currently being investigated to reduce SBS.

During the past year, work has been done to develop an FRA that achieves both high output power and narrow spectral linewidth at 1271 nm for use in ground based measurements of atmospheric O_2 and proof-of-concept for the utilization of a FRA in ITT's LAS measurement architecture. The current amplifier design is based on P_2O_5 doped silica fiber which offers strong Raman gain at a frequency shift of approximately 1330 cm^{-1} [13]. This shift is much larger than can be achieved with other common fiber dopants and allows the 1270 nm wavelength region to be reached by pumping the amplifier with a commercially available Yb fiber laser at 1088 nm in a single stage to reach the 1270 nm region.

The effort to date has resulted in an amplifier configuration that is split into two separate gain stages for the online and offline wavelength channels. The two amplifier arms are combined prior to the transmitter collimation optics to facilitate simultaneous transmission of the on and off lines and achieve full spatial overlap. Each stage is independently pumped in the forward direction and each is seeded by an independent DFB source at the desired wavelength. Two stages were necessary to avoid Four Wave Mixing (FWM) which occurred in the current fiber design when the on and offline wavelengths were simultaneously amplified in the same fiber. Simultaneous amplification was realized and demonstrated but the total output power was limited. The small spectral separation between the online and offline wavelengths (~50 pm) coupled with the length of fiber needed for Raman amplification is conducive to FWM. Techniques are currently being explored to limit this effect in addition to minimizing SBS for the next generation of fiber, and is set for manufacture later this year.

For the current amplifier, the online channel is pumped by a Manlight 1088 nm 10 W Yb fiber laser and uses ~ 500 m of P_2O_5 fiber for its Raman gain stage. The fiber used in this channel is designed to reduce SBS by varying the core diameter longitudinally along the length of the fiber as has been suggested in the literature [12]. This technique was largely driven by the limited availability of P_2O_5 fibers and challenges encountered with manufacturing more complex approaches. A stable average output power of ~ 1.5 W CW was achieved on this channel, with a spectral linewidth of < 3 MHz, and ~25% optical to optical efficiency.

In contrast, the offline channel employs 1 km of standard P_2O_5 doped fiber (non SBS suppressed) and is pumped by a Nufern 6 W Yb fiber amplifier seeded at 1088nm. Due to the lower pump power and use of non SBS suppressed fiber in the gain stage, the total average output power for this channel was 0.3W, and also exhibited a linewidth of < 3 MHz.

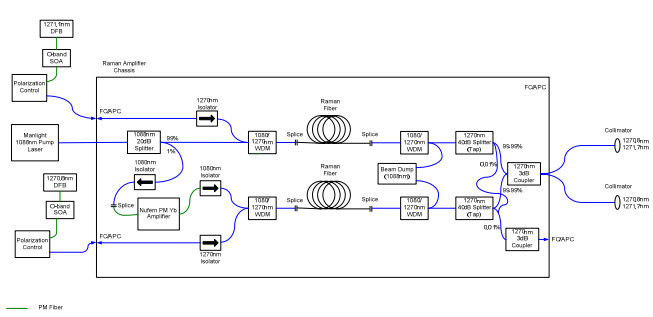

Figure 3. Generation I FRA design schematic based on P_2O_5 as primary dopant in the gain fiber.

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The total modulated output of the amplifier using both on and off lines was 1.8 W average power. Had this first amplifier not been limited by pump power the remaining SBS suppressed fiber would have been used in both arms and would have resulted in a maximum of 3W average power

O2 LAS MEASUREMENTS

The O_2 lidar was operated at ITT's field test site located in New Haven, IN. The instrument is housed in a trailer, which is located 680 m from a stationary target. The target consists of both light and dark surfaces, each has been shown to have fairly Lambertian reflectance profiles. The two targets allow both high and low power measurements to be conducted at this site. Additional ranges can be achieved using the visible tree lines as the target. These facilities are illustrated in Fig. 4. This test site is also equipped with instrumentation for monitoring atmospheric pressure, temperature, humidity, wind speed and direction, CO_2 in ppm and H_2O in ppt.

The first generation amplifier is shown in Fig.5, consists of an Agilent two channel power supply for the Nufern amplifier, the Manlight pump laser, the amplifier box containing the Nufern amplifier used as the pump for the off line channel, a heat sink for the amplifier, the gain fibers and all of the other Raman amplifier components.

The complete transmitter setup, shown in Fig. 6, includes the modulation electronics, Distributed Feedback Lasers (DFB's) and Semiconductor Optical Amplifiers (SOA's), polarization control for each channel and a wavelength meter for each of the transmitted channels. All control and data acquisition was

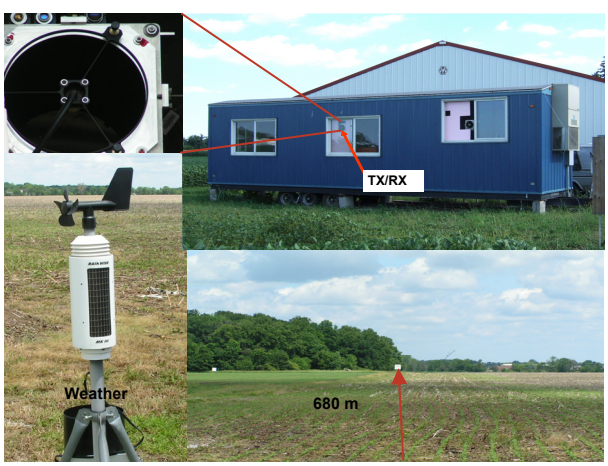

Figure 4. ITT's lidar ground test facility, New Haven, IN.

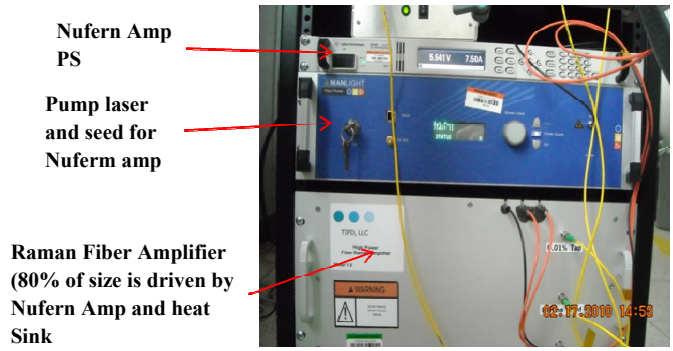

Figure 5. Raman amplifier components for O_2 LAS demonstration.

done by interfacing with the ITT EDU, shown in Fig. 7. The receiver utilized the same telescope, detector and electronics that are used for measuring CO_2 with the EDU. The only modification was replacement of the single-band optical bandpass filter with a dual-bandpass filter to accommodate the 1271 nm return signal. The same software developed for generating the modulation sequences and processing the digitized return signal for the CO_2 instrument were used for the O_2 measurements.

Starting in February, 2010 ITT was able to perform a series of measurements using the integrated first generation high power amplifier at our ground test site facility. All measurements were taken with one collimator transmitting to the target while the other was monitored on a power meter to determine the average power being generated by the amplifier. Measurements were taken to

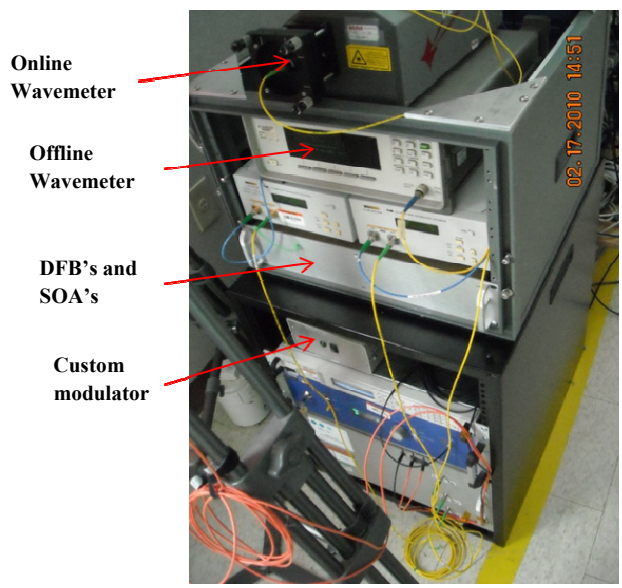

Figure 6. Complete 1271 nm Transmitter assembly for O_2 LAS demonstration.

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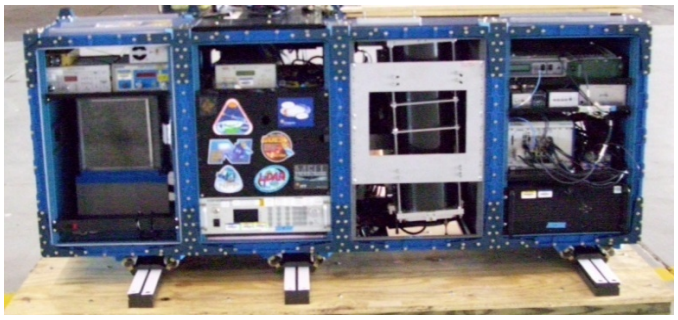

Figure 7. Image of ITT's validated airborne CO_2 EDU

various targets, mainly trees, from 680 m to 2750 m. The off line wavelength was monitored using a 1 pm resolution HP wave meter, while the on line wavelength was monitored using a 0.2 pm resolution Bristol wave meter.

RETRIEVAL OF XO2 FROM LAS MEASUREMENTS

A companion suite of software simulation and analysis tools were also developed in concert with the LAS EDU instrument design and deployment activities. The design objective for these tools was twofold: 1) To assess the sensitivity of nominal spectral lines to changes in XO2 concentrations in relationship to environmental noise sources, e.g. uncertainties in temperature and water vapor knowledge and 2) To compare instrument measurements to modeled results. These tools combine sources of data necessary to calculate optical depth using a Line-By-Line Radiative Transfer Model (LBLRTM). Data sources used include: local weather station data (Pressure, Temperature, Relative Humidity), laser altimeter measurements of distance to target, and measured wavelengths from the LAS for selection of online/offline optical depth values.

The data is fed into LBLRTM to generate values of optical depth for a given pressure, temperature, relative humidity, and distance to target. The values for optical depth are computed in the wavelength range of the LAS, and values for online/offline optical depth are selected based upon the measured wavelengths provided by the LAS system. The difference between online and offline optical depths are taken to compare with measurements of differential optical depth taken with the LAS.

The preliminary model comparisons completed to date show good correlation with the O_2 LAS measurements. Some issues related to the wavelength monitor's absolute accuracy and some instabilities in the reference tap for the online need to be resolved before absolute comparisons with the model results can be completed. Figures 9 and 10 show some of the

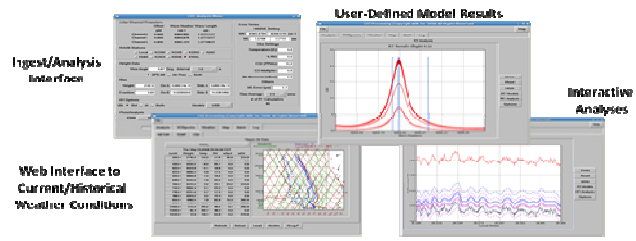

Figure 8. Example of the software suite developed for both simulation and analysis of both the CO_2 and O_2 LAS measurements.

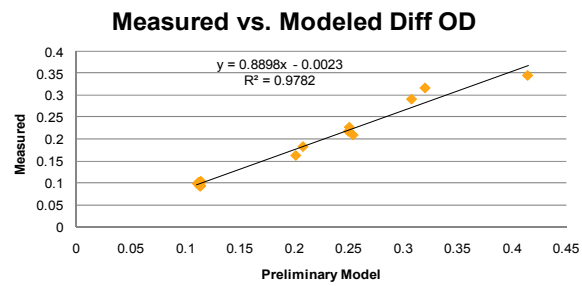

Figure 9. Measured differential optical depth versus preliminary model values showing high correlation over a wide range of optical depths.

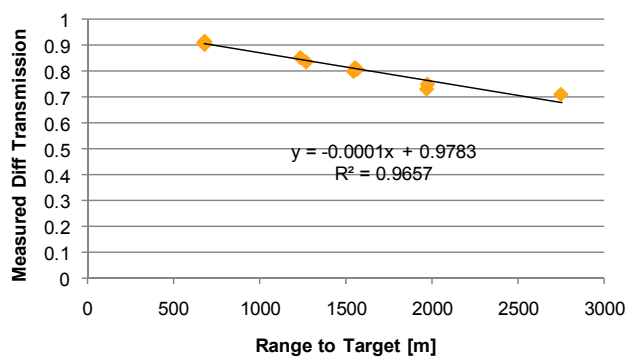

Figure 10. Measured differential transmission for the O_2 LAS on and off line channels as a function of range

results from the initial look at the ground LAS data. Further details will be given in the presentation.

CONCLUSIONS AND FUTURE WORK

An FRA has been developed which produced 1.8 W of average power, with a linewidth of < 3 MHz using P_2O_5 as the primary dopant for the gain fiber. This amplifier has been integrated into the ITT LAS EDU and initial ground tests have been conducted. The retrieved optical depths were processed and initial comparisons with model data show a high correlation between the two.

Some instability in the peaks of the modulation were discovered during the initial field measurements (namely the

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on line tap signal). The cause of these instabilities is being investigated further by TIPD to ensure this is corrected in the second generation amplifier.

While the SBS suppressed fiber used in the current FRA exhibited moderate increases in the output power, further work is underway to reduce the SBS sufficiently to realize an amplifier that can produce at least 5W of average power necessary for scaling measurements of O2 to high altitude aircraft platforms and eventually to space.

The lessons learned in the development and testing of this first amplifier are being used to guide the development of an additional amplifier. The goal for the second amplifier is to achieve a minimum of 4 W average power and to reduce the size weight and power of the second amplifier to be no more that 3 times that of current commercial EDFA devices. The amplifier will again be integrated into the ITT EDU and tested at the ITT ground test facility.

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