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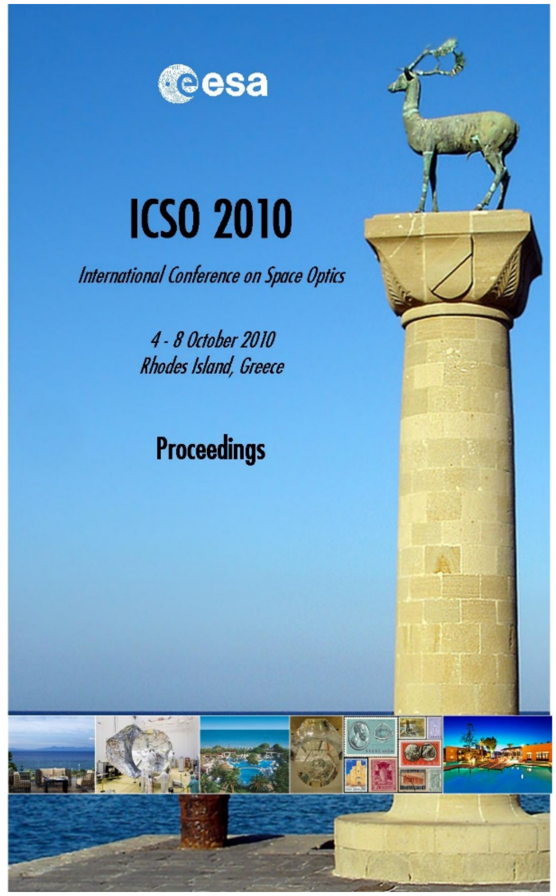

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A FEASIBILITY STUDY FOR POTENTIAL CO_2 MEASUREMENT FROM SPACE USING THE 1.57-μm DIFFERENTIAL LASER ABSORPTION MISSION

D. Sakaizawa[1], S. Kawakami[1], M. Nakajima[1], T. Tanaka[2], Y. Miyamoto[2,*], I. Morino[2], O. Uchino[2], S. Kameyama[3], M. Imaki[3], Y. Hirano[3]
[1]*Japan Aerospace Exploration Agency (JAXA), Japan*
[2]*National Institute for Environmental Studies (NIES), Japan*
[3]*Mitsubishi Electric Corporation, Japan*
**Present address: Graduate School of Nature Science and Technology, Okayama University, Japan*

I. INTRODUCTION:

Observation of the Earth's environment from space is important for resolving issues resulting from global climate change. Increasing anthropogenic carbon dioxide (CO_2) and methane are species to climate change. To estimate accurately sinks and sources of CO_2 in the biosphere, measurement uncertainties of the column averaged dry air mole fraction of CO_2 (XCO_2) are expected to be 1-3 ppm (0.3%-1%)[1]. The Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory (OCO-2) have proceeded to reveal the global carbon exchange [2, 3]. The GOSAT sensor observes trace gases using a passive remote sensing technique. However, passive techniques using solar light limits observation because 1) the total column CO_2 can only be evaluated only during the daytime, 2) solar seasonal dependence reduces global coverage, such as the northern hemisphere in winter, 3) unknowns and variations in broken clouds and aerosol contamination also cause bias errors.

To resolve these issues, active remote sensors, such as a differential absorption lidar (DIAL) or a laser absorption spectrometer (LAS), are valuable tools for future trace gas sensing from space as they involve no seasonal dependence, can mitigate the impact of broken clouds and aerosol, and can evaluate XCO_2 all day. According to earlier studies [4-8], a precision of up to 0.7 percent has already been achieved. This study aims at demonstrating a sensitivity analysis for a space-borne system and the results of the airborne test to evaluate column-averaged CO_2.

II. METHODOLOGY

A. Principle of LAS

The analytical model used in this study assumes a space-borne or airborne platform to measure the light scattered or reflected by a ground or sea surface. Active remote sensing using a direct detection modulated CW LAS can measure the optical depth of a trace gas. Extinction at an online wavelength results in a significantly larger atmospheric extinction than that for the offline wavelength used as a reference. Considered as an intensity ratio of two scattering signals, the column-averaged XCO_2 ($\bar{x}$) can be described by the following equations [1]:

$$\Delta\tau = \frac{1}{2}\ln\frac{P_{mon,off}P_{rec,on}}{P_{mon,on}P_{rec,off}} + K \tag{1}$$

$$\bar{x} = \Delta\tau / iwf\,(\lambda_{on}, \lambda_{off}) \tag{2}$$

$$iwf\,(\lambda_{on}, \lambda_{off}) = \int_{z_a}^{z_g} wf\,(\lambda_{on}, \lambda_{off}, z)dz \tag{3}$$

$$wf(\lambda_{on}, \lambda_{off}, z) = \Delta\sigma n_{air}(1 - XH_2O(z)) \tag{4}$$

Here, $\Delta\tau$ is the optical depth obtained from the receiving signal ($P_{rec,on|off}$) and monitored signal ($P_{mon,on|off}$), K is the bias factor including the aerosol integrated backscatter and instrumental offset, *iwf* is the integrated weighting function calculated from the target height to the top of atmosphere for space and airplane height for airborne measurement, $\Delta\sigma$ is the differential absorption cross section of interest between on-line and off-line, n_{air} is the air number density, and XH_2O is the water vapor mixing ratio.

B. Error analysis

To determine the precision of the measurement, certain factors have to be quantified as follows:

$$\left(\delta\bar{x}/\bar{x}\right)^2 = 0.5\sum_i SNR_i^{-2} + \sum\left(\frac{\partial iwf}{\partial y}\right)^2 \tag{5}$$

Here, y indicates measured range, pressure, temperature, relative humidity and wavelength stability. Equation (5) consists of two factors: receiving signal SNRs and the integrated weighting function for meteorological data, wavelength stability, and range measurement precision. The quadratic summation of the integrated weighting function is evaluated as 10 m for range measurement precision, 1 hPa for the pressure, 1 K for the temperature, 10 percent for the relative accuracy, and 1 MHz for wavelength stability. The bias errors due to instrumental factors are assumed as 0.998 for the spectral purity and 1 MHz for the laser linewidth. Another bias error factor due to spectroscopic parameters is denoted using the Voigt profile function and parameters in earlier studies [9-11].

III. FLIGHT TEST TO DEMONSTRATE THE POTENTIAL CO_2 MEASUREMENT USING LAS

Figure 1 shows the diagram of our LAS system. The system is entirely composed of optical fiber circuits and employs a master oscillator power amplifier (MOPA) using a fiber amplifier, which makes the simultaneous oscillation and complete optical axis matching between on-line and off-line. The on-line and off-line sources are the distributed feedback laser diodes. The onboard system measures $\Delta\tau$ from ground scattering and monitoring signals. To receive return signal intensity simultaneously, on-line and off-line signals are amplitude-modulated with sinusoidal frequencies of 10 kHz for the online signals and 11 kHz for the off-line signals. The sinusoidal signals are also used to determine the range from the aircraft to the ground using the phase difference between receiving and monitoring signals.

An airborne test to measure XCO_2 was performed in August 2009 and February 2010. A visible CCD camera (ARTRAY Inc., Model: ARTCAM-150PIII) also monitored the landscape under the aircraft. To validate the results, the atmospheric CO_2 was taken from 0.5 km to 7 km by flask sampling and in situ measurements. The aircraft flight track is given by an on-board GPS. Additional ground speed and ellipsoid height are provided by the aircraft instruments. The radiosonde measurement was performed during decent spiral, and its meteorological data can be used to validate the column-averaged CO_2.

Figure 2 (a) indicates $\Delta\tau$ obtained from the LAS and $\Delta\tau$ calculated from onboard flask sampling measurements of atmospheric CO_2 performed in August 2009. As shown in the figure, the vertical profile of measured $\Delta\tau$ is consistent with the calculated $\Delta\tau$ from 1 km to 7 km. The gap of 0.5 km is believed to be due to a misfit of a footprint overlap of the laser and receiver. The additional error source is due to a very small footprint (a diameter less than 20 cm) along track. The weighted column-averaged CO_2 up to 7 km is estimated

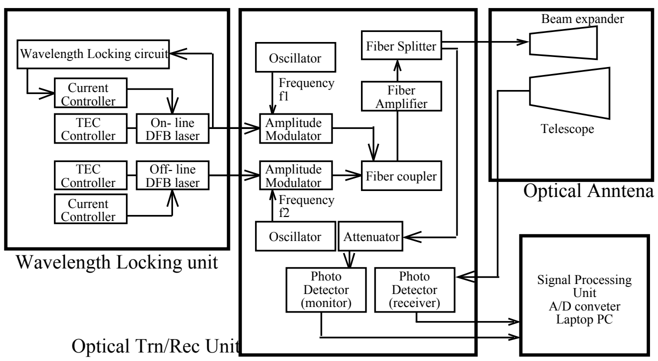
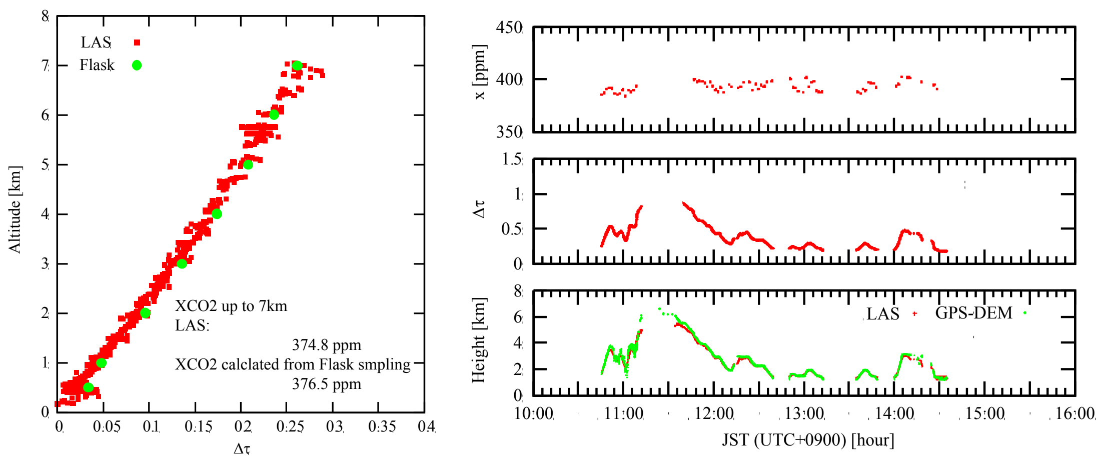
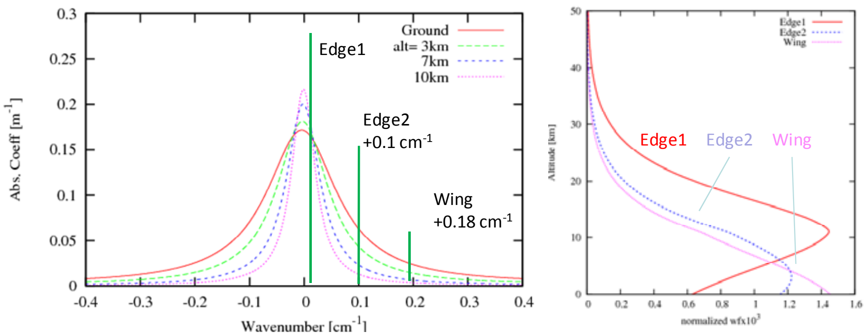


Fig. 1 Schematic diagram of the 1.57-µm laser absorption spectrometer.



(a) (b)

Fig. 2 Results of the airborne test. (a) Vertical profile of $\Delta\tau$ from LAS and flask sampling measured in August 2009, (b) XCO_2, $\Delta\tau$, and range from aircraft to ground measured along track in February 2010.



(a) (b)

Fig. 3 Weighting function and operating on-line positions. (a) Molecular absorption coefficient at different on-line wavelength positions, (b) Weighting functions for CO_2 measurement at the different online wavelength positions.

to be 374.8 ppm ($\delta\bar{x}/\bar{x}$ =1.4%) for the LAS and 376.5 ppm for the flask sampling. The difference of 0.7 ppm-1.7 ppm was also observed at the decent spiral measurement in August 2009 and February 2010. Figure 2 (b) shows the results for $\bar{x}$, $\Delta\tau$, and height along track in February 2010. Aircraft height obtained from the LAS is in good agreement with the geometric height calculated from the onboard GPS and the Digital Elevation Model (DEM) of ASTER. The experimental $\bar{x}$ is evaluated from $\Delta\tau$ and *iwf* is calculated using the meso-scale model analysis. The differences between radiosonde and meso-scale analysis up to an altitude of 7 km are evaluated as 1.5 hPa for pressure, 1.7 K for temperature, and 15 percent for relative humidity. These values cause an additional bias error of 1-2 ppm for measured operating wavelength. Considering the degeneration of precision and accuracy using meso-scale model analysis, the measured column-averaged CO_2 of February is 20 ppm greater than that of August.

IV. PERFORMANCE MODEL FOR SPACE-BORNE LAS

The space-borne CO_2 LAS based on the airborne test was designed using an end-to-end simulation with analytical equations. To derive the sensitivity analysis for the space-borne sensor, the instrumental parameters depend on the specifications of the weighting function. The weighting function provides the strength of CO_2 absorbance, which constrains required SNR of receiving signals. The weighting function of the lower atmosphere varies with the on-line position, as shown in Fig. 3 and Table 1. The wavelength nearest the CO_2 absorption center (Edge1) indicates the constant averaging kernel from the ground to an altitude of 10 km. The others (Edge2, and Wing) are advantageous with respect to favorable weighting functions for high sensitivity

Table 1 Sensitivity in the lower atmosphere for three different weighting functions

	Edge1	Edge2	Wing
Optical depth	1.51	0.45	0.14
Required SNR of receiving signals	330	1110	3580
$\bar{x}$ from the ground to top of the air	385	385	385
0-1 km/%/km	7.6	13.4	16.4
1-3 km/%/km	7.7	12.0	13.4
3-10 km/%/km	7.1	7.0	6.6

Table 2 Instrumental parameters for space-borne CO_2 sensing (Edge1)

Absorption line		Receiver	
Center	6327.060897 cm^{-1}	Telescope	0.75 m (1.0 m)
Line intensity	1.2717×10^{-23} cm^2/molec	Field of view	50 μrad
Lower state energy	234.0833 cm^{-1}	Overall efficiency	0.85
Air-broadening Coeff.	0.07174 cm^{-1}	Optical filter	1 nm
Self-broadening Coeff.	0.097 cm^{-1}		
Temperature Coeff.	0.722	Detector	
Pressure shift Coeff.	-0.007 cm^{-1}	Avalanche gain	10
Online	See Fig. 3	Dark current	0.5 pA
Offline	6327.0609 cm^{-1}	Noise Figure	2
		Trans-impedance gain	10^9 Ω(?)
Transmitter		Quantum efficiency	0.79
Laser power	25 W (15 W)	Operating temperature	300 K
Linewidth	1 MHz		
Spectrum purity	> 0.998	Orbit	400 km
Wavelength stability	300 kHz rms.	Surface reflectance	0.3

near the ground compared with Edge1. The instrumental parameters used to realize the precision of 1 ppm are shown in Table 2. The results show the trade-off between the essential SNR and weighting for the lower atmosphere.

Since LAS instruments are not free from calibration, accurate monitoring of the higher transmitted power and receiver optical efficiency, which may be different for the on- and off-line wavelengths, are important issues. Highly accurate path length measurements are also desired, especially over inhomogeneous regions with strongly varying surface heights. In addition, the impact of integrated aerosol backscattering is believed to be a critical bias factor on CW direct detection. The use of modulation and demodulation techniques, such as our LAS system, helps to infer range information and to discard unwanted integrated backscattering signals. Other options, such as the combination of the LAS system with a CALIPSO-like pulsed backscatter lidar for detection of aerosols and clouds as well as determination of the sounding path length, could be promising.

V. SUMMARY

We performed an airborne test using the 1.57-μm continuous laser-based direct detection LAS to evaluate weighted column-averaged CO_2. The differential optical depth and weighted column-averaged CO_2 obtained from the LAS indicates good agreement with the expected value calculated from flask sampling. The performance model to manufacture the prototype model leaded to the instrumental parameters for state-of-the-art and environmental conditions for a space-borne platform. It is also expected that those results will improve even further as higher order instrument characteristics (larger telescope, high power laser, wavelength stability, etc.) are accounted for.

The performance evaluation of the space-borne instrument indicates that the stringent target and observational requirements for a precision of 0.3 percent (1 ppm) can be met for CO_2. The LAS system considered in the evaluation must have a telescope aperture of 0.7-1.0 m for a 400-km altitude and a laser power of 25 W-15 W. Other requirements for laser specification have to be met for the stability of 300 kHz and a laser linewidth less than 1 MHz. For direct detection instruments, the difficulty of developing a sensor for a 2-μm wavelength region increases mainly due to the decreasing detector performance compared with 1.57-μm region. The size of the receiving telescope on the ISS-JEM is limited to less than 0.7 m due to the module size (1 m height × 0.8 m width × 1.6 m length).

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