SENSITIVITY STUDIES FOR SPACE-BASED LASER MEASUREMENTS OF ATMOSPHERIC CO_2 CONCENTRATION TOWARDS FUTURE NASA MISSION ASCENDS

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Abstract

Global measurement of atmospheric CO_2 concentration from space is greatly desired for global and regional carbon budget studies. The biggest challenge for CO_2 remote sensing from space is to achieve the high-precision science measurement requirement (~ 1 ppmv or 0.3% on regional scales) so that the satellite measurements will be able to remarkably reduce current large uncertainties about carbon sources and sinks (Tans et al., 1990; Fan et al., 1998).

CO_2 shortwave infrared bands at 1.57, 1.6 and 2.1 μm have been studied and shown to possess great potential to achieve such high-precision measurement (O'Brien and Rayner, 2002; Kuang et al., 2002; Dufour and Breon, 2003; Mao and Kawa, 2004). The Orbiting Carbon Observatory (OCO), the NASA Earth System Science Pathfinder Project (ESSP) mission, and the Japanese Greenhouse gases Observation SATellite (GOSAT) have adopted these bands to measure CO_2 from space using surface reflected sunlight (Crisp *et al.*, 2004; Yokota *et al.*, 2004). However, using these weak vibration-rotation bands requires line-resolving spectral resolutions to achieve measurement precision (Dufour and Breon, 2003; Mao and Kawa, 2004; Fu *et al.*, 2008). In other hand, a major issue in the passive approach using reflected sunlight with these bands is the contamination of aerosol and/or cirrus cloud scattering in the sunlight path (Mao and Kawa, 2004; Aben *et al.*, 2007). Scattering by the particles in the atmosphere will modify the sunlight path length and thus change total column CO_2 absorption and then result in retrieval errors greater than measurement precision target. This type of errors varies in time and space, depending on solar illumination and satellite viewing geometry, surface reflectivity and aerosols/clouds physical (*i.e.*, altitude) and optical properties (*i.e.*, scattering phase function).

The National Research Council of the U.S. National Academies has recommended a future mission called Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) in its Decadal Survey *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. This mission aims "*to produce global atmospheric column CO_2 measurements without seasonal, latitudinal, or diurnal bias using simultaneous laser*

remote sensing of CO_2 and O_2." NASA Goddard Space Flight Center is developing an active approach as a candidate toward this mission. A series of sensitivity studies have been conducted for this development. Following is a summary of the sensitivity study results and more details will be presented during the meeting.

(1). Measurement Strategy

The laser technique for this approach uses the 1.57 μm CO_2 absorption band and samples several wavelengths on one strong absorption line in this band (Abshire *et al*., 2008). It measures differential absorption at local nadir mode and uses the ratio of the on-line to off-line signal to retrieve CO_2 amount without aerosol and thin cloud absorption terms. The lasers in this approach are pulsed and the surface return signal can be well separated from that returned by the atmosphere using time gating in the receiver. Thus, compared to passive approaches and other active laser approaches (Menzies and Tratt, 2003; Ehret *et al*., 2008; Browell *et al*., 2008; Heaps *et al*., 2008), the aforementioned influences from atmospheric scattering can be greatly reduced by this method.

Meanwhile, on-board O_2 measurement using O_2 A-band at 0.76 μm is recommended using the same method and technology for dry air abundance in the same atmospheric path in order to retrieve CO_2 concentration (mixing ratio) with regard to dry air. The time-gating and pulsed laser approach will yield even greater benefits in the O_2 A-band where atmospheric scattering is larger and was a major error source in path length and surface pressure measurements (*e.g*., Mitchell and O'Brien, 1987).

(2). Line and Wavelengths Selections

Sensitivity studies showed the optimal CO_2 line in the 1.57 μm band was the strongest CO_2 line in the *R*-branch centered at 1572.335 nm. This line has overall the minimum sensitivity to atmospheric temperature change, particularly to the lower atmospheric temperature change, and is close to the available laser which is centered at 1530 nm. Absorption measurements on several wavelengths on this line provide vertical weighting functions peaking at desired layers. Measurement at wavelength with approximately 50% absorption targets CO_2 variation in the atmospheric boundary layer for sources and sinks estimate. Measurements at wavelengths closer to the line center have greater absorption, providing free troposphere CO_2 information related to vertical and horizontal CO_2 transport, equivalent to CO_2 retrievals from advanced temperature sounders such as AIRS and IASI. Measurement at line center can yield stratospheric CO_2 which is about 4-5 years older than tropospheric CO_2.

The optimal line for the on-board O_2 measurement is located in the middle of *P*-branch of O_2 A-band and centered at 764.7 nm with the minimum sensitivity to atmospheric temperature variation. The wavelength in the ridge of the doublet line is ideal for O_2 measurement from space for the least temperature sensitivity, vertical weighting function peaking at the surface and the smallest impact of potential wavelength drift in the fly.

(3). Ancillary Data Requirements

Atmospheric temperature fluctuations can modify line absorption measurements and change CO2 mixing ratio as well even without any CO_2 source/sink changes. High spatial and temporal resolution atmospheric temperature profiles are thus required to accurately derive CO_2 concentration from O_2/CO_2 absorption measurements. Advanced temperature sounders, AIRS, IASI and future NPOESS/CrIS can provide mesoscale temperature profiles within a precision better than 1 K in 1-km-thick layers (Susskind *et al.*, 1998). Temperature analyses from weather forecast models can provide similar precision of temperature data also to meet high-precision CO_2 retrievals.

Atmospheric water vapor is another ancillary data required for CO_2 mixing ratio calculation. Besides minor water vapor absorption in the CO_2 line used in this development, water vapor exerts a partial pressure cause line broadening and an error in the retrievals. High spatial and temporal resolution atmospheric water vapor profiles from advanced sounders like AIRS or from weather forecast models are also needed in deriving CO_2 concentration particularly in the tropics and other moisture atmospheres.

(4). Laser Requirements and other Measurement Optimizations

For a given sensor design the surface returned pulse strength and hence signal-to-noise ratio (SNR) depends strongly on laser peak power, orbit altitude, the atmospheric transmission and surface reflectivity. For an example, SNRs at both off-line and on-line are a function of laser peak power. The relative error of retrievals inferred from on-line to off-line ratio decreases to less than 0.003 or 0.3% (measurement precision target) when laser peak power increases to 3000 watts or greater. Meanwhile, lower orbit altitude, higher surface reflectivity and atmospheric transmission will enhance SNR and reduce retrieval errors.

Bibliography

Aben, I., O. Hasekamp, and W. Hartmann, Uncertainties in the space-based measurements Of CO2 columns due to scattering in the Earth's atmosphere, JQSRT, 104, 450-459, 2007.

Abshire, J. B., S. R. Kawa, H. Riris, G. R. Allan, X. Sun, M. A. Stephen, E. Wilson, J. F. Burris, and J. Mao (2008), Laser sounder for measuring atmospheric CO2 concentrations: Progress toward ASCENDS, 2008 EGU Meeting, Vienna, Austria, 13-18 April.

E. V. Browell, M. E. Dobbs, J. Dobler, S. Kooi, Y. Choi, F. W. Harrison, B. Moore, T. S. Zaccheo (2008), First Airborne Laser Remote Measurements of Atmospheric Carbon Dioxide, A41D-0145, Fall AGU 2008, San Francisco, Calif., 15-19 December.

D. Crisp, R.M. Atlas, F.M. Bréon, L.R. Brown, J.P. Burrows, P. Ciais, B.J. Connor, S.C. Doney, I.Y. Fung, D.J. Jacob, C.E. Miller, D. O'Brien, S. Pawson, J.T. Randerson, P. Rayner, R.J. Salawitch, S.P. Sander, B. Sen, G.L. Stephens, P.P. Tans, G.C. Toon, P.O. Wennberg, S.C. Wofsy, Y.L. Yung, Z. Kuang, B. Chudasama, G. Sprague, B. Weiss, R. Pollock, D. Kenyon, S. Schroll, "The orbiting carbon observatory (OCO) mission," Adv. Space Res. **34**, 700-709 (2004).

E. Defour and F. M. Breon, "Spaceborne estimate of atmospheric CO2 column by use of the differential absorption method: error analysis," Appl. Opt. **42**, 3595-3609 (2003).

G. Ehret, C. Kiemle, M. Wirth, A. Amediek, A. Fix, S. Houweling, "Space-borne remote sensing of CO2, CH4, and N2O by integrated path differential absorption lidar: a sensitivity analysis," Applied Physics, B 90(3-4): 593-608 (2008).

S. Fan, M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, "A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models," Science **282**, 442-446 (1998).

Dejian Fu, Keeyoon Sung, Chris D. Boone, Kaley A. Walker, Peter F. Bernath, Ground-based solar absorption studies for the Carbon Cycle science by Fourier Transform Spectroscopy (CC-FTS) mission, Journal of Quantitative Spectroscopy and Radiative Transfer, Volume 109, Issues 12-13, 2219-2243 (2008).

W. S. Heaps, E. L. Wilson and E. Georgieva (2008), Simple, robust, CO2 sounder employing a broadband laser source, The ASCENDS Workshop, Ann Arbor, Michigan, July 23-25, 2008

Z. Kuang, J. Margolis, G. Toon, D. Crisp and Y. Yung, "Spaceborne measurements of atmospheric CO_2 by high-resolution NIR spectrometry of reflected sunlight: An introductory study," Geophys. Res. Let. **29**(15), doi:10.1029/2001GL014298 (2002).

J. Mao and S. R. Kawa, "Sensitivity studies for space-based measurement of atmospheric total coloumn carbon dioxide by reflected sunlight," *Applied Optics*, **43**, 914-927 (2004).

R. T. Menzies and D. M. Tratt, "Differential Laser Absorption Spectrometry for Global Profiling of Tropospheric Carbon Dioxide: Selection of Optimum Sounding Frequencies for High-Precision Measurements," *Appl. Opt*. **42**, 6569-6577 (2003).

Mitchell, R. M., and D. M. O'Brien, 1987: Error Estimates for Passive Satellite Measurement of Surface Pressure Using Absorption in the A Band of Oxygen. *J. Atmos. Sci.*, **44**, 1981–1990.

D. M. O'Brien and P. J. Rayner, "Global observations of carbon budget 2, CO_2 concentrations from differential absorption of reflected sunlight in the 1.61 m band of CO_2," J. Geophys. Res. **107**, 4354, doi:10.1029/2001JD000617 (2002).

J. Susskind, C. Barnet and J. Blaisdell, "Determination of atmospheric and surface parameters from simulated Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU)/Humidity Sounder Brazil (HSB) sounding data: retrieval and cloud clearing methodology," Adv. Space Res. **21**, 369-384 (1998).

Tatsuya Yokota, Hiroyuki Oguma, Isamu Morino, Akiko Higurashi, Tadao Aoki, and Gen Inoue, 2004,Test measurements by a BBM of the nadir-looking SWIR FTS aboard GOSAT to monitor CO2 column density from space, Proc. SPIE 5652, 182, DOI:10.1117/12.578497