

Analysis of the Differences of Overlap Function of Dual Laser Beams in SO₂/NO₂ DIAL System

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Abstract. Geometric Form Factor(GFF) or overlap function in transition range is an important factor of a lidar system, especially in a SO₂ and NO₂ DIAL system. An unstable overlap function will seriously affect measurements of gas concentration and degrade its retrieval accuracy in transition range. In technique of SO₂ and NO₂ DIAL, retrieval of gas concentration is directly related with ratio between two return signals of emitting laser beam. Construct stability of overlap between two laser beam and receiver can be estimated using the ratio between two return signals. In this paper data acquired from SO₂/NO₂ DIAL measurements was analyzed. Relative standard deviation of ratio between two return signals in transition range is less than 1%. It shows that Construct stability of overlap between two laser beam and receiver, and quality of laser beam are very good.

1. INTRODUCTION

Atmospheric SO₂ and NO₂ are important pollutant air gases which damage respiratory system and harms human's health. In past decades, with the fast development of industry increasing of automobile number and deterioration of zoology environment, atmospheric pollution is becoming more and more serious.

Differential absorption lidar has many advantages in profiling atmospheric absorption gases. And it has high accuracy and is becoming a useful tool in monitoring emission of SO₂ and NO₂. This technique was well performed by several researchers in the past several decades^[1-4]. In China, first mobile DIAL system AML-1 for air pollution monitoring was developed by Zhang based on Ti:Sapphire laser^[5]. Now a differential absorption lidar system(DIAL) based on dye lasers is being developed for atmospheric SO₂ and NO₂ monitoring. Picture of DIAL and its deployment is shown in Fig.1.





Fig.1 Picture of SO₂ and NO₂ DIAL and its deployment being developed

Wavelengths of 300nm and 301.5nm are used as strong absorption line(on-wavelength) and weak absorption line(off-wavelength) for measuring SO₂, respectively. This wavelength pair is the second harmonic of 600nm and 603nm produced by two dye lasers pumped by second harmonic of Nd:YAG laser. Wavelength of 448.1nm and 446.8nm are utilized as on-line and off-line for profiling NO₂ respectively. Block diagram of the DIAL is shown in Fig.2. A Nd:YAG laser generates the second and third harmonic wavelengths simultaneously. Four dye lasers are divided two groups and pumped by two Nd:YAG laser alternately. And two wavelength pairs are combined and directed into the atmosphere via a three-dimension scanning optical system. This DIAL is capable of profiling SO₂ and NO₂ concentration ranging from 600m to 3000m in spatial resolution of 15m. In this paper we focus on construct stability in our lidar system, and discuss standard deviation of overlap function between two laser beam and receiver.

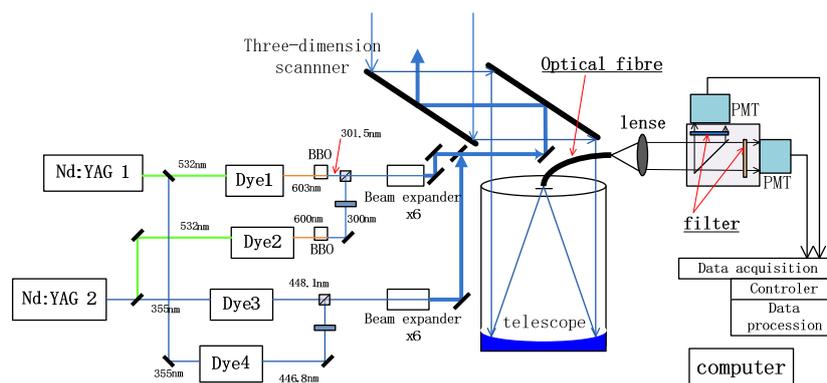


Fig.2 Block diagram of SO₂/NO₂ DIAL system

2. DIAL Principles

Dual-wavelength differential absorption lidar(DIAL) usually utilizes absorption properties of target gas to detect and retrieve target gas concentration. A DIAL system transmits alternately two laser beams into the atmosphere. Two proper wavelengths are chosen. One wavelength is located on the peak of strong absorption line of target gas, written as λ_{on} , it has a maximum absorption of target gas. Another wavelength is located on the valley of weak absorption, written as λ_{off} , it is a light or no absorption of target gas. They have a small interval of wavelength ($\Delta\lambda=\lambda_{on}-\lambda_{off}$). It means that there are small differences of atmospheric extinction and backscattering at two wavelength, including molecule and aerosol. Difference of return signal intensity between two wavelengths is mostly caused by absorption of target gas. Therefore target gas concentration can be retrieved from the difference of return signals back-scattered by molecules and aerosol on the path laser beams pass through. If effects of the atmospheric extinction and backscattering of molecule and aerosol are clearly large, it means that target gas concentration should be corrected.

Number density of the detected gas at range z can be expressed as follow,

$$N(z) = -\frac{1}{2\Delta\sigma} \frac{d}{dz} \left[\ln \frac{P(\lambda_{on},z)}{P(\lambda_{off},z)} \right] + B - E_A - E_M$$

$$\Delta\sigma = \sigma(\lambda_{on}) - \sigma(\lambda_{off})$$

$$B = \frac{1}{2\Delta\sigma} \frac{d}{dz} \left[\ln \frac{\beta(\lambda_{on}, z)}{\beta(\lambda_{off}, z)} \right]$$

$$E_A = \frac{1}{\Delta\sigma} [\alpha_A(\lambda_{on}, z) - \alpha_A(\lambda_{off}, z)]$$

$$E_M = \frac{1}{\Delta\sigma} [\alpha_M(\lambda_{on}, z) - \alpha_M(\lambda_{off}, z)]$$

Where, $\Delta\sigma$ is the difference of absorption cross-section of gas being measured at wavelength between λ_{on} and λ_{off} , $\sigma(\lambda_{on})$ and $\sigma(\lambda_{off})$ are absorption cross-section of gas at wavelength between λ_{on} and λ_{off} , respectively. $P(\lambda_{on}, z)$ and $P(\lambda_{off}, z)$ are lidar return signals backscattered from atmospheric molecules and aerosol at altitude z at wavelength of λ_{on} and λ_{off} , respectively. B , E_A and E_M are the items caused by atmospheric molecular backscattering, aerosol extinction and molecular extinction. They are called correction items. $\beta(\lambda_{on}, z)$ and $\beta(\lambda_{off}, z)$ are total backscattering coefficient at altitude z at wavelength of λ_{on} and λ_{off} ; $\alpha_A(\lambda_{on}, z)$ and $\alpha_A(\lambda_{off}, z)$ are aerosol extinction coefficients at altitude z at wavelength of λ_{on} and λ_{off} ; $\alpha_M(\lambda_{on}, z)$ and $\alpha_M(\lambda_{off}, z)$ are molecular extinction coefficients at altitude z at wavelength of λ_{on} and λ_{off} ; If wavelength interval between λ_{on} and λ_{off} is very small, then B , E_A and E_M are small and can be neglected. In real calculation, the gas concentration at altitude z is not calculated from return signal from altitude z . but averaged concentration from altitude z to $z + \Delta z$ is calculated, Δz is called range resolution.

Therefore, calculation of $\frac{P(\lambda_{on}, z)}{P(\lambda_{off}, z)}$ in DIAL equation is important. Due to small absorption cross-section of SO_2 or NO_2 , there is no obvious difference of light backscattering signals between two laser beams passing through the atmosphere with low concentration of SO_2 or NO_2 . We can calculate the difference of geometrical form factor between two laser beams by calculating ratios of backscattering signal of two laser beams.

3. Analysis of difference of geometrical form factor

On 24th March, 2016, horizontal backscattering return signals of laser beams at wavelength 300.2nm and 301.5nm were acquired by developed SO_2/NO_2 DIAL system, every pulse return intensity was documented. To improve signal-noise ratio, 10 minutes integrated time is set, which means averaged time is 10 minutes. Ratio profile of on-signal and off-signal were calculated after they were taken off background noise, respectively. It can be seen that large variation among every ratio profile can be seen, as shown in Fig.3.

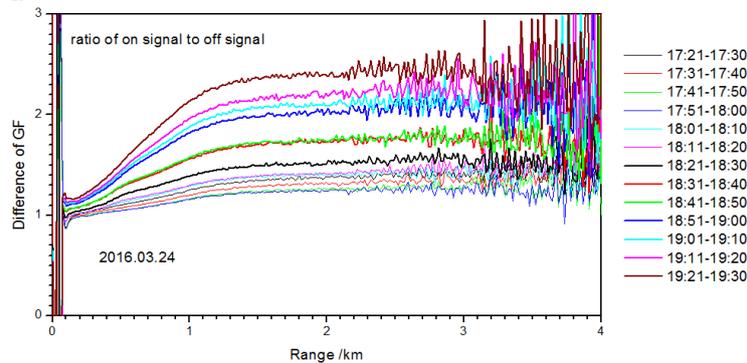


Fig.3 ratio profiles of on-signal to off-signal taken off background noise

Conventionally, within complete overlap range, ratio of on-signal to off-signal should be a constant and it can be normalized to a constants usually expressed as constant GFF=1. As data acquired on 23th March, 2016, normalized and shown in Fig.4. It can be seen that wide variation of the difference of geometrical form factor between two laser beams. It looks like that the difference of geometrical form

factor between two laser beams cannot be repeated, and correction of the differences cannot be done due to the large uncertainty of GFF.

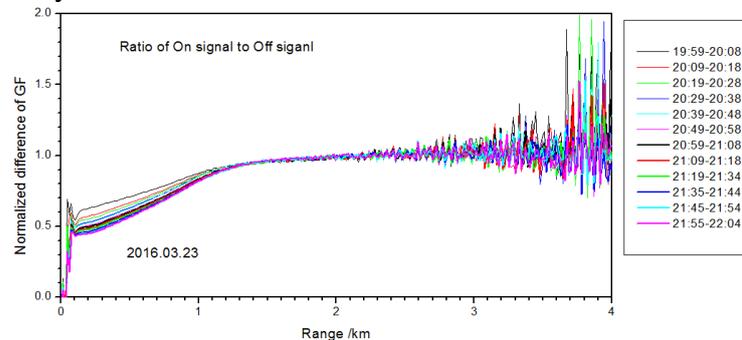


Fig.4 Normalized differences of geometric form factor between dual laser beams

A DIAL system is normally running without disruption after optics alignment. We assume (1) system stability of mechanical structure can be kept. (2) The quality of laser beam can change, but it is averaged by several thousand or up to ten thousand return pulses, it may obey statistical distribution. Based on above two assumptions, we present two condition in boundary: GFF=2 in full receiver range, and GFF=1 at range of 100m or 200m (or other constant C, which does not affect the final conclusion), ratio function as Ratio(z),

A function f(z) is introduced, which makes the geometrical form factor function GF(z) satisfy $GFF(z) = Ratio(z) * f(z)$,

$GFF(200m) = 1$, and $GFF(2000m) = 2$

Ratio(z) can be transferred as follow,

- A. Normalized at 200m, then ratio function becomes as: $Ratio(z)/Ratio(200m)$
- B. $Ratio(z)/Ratio(200m) - 1$
- C. $GFF(z) = [Ratio(z)/Ratio(200m) - 1] / [Ratio(2000m)/Ratio(200m)] + 1$

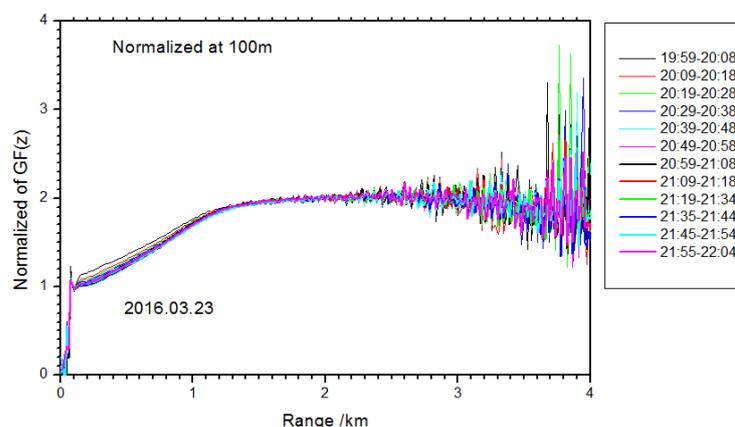


Fig.5 Range distribution of on/off normalized to constant 1 at 100m

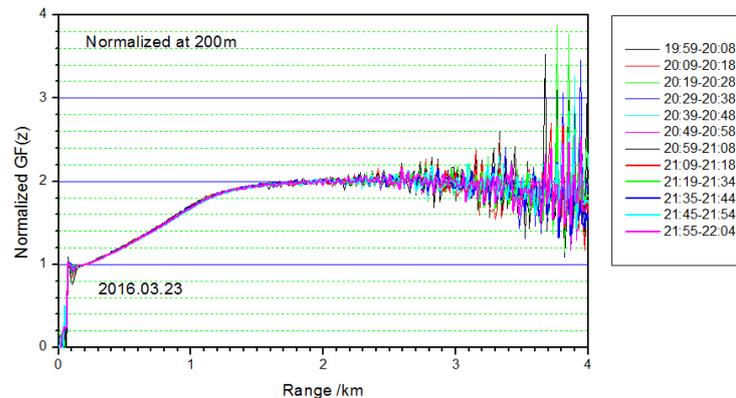


Fig.6 ratio profile of on-signal to off-signal, normalized to constants 1 at range 200m

Fig.5 and Fig.6 are ratio profiles of on-signal to off-signal normalized at range 100m and 200m, respectively. It can be seen from Fig.5, large differences of geometrical form factor between two return signals, but from Fig.6, the differences are very small. We calculated the mean values, standard deviations and its relative standard deviations and shown in Fig.7. It can be seen from Fig.7, at range from 200m to 2km, several groups of relative standard deviations were less than 1%.

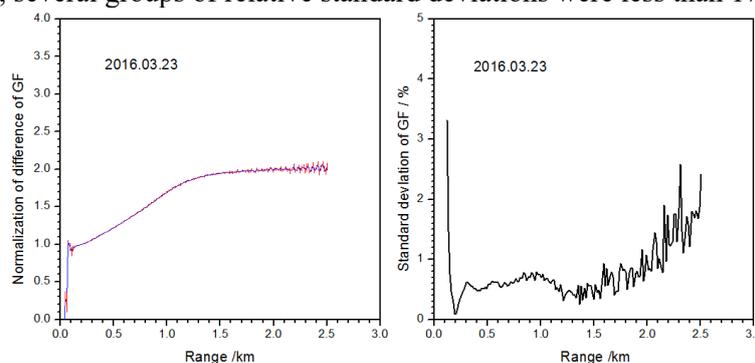


Fig.7 distribution of mean value, standard deviations and its relativity of differences of geometrical form factor between on-signal and off-signal after normalization at range of 200m

It can be seen, results are big difference at different normalization range, such as 100m and 200m. By choosing a proper range to normalize, it can make the uncertainty lower than 1%. When normalizing at 100m, it can be seen the uncertainty at 200m has the largest. It means that we can input an initial range to normalize, then find a range where uncertainty is largest, and as the next range to normalize.

4. Conclusions

During measurements, construct stability of transmitting unit and receiver in lidar system, and quality of laser beams can be kept for long time. It is indicated from real observation case that standard deviation of ratio of on-signal to off-signal is limited less than 1%. It also includes the effects of variation of SO₂ concentration on the path of laser beam passing through. It shows that the developed system is stable and reliable during measurements. In this paper data analysis of difference of geometrical form factor between two return signals cannot resolve data retrieval in transition range, but it is important and has a reference for development of SO₂/NO₂ DIAL system.

Acknowledgment

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References

- [1] Fredriksson K., B. Galle, K. Nystrom, and S. Svanberg, Mobile lidar system for environmental probing, *Appl. Opt.*, 1981, Vol. 20(24),4181-4189

- [2] Hans Edner, Kent Fredriksson, Anders Sunesson, Sune Svanberg, Leif Uneus, and Wilhelm Wendt, Mobile remote sensing system for atmospheric monitoring, *Appl. Opt.*, 1987, Vol. 26(19),4330-4338
- [3] Takashi Fujii, Tetsuo Fukchi, Naohiko Goto, Koshichi Nemoto, and Nobuo Takeuchi, Dual differential absorption lidar for the measurement of atmospheric SO₂ of the order of parts in 10⁹, *Appl. Opt.*, 2001, Vol. 40(6), 949-956
- [4] Tetsuo Fukchi, Naohiko Goto, Takashi Fujii and Koshichi Nemoto, Error analysis of SO₂ measurement by multi-wavelength differential absorption lidar, *Opt. Eng.* 1999, Vol. 38(1), 141-145
- [5] Zhang Y, Hu H, Tan K, et al. Development of a mobile lidar system for air pollution monitoring[J]. *ACTA OPTICA SINICA*, 2004, 24(8):1025-1031(in Chinese).