A-3.1.1 Development of a Spectroscopic Method for Earth-Satellite-Earth Laser Long-Path Absorption Measurements

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Abstract

Spectroscopic method for earth-satellite-earth laser long-path absorption measurements of atmospheric trace species has been established. The ground laser transmitter/receiver system and data processing system based on the method were developed for the experiment using the Retroreflector in Space (RIS) for the ADEOS satellite. The ground system employs two single-longitudinal-mode pulsed CO_2 lasers. High resolution atmospheric absorption spectra are measured by using the Doppler shift of the return light caused by the movement of the satellite. Vertical profiles of O_3 and CH_4, and column contents of CFC12, HNO_3, CO, N_2O, etc. will be measured in the RIS project.

Key Words Ozone, Atmospheric Trace Species, Remote Sensing, Laser Long-Path Absorption, Satellite Retroreflector

1. Introduction

The laser long-path absorption method between the ground and a satellite is one of the most sensitive remote sensing techniques for measuring concentration of atmospheric trace species. This method is useful for measuring vertical profile of ozone and column contents of trace species related to ozone depletion. The measurement can be performed both in the daytime and nighttime. The concept of the laser long-path absorption measurement using a satellite retroreflector was presented by Hinkley[1)] in 1976. In the measurement, a laser beam is transmitted from a ground station, reflected by the satellite retroreflector, and received at the ground station. Absorption of the atmosphere is measured in the round-trip optical path. Column contents or vertical profiles of atmopspheric trace species are derived from the measured spectra.

The first experiment on the earth-satellite-earth laser long-path absorption measurements of atmospheric trace species is planned with the Retroreflector In Space (RIS) for the Advanced Earth Observing Satellite (ADEOS)[2)] which is scheduled for launch in 1996.

In this study, we have developed the optical design of the RIS, the spectroscopic method for the experiment, the laser transmitter/receiver system, and data reduction method.

2. The Retroreflector in Space (RIS)

Figure 1 shows the structure we designed for the RIS. The RIS has a single element structure instead of a retroreflector array which is commonly used for geodetic satellite, because speckle effect due to interferenece between elements in an array will cause noise in the spectroscopic measurement. The RIS uses an unique retroreflector design which includes a spherical mirror with a small curvature for one of the three mirrors forming the corner cube. Also, the dihedral angles between the spherical mirror and the two plane mirrors are slightly changed from right angles.[3)-5)] The effects of the spherical mirror and spoiled dihedral angles compensate the velocity aberration caused by the movement of the ADEOS which has a velocity of approximately 7 km/s. The radius of curvature for the spherical mirror is approximately 14 km, and the size of the mirror is approximately 36 cm.

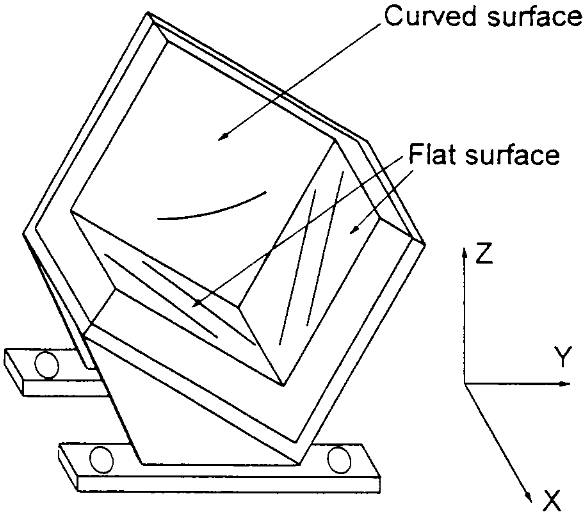

Fig. 1. Structure of the RIS.

The mirror panels for the RIS is made of quartz with a light-weighted structure. The mirror surface is finished with silver-based optical coating which has high reflectance in a wide wavelength range from 350 nm to 14 μm. The RIS is installed on the ADEOS with a direction cosine of the optical axis of (0.508, - 0.279, 0.815) in the satellite coodinate system, where X is the direction of the satellite movement and Z is the nadir.

3. Ground System and the Measurements of Atmospheric Trace Species

The ground system for the earth-satellite-earth laser long-path absorption experiment consists of an optical satellite tracking system and a laser transmitter/receiver system for spectroscopic measurements. Figure 2 shows a schematic diagram of the ground system. A satellite tracking system with a 1.5-m diameter telescope at the Communications Research Laboratory (CRL) located in Koganei, Tokyo will be used in the experiment.

An active satellite tracking method has been developed by CRL (subject A-3.1.2) to achieve the tracking accuracy required in the RIS experiment. The method utilizes the image of the RIS lit by a second-harmonics Nd:YAG laser.

For the spectroscopic measurements, we developed a method which utilize the Doppler shift of the reflected beam resulting from the satellite movement.[6] Because the magnitude of the Doppler shift depends on the satellite position relative to the ground station, high-resolution absorption spectra of the atmosphere can be measured by using the change in the wavelength of the return beam. We developed the ground system using two single-longitudinal-mode TEA-CO_2 lasers. One of the lasers is tuned to the laser lines close to the absorption lines of the target molecule. The other is used for measuring reference signals to correct atmospheric effects and the angular dependence of the reflectance of the RIS. The spectral range covered by the Doppler shift is 0 - 0.04 cm^{-1} at 10 μm.

Table I lists the target molecules and wavelengths for the measurements using TEA-CO_2 lasers with $^{12}C^{16}O_2$, $^{13}C^{16}O_2$ isotopes and their second and third harmonics. The wavelength of the laser is switched over several laser lines when there are suitable lines in order to measure the absorption spectra in wider wavelength regions. We developed wavelength agile single-longitudinal-mode TEA CO_2 lasers using time-gated gain cell method.[7),8)]

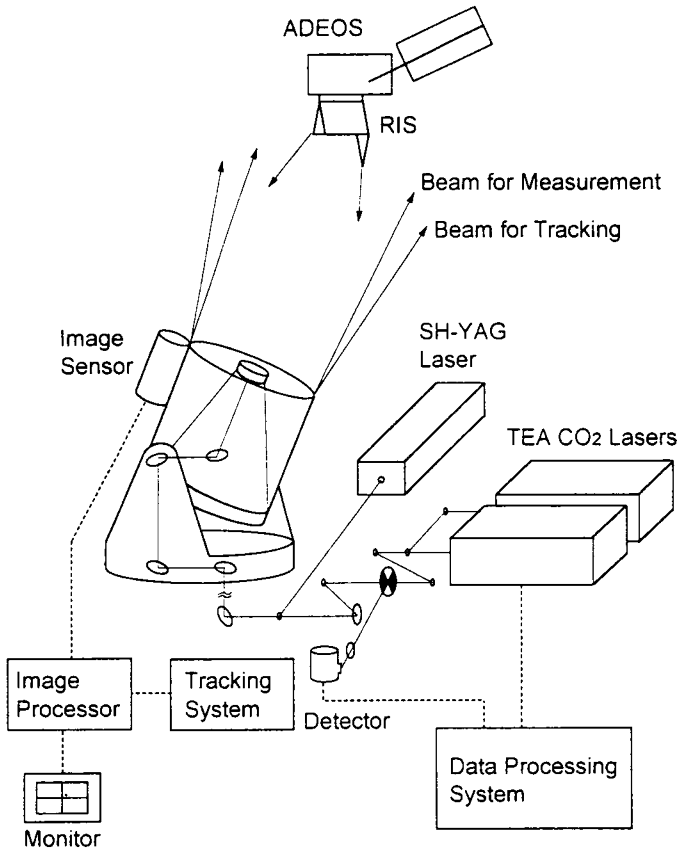

Fig. 2. Ground system for the RIS experiment.

Table I. Target molecules and CO_2 laser lines.

Molecule	Laser line	CO_2 isotope	Wave number (cm^{-1})
O_3	P(18)	636	1002.4778
	P(20)	636	1000.6473
CO_2	P(26)	626	938.6883
	R(36)	636	938.7776
HNO_3	P(8)	636	907.0528
CFC12	R(6)- R(12)	636	918.74 - 923.11
CO	R(28)*	626	2166.96
	R(30)*	626	2169.27
N_2O	R(38)*	626	2178.002
CH_4	R(14)**	626	2915.79
	R(16)**	626	2919.87
Reference	R(34)	636	937.5844
	R(8)*	626	2140.925
	R(26)**	626	2939.12

*Second harmonic; **Third harmonic.

Figure 3 shows a block diagram of the CO_2 laser transmitter/receiver system. The beams from the two lasers are directed to the Coude optics of the satellite tracking telescope. Laser pulses reflected by the RIS are received with the same tracking telescope. The received pulses are detected with photovoltaic detectors cooled at 77 K. The wave forms of transmitted and received laser pulses are recorded with a transient digitizer every shot for both of the two lasers. Time window for recording the received pulses is calculated from the orbital parameters for the satellite. The visible laser pulses reflected by the RIS are separated with a dichroic mirror and detected with an image-intensified CCD camera for fine tracking. The specification of the ground system is listed in Table II.

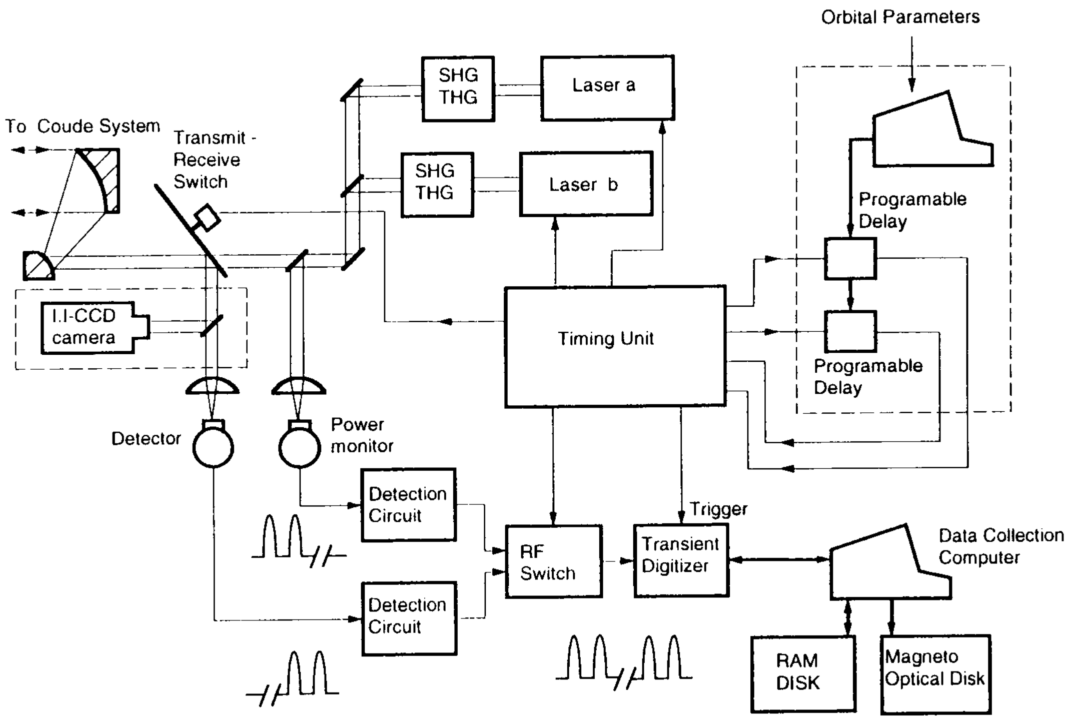

Fig. 3. Block diagram of the CO_2 laser transmitter/receiver system.

4. Data reduction method

In the measurement, four quantities, P_{si0}, P_{ri0}, P_{si}, P_{ri}, are recorded every shot. P_{si0} and P_{ri0} represent the intensity of transmitted pulses of the signal laser and the reference laser, respectively. P_{si} and P_{ri} represent intensity of the received pulses of corresponding lasers. Subscript i represents shot number. P_{si} and P_{ri} can be written as

$$P_{si} = P_{si0} C_{Ri} C_s [T(\lambda_{s0}) T(\lambda_{si})]^{k_i}, \quad (1)$$

$$P_{ri} = P_{ri0} C_{Ri} C_r [T(\lambda_{r0}) T(\lambda_{ri})]^{k_i}, \quad (2)$$

where C_{Ri} represents the reflectivity of the RIS. C_s and C_r represent efficiency of the transmitter/receiver system for the signal and reference lasers. $T(\lambda)$ is transmittance of the atmosphere in the earth to satellite zenith path. k_i is a coefficient representing the change of the optical path length, which can be written as

Table II. The ground system parameters

Laser pulse energy	100 mJ (10 μm)
	10 mJ (5 μm)
	5 mJ (3 μm)
	100mJ (532nm, Avtive tracking)
Laser beam divergence	0.1 mrad (10, 5, 3 μm)
	0.3 - 3 mrad (532 nm)
Receiver telescope diameter	1.5 m
Overall optical efficiency	0.005
Detectivity of detector	$7x10^{10}cmHz^{1/2}/W$ (10 μm)
	$1x10^{11}cmHz^{1/2}/W$ (5 μm)
	$6x10^{10}cmHz^{1/2}/W$ (3 μm)
Area of detector	0.001 cm^2
Quantum efficiency	0.6
Time constant	1 μs

$$k_i = 1/\sin\theta_i. \quad (3)$$

$T(\lambda)$ is written as

$$T(\lambda) = \exp[-\int q(z)\sigma(\lambda,z)dz]\exp[-\tau], \quad (4)$$

where $q(z)$ is the vertical profile of the target molecule, and $\sigma(\lambda,z)$ is the absorption cross section of the target molecule. We assumed that the atmosphere consists of homogenious layers. τ in eq.(4) represents continuum absorption of water vapor and aerosols which does not have fine structure in the spectrum. We assumed that there are no interfering absorption except for the continuum.

From eq.(1)-(4), we can derive the following equation.

$$\ln[(P_{si}/P_{si0})/(P_{ri}/P_{ri0})] = \ln(C_s/C_r) + \{q(z)[- \sigma(\lambda_s,z) - \sigma(\lambda_{si},z) + \sigma(\lambda_r,z) + \sigma(\lambda_{r0},z)]\, k_i\}dz + \tau' k_i, \quad (5)$$

where

$$\tau' = 2(\tau_r - \tau_s). \quad (6)$$

Equation (5) can be written in a matrix form as

$$\mathbf{Y} = \mathbf{A}\ \mathbf{X}, \quad (7)$$

where

$$\mathbf{Y} = \begin{vmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ y_m \end{vmatrix}, \qquad (8)$$

$$y_i = \ln[(P_{si}/P_{si0})/(P_{ri}/P_{ri0})], \qquad (9)$$

$$\mathbf{A} = \begin{vmatrix} w_{11} & w_{12} & \cdot\cdot & w_{1n} & k_1 & 1 \\ w_{21} & w_{22} & \cdot\cdot & w_{2n} & k_2 & 1 \\ & \cdot & \cdot & \cdot & & \\ w_{m1} & w_{m2} & \cdot\cdot & w_{mn} & k_m & 1 \end{vmatrix} \qquad (10)$$

$$w_{ij} = [-\sigma(l_s,z_j) - \sigma(l_{si},z_j) + \sigma(l_r,z_j) + \sigma(l_{r0},z_j)]\Delta z_j k_i \qquad (11)$$

$$\mathbf{X} = \begin{vmatrix} q_1 \\ \cdot \\ q_n \\ \tau' \\ \ln(C_s/C_r) \end{vmatrix}, \qquad (12)$$

In the case the laser line is switched over several laser lines during the measurement, matrix **A** can be written as

$$\mathbf{A} = \begin{vmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \\ \cdot \\ \mathbf{A}_k \end{vmatrix}, \qquad (13)$$

where k indicates the laser line.

It can be seen that the general inversion method can be applied to eq.(7) to obtain **X,** or the vertical profile of the target molecule.

When the information contained in the measured spectrum is not sufficient for applying the inversion method, we can obtain column content by the least squares method assuming that the relative profile is known. In this case, the profile can be written by

$$q_n = c_n\, q \qquad (14)$$

where, c_n are constants describing the assumed profile and q is the parameter to be determined.

5. Evaluation of the measurement and data reduction methods

We evaluated the measurement method and the data redution method using a simulator program. The simulator program generates simulated received signals based on the system parameters and atmospheric absorption spectrum. The ground system parameters listed in Table II and the reflection characteristics of the RIS were used in the calculation. Atmospheric absorption spectrum were generated with the HITRAN database[9)] by giving a vertical profile of the target molecule. Noise in the measurement estimated for the system was also included in the simulated data.

We applied the data reduction program to the simulated data and calculated the vertical profile or column content. We evaluated the measurement method and the data reduction methods by comparing the retrieved profile or column contents with the true profile given in the simulation.

Figure 4 shows an example of the simulated return signals for ozone measurement generated by a simulator program. In this example, the line of one of the CO_2 lasers is switched over P(18) and P(20) laser lines every 50 shots (1 second). Two types of noise were considered in the simulation. One is the noise independent on the signal intensity, and the other is the noise proportional to the signal intensity. Detector noise has the former characteristics. The detector noise at an equivalent photon number of 3×10^4 was included in the simulation. The latter type of the noise is caused, for example, by fluctuation of the laser beam pattern. One percent noise of this type was included.

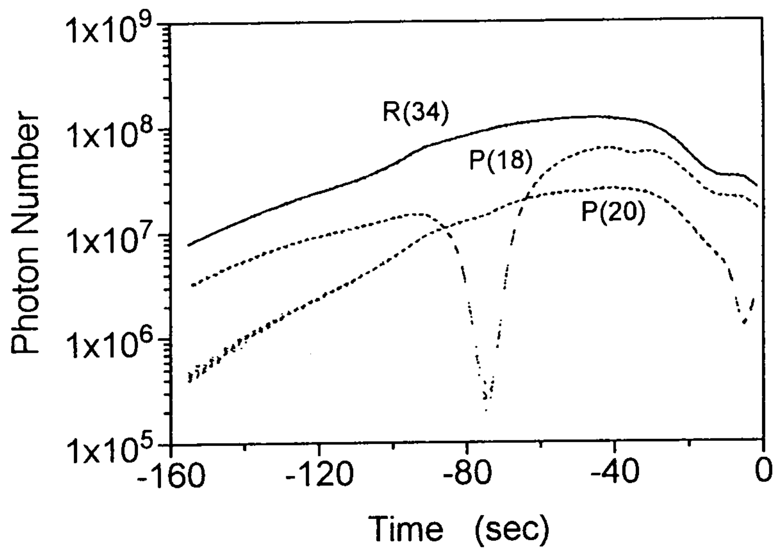

Fig. 4 Simulated return signal (photon number per shot) for the ozone measurement.

Figure 5 shows the ozone profile retrieved from the simulated data shown in Fig.4. We used an inversion algorithm based on the singular value decomposition method. The retrieved ozone profile agreed well with the true profile. We applied the same method to the measurement of methane and obtained a good result. Table III and IV list errors in the retrieved profiles of ozone and methane. The random noise and the systematic noise in the Tables represent standard variation and shift of mean value, respectively.

Table III. Error in the vertical profile measurement of ozone

Altitude (km)	Random error (%)	Systematic error (%)
0	18.2	14.3
10	12.1	-10.6
20	5.2	-1.3
30	5.3	1.1
40	6.2	-2.3
50	33.7	-33.2

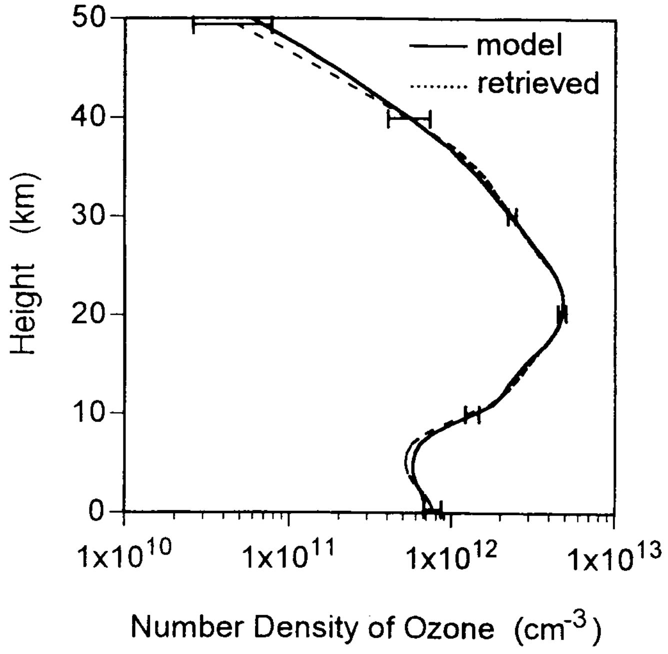

Fig. 5 Ozone profile retrieved from the simulated signal.

Table IV. Error in the vertical profile measurement of methane

Altitude (km)	Random error (%)	Systematic error (%)
0	0.9	2.2
10	1.0	-0.2
20	2.9	0.6
30	4.6	-0.6
40	8.0	-5.8
50	5.6	-11

In the same manner, we applied the data reduction program for obtaining column contents to the simulated spectra of CFC12, HNO_3, CO_2, N_2O, and CO. Errors in the obtained column contents are listed in Table V.

6. Conclusion

The spectroscopic method and techniques for the earth-satellite-earth laser long-path absorption experiment have been established in this study. In the experiment using the RIS for the ADEOS satellite, we will carry out measurements of vertical profiles of ozone and methane, and measurements of column contents of CO_2, HNO_3, CFC12, CO, N_2O, etc. using the isotope TEA CO_2 lasers and their second and third harmonics. We expect to obtain useful data for the analysis of ozone layer depletion.

Table V. Error in the column content measurements of $CFC12$, HNO_3, CO_2, N_2O, and CO

Altitude (km)	Random error (%)	Systematic error (%)
CFC12	0.6	1.4
HNO_3	6.3	1.3
CO_2	0.2	-0.2
N_2O	0.2	1.8
CO	1.8	-

A science team are formed for the RIS experiment from the ground station in Tokyo. Also, experiments using RIS from other stations are organized based on the proposals to the Joint Research Announcement by NASDA and Environment Agency of Japan. These experiments include atmospheric measurement using a tunable infrared laser and dual-color laser ranging.

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