Progress Report on the Laser Absorption Spectrometer Development

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***Abstract*- We provide an overview of progress on the laser absorption spectrometer development that has been funded under the Instrument Incubator Program.**

I. INTRODUCTION

Observations of carbon dioxide mixing ratios from Earth orbit, primarily in the lower and middle troposphere with measurement precision equivalent to 1-2 ppmv, are desired to define spatial gradients of carbon dioxide, from which sources and sinks can be derived and quantified and separated from the 1.4% seasonal fluctuation component [1]. Data will be needed over a wide distribution of latitude, with spatial resolution sufficient to provide global monthly mean values on a spatial scale of order 10^6 km^2. There is currently no available remote sensing instrumentation that is capable of providing the high-accuracy carbon dioxide mixing ratio measurements with the vertical and horizontal spatial resolution required by the carbon cycle research program. We are developing an aircraft based integrated path differential absorption instrument known as the laser absorption spectrometer (LAS) operating in the 2-µm spectral region that has the potential to achieve the required precision. The use of this technique for atmospheric profiling dates to the mid-1970's [2] and an aircraft instrument for measuring ozone transport has previously been described [3].

A paper outlining the project was presented at the prior Earth Science Technology Conference [4]. The project consists of the development and demonstration of the instrument. A number of instruments will co-fly with the instrument in order to valid the measurement.

The laser absorption spectrometer has undergone a number of risk reduction experiments and considerable design effort during the past year. A critical design review for the LAS transceiver is to be held in late May 2003, with most of the hardware being completed during the remainder of 2003. Integration and testing of the LAS instrument will take place during the first half of 2004 with a field flight test on the DC-8 planned in the latter half of 2004.

II. LAS INSTRUMENT DESCRIPTION

The coherent LAS transceiver includes three CW Tm,Ho:YLF lasers and a reference CO_2 gas cell. All three lasers are based on CTI's METEOR^{TM} single frequency laser product, scaled in power from 50mW to 200mW.

The LAS transceiver consists of two separate transmit/receive channels for the on-line and off-line components of the measurement. Each channel has a dedicated heterodyne detector and telescope, and a cw laser which acts both as the transmitter and as the local oscillator for heterodyne detection of the return signal. The third laser acts as an optical reference frequency source and is locked to line center using the temperature controlled, hermetically sealed reference absorption cell. The online transmitter frequency is offset locked from this frequency reference using a wide-band heterodyne detector that monitors the beat frequency between the outputs of the two lasers. CTI and JPL have jointly demonstrated that the center frequencies of two single frequency Tm,Ho:YLF lasers can be locked to an accuracy better than 5 kHz. The effective linewidth of the offset-locked laser is then dominated by the short-term frequency jitter of the reference laser. The online transmitter frequency can be tuned over a range of +/- 5GHz with respect to the reference oscillator using a piezo-electrically-positioned resonator end-mirror. In a similar fashion, the offline transmitter is also frequency offset-locked to the line center reference laser for improved frequency knowledge. Since this laser is detuned by about 20GHz from the reference laser, it is convenient to impose frequency modulation sidebands on the reference laser and to lock the offline laser to one of these sidebands. FM sideband locking (FMSL) reduces the detection bandwidth requirements needed for the offset-locking function from more than 20GHz to a few GHz, depending on the selection of the sideband frequency spacing.

Figure 1 shows the vacuum wavelengths of the three onboard laser sources, where L1 represents the wavelength of the line center reference laser, L2 the wavelength of the on-line broadcast laser, and L3 the wavelength of the off-line broadcast laser. The figure also shows a representative plot of atmospheric absorption in the region of 2051nm for a horizontal looking path in the PBL. This absorption plot is for wavelength reference only and does not represent the expected absorption profile strength (extinction coefficient) as seen from the planned aircraft platform. The on-line and off-line lasers are tuned to the shorter wavelength side of the absorption line at 2050.98nm to access absorption features that are less temperature sensitive. Laser L2 is directly offset-locked to Laser L1, while Laser L3 is offset-locked to Laser L1 via FM sideband locking (FMSL). The frequency spacing of L1 and L2 is tunable over 8GHz, with a center detuning of 4GHz. The frequency spacing of L1 and L3 is set at 20GHz, where the effect of the CO_2 profile on the offline channel is minimal.

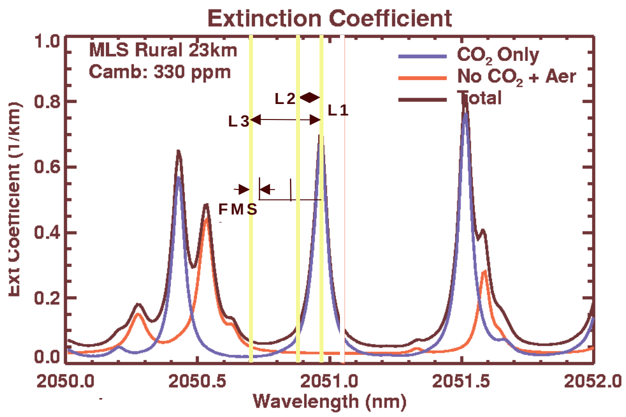

Figure 1. Wavelengths of the three lasers in the LAS transceiver

The functional layout of the LAS transceiver is depicted in Figure 2. The transceiver head consists of several components mounted on two surfaces of a water-cooled aluminum optical bench. Most of the beam paths and components for optical mixing and frequency locking are located on one side of the optical bench, while the beam-expanding telescopes and the three laser sources are located on the other surface. The output beams from the lasers are fiber-coupled and routed to the main surface of the optical bench, while the transceiver beams are routed to and from the telescopes using through-the-bench periscope assemblies. The transceiver is configured as two monostatic, heterodyne assemblies, one for the on-line channel and one for the off-line channel. The frequency shift in each channel between the outgoing signal and the return signal is accomplished by pointing the transmit beams slightly away from nadir below the aircraft. The off-nadir angle is selected to set the center frequency shift and variation to a preferred operating range (10 to 20MHz is the baseline design) based on the aircraft flight speed and attitude control. A polarization transmit/receive architecture is implemented to route signals to and from the transceiver, with circularly polarized light being broadcast through the atmosphere.

The output powers of all three lasers are monitored; the output power values for Lasers 2 and 3 are used in the determination of the on-line and off-line absorption as part of the LAS measurement; the output power value for Laser 1 is available primarily as a laser health status to check on the integrity of the CO_2 line center servo lock. The output of Laser 1 is passed through a high diffraction efficiency acousto-optic modulator (AOM). The main function of the modulator is to introduce a frequency shift between the line center servo lock optics and the rest of the instrument optics. This eliminates unplanned interferometric feedback between surfaces that would otherwise disturb the locking process.

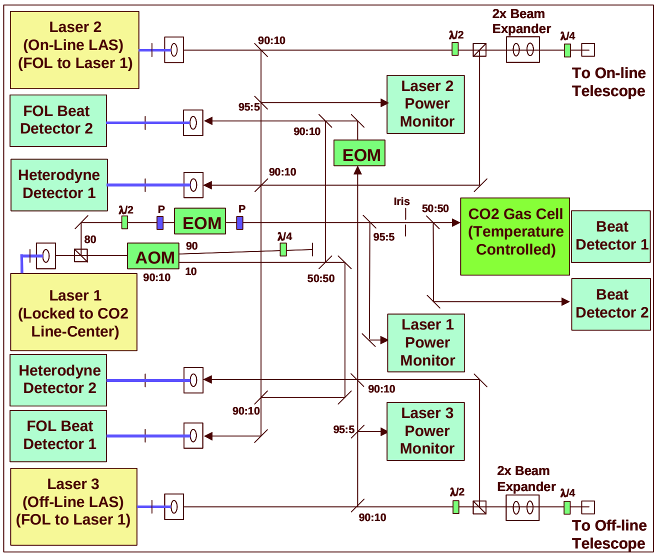

Figure 2. Functional layout of the LAS transceiver (one of two surfaces)

The figure shows the AOM operating in double pass with a quarter-wave retardation plate and polarizer acting as a polarization router after the second pass. With suitable optical design, this configuration allows the AOM frequency to be tuned without displacing the doubly passed diffracted beam. This configuration was initially selected to allow AOM frequency tuning to be used as part of the servo lock process. The latest locking servo design no longer requires tuning of the AOM frequency and so this double pass configuration may be replaced with a simpler single pass configuration.

The AOM diffracted beam is passed through an electro-optic modulator (EOM) that imposes 1[st] order frequency modulation sidebands (modulation index ~1) on the beam prior to its entering the reference CO_2 cell. These sidebands allow FM spectrometry of the CO_2 absorption spectrum. The phase-sensitive beat detector located after the gas cell monitors the sum of the beat frequencies generated between the carrier and the lower frequency sideband and between the carrier and the higher frequency sideband. These two beat

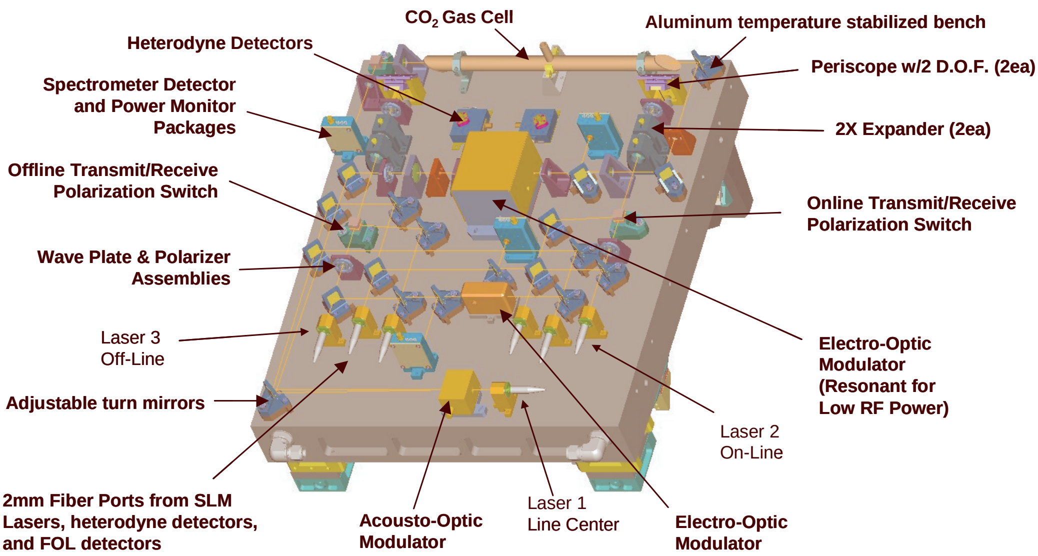

Figure 3. Engineering Model of Optical Bench (showing one of two surfaces)

frequency components are equal and in anti-phase when the carrier is tuned to line center or when it is tuned well away from the absorption feature. The servo-lock process finds the absorption feature at 2050.98nm and then uses the FM spectrometer to lock to line center. Risk reduction measurements have shown that the line center laser can be locked in this manner to an absolute frequency accuracy of about 300kHz (peak-to-peak variation) with respect to the center of the reference CO_2 line center. This result represents nearly a 100 times improvement in frequency accuracy over previously reported demonstrations of absolute CO_2 frequency locking [3] and allows LAS and DIAL (range resolved differential absorption lidar) measurements to be made to the 1ppmv level of precision required. The half-wave retardation plate, polarizers (P) and iris are used to reduce residual amplitude modulation (RAM) detectable in the servo-lock error signal. It is this RAM signal pick-up that limits the frequency lock accuracy of the servo, and is the result of transverse phase changes imposed on the probe beam by the EOM. A second beat detector is currently being considered to provide a reference leg for beat detection in the absence of the CO_2 absorption feature. The main purpose of this reference leg is to reduce the warm-up time of the instrument (as beam alignment is being re-established) from about 30 minutes to just a few minutes.

The fraction of light from Laser 1 which is not diffracted by the AOM (about 10%) is split in two by a 50:50 beamsplitter and used to frequency offset-lock Lasers 2 and 3. A second EOM is used to introduce the FM sidebands required for offset-locking of Laser 1 to Laser 3. The two frequency offset-lock (FOL) beat detectors require detection of signals at several GHz frequency. To avoid signal attenuation and noise pick-up at these high frequencies, the optically mixed light is coupled into single mode fibers and routed to detectors remotely located in the frequency offset-locking elec tronics unit. In contrast, the heterodyne detectors (with preamplifier packages) used for the on-line and off-line LAS measurements require detection of signals of just a few tens of MHz and may be located on the optical bench. All lasers and RF detectors (with the exception of the CO_2 servo lock detector) are fiber-coupled to the optical bench with an intervening fiber-to-fiber connector in each fiber lead. This facilitates component replacement in the field if necessary, allows BPLO (back-propagating local oscillator) alignment of the receive path to the transmit path for each LAS channel, and allows laser source switching for relative alignment of the two transmit/receive telescopes to ensure monitoring of the same volume of atmosphere and ground surface return.

Figure 3 shows an engineering model of the transceiver optical bench, showing the main optical components for heterodyne LAS signal detection and absolute frequency locking of the three onboard lasers and Figure 4 shows a analysis of the thermal gradients within one of the telescopes. The optical bench will be located in a positive-pressure enclosure, designed to permit hermetic sealing of the transceiver optical head and to accommodate mounting on a number of different aircraft platforms.

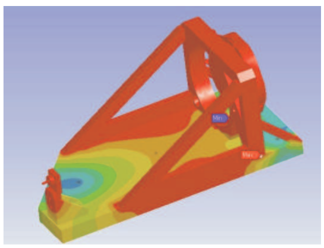

Figure 4. Temperature Distribution within a Telescope

The meeting presentation will discuss details of the transceiver design, including results of the risk reduction measurements demonstrating absolute frequency locking to CO2 line center and the status of the ancillary instruments for validating the measurement.

Acknowledgment

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