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Application of α–β–γ filtering to real-time atmosphere methane concentration measurement*

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A real time α–β–γ filtering technique is applied to the monitoring of atmosphere CH_4 based on a tunable diode laser spectrum system operating at 1.654 μm. This technique is developed for improving the sensitivity and precision of CH_4 concentration measurement with slow concentration change. The effectiveness of this technique is evaluated by performing CH_4 concentration measurement and using it to monitor the varying methane level in the atmosphere. It was proved that signal noise ratio enhancement factor is 4.25. The comparison between this filter and moving average is also included in this article. It indicates the advantage of the α–β–γ real time filter.

Keywords: tunable diode laser absorption spectroscopy, multi-pass cell, harmonic detection
PACC: 8670L, 0765G

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) is a sensitive, selective and fast response technique which has been widely used in trace gas measurements.[1−6] The noise in the TDLAS system such as of laser, electrical and optical, caused short-term variations in trace gas measurements. Though the fluctuation of laser power can be removed[7], but the fast fluctuations of measured concentration cannot reflect the true gas concentration variations, and in most cases, the trace gas concentration does not change quickly. In order to eliminate the virtual concentration fluctuation and enhance the sensitivity of the TDLAS system, we applied α–β–γ filtering to real time atmospheric methane concentration monitoring, and enhanced the sensitivity, which cannot always be improved by increasing the average time.[8]

The filtering techniques used in trace gas measurement systems must be able to on-line filter the concentration measurements. There are only a few successful techniques that have been regarded as efficient on-line filtering of concentration measurements. The simple one is the n points moving average; the most efficient one is Kalman filter, but the equations are more complex than the moving average. The filter included in this article is a little more complex than the moving average but much simpler than the Kalman filter; it can be used in the trace gas measurements that the gas concentration will not change tempestuously, such as the trace gas of atmosphere.

2. Theory of the filter—α–β–γ filter model for atmosphere trace gas concentration measurements

The α–β–γ filter is usually used to filter the measured data with equal interval by estimating the true value.[9] In this article, the concentration x_k^* of atmospheric methane measured with a 1.654 μm near-infrared diode-laser-based sensor can be expressed as

$$x_k^* = x_k + \eta_k, \tag{1}$$

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where x_k is the true gas concentration, η_k is the 'whiteness' noise and its expected value is zero:

$$\mathrm{E}\{\eta_k\} = 0. \tag{2}$$

The equations of concentration estimation with prior data are shown below:

$$\widetilde{x}_{k+1/k} = \widetilde{x}_k + \widetilde{x}'_k T + \widetilde{x}''_k (T^2/2), \tag{3}$$

$$\widetilde{x}'_{k+1/k} = \widetilde{x}'_k + \widetilde{x}''_k T, \tag{4}$$

$$\widetilde{x}''_{k+1/k} = \widetilde{x}''_k, \tag{5}$$

where $\widetilde{x}_{k+1/k}$ is the estimated gas concentration, $\widetilde{x}'_{k+1/k}$ is the estimated velocity of the trace gas concentration change, $\widetilde{x}''_{k+1/k}$ is the estimated acceleration of the trace gas concentration change.

The equations of filtering the estimated data are given as

$$\widetilde{x}_{k+1} = \widetilde{x}_{k+1/k} + \alpha(x^*_{k+1} - \widetilde{x}_{k+1/k}), \tag{6}$$

$$\widetilde{x}'_{k+1} = \widetilde{x}'_{k+1/k} + \frac{\beta}{T}(x^*_{k+1} - \widetilde{x}_{k+1/k}), \tag{7}$$

$$\widetilde{x}''_{k+1} = \widetilde{x}''_{k+1/k} + \frac{2\gamma}{T^2}(x^*_{k+1} - \widetilde{x}_{k+1/k}), \tag{8}$$

where $\widetilde{x}_{k+1}$ is the filtered estimated gas concentration, $\widetilde{x}'_{k+1}$ is the filtered estimated velocity of the trace gas concentration change, $\widetilde{x}''_{k+1}$ is the filtered estimated acceleration of the trace gas concentration change. α, β, γ are the adjustable structural parameters of the filter, T is the sampling periodic time. Figure 1 shows

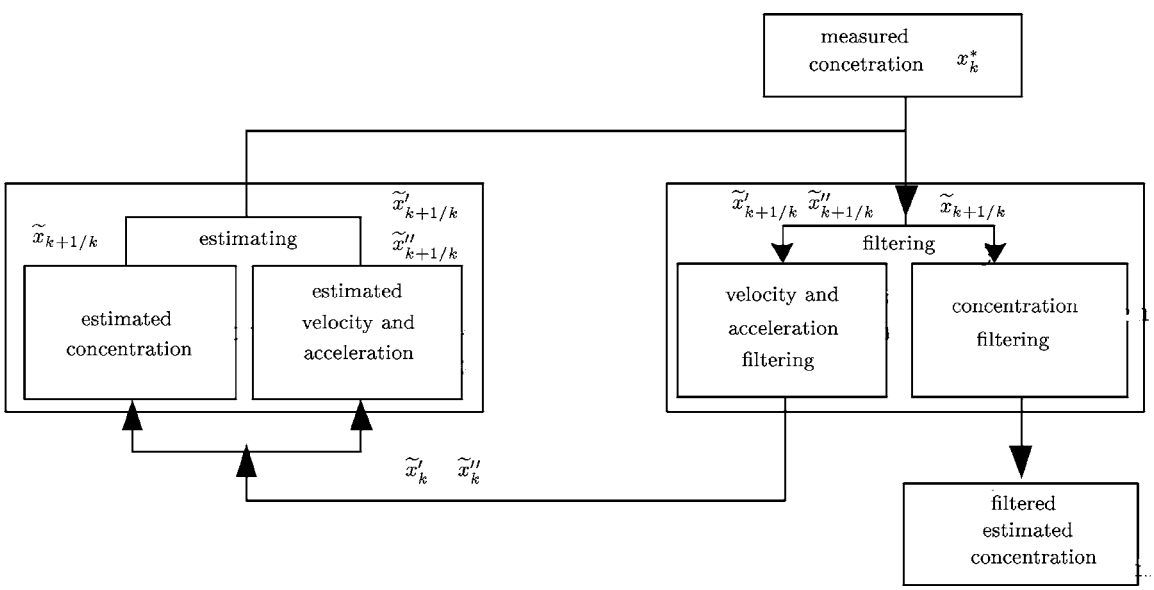


Fig.1. Complete α–β–γ filter cycle, including estimating and filtering.

the complete filter cycle. When the first concentration is measured, it is regarded as the filtered estimated concentration. When the second concentration is measured and substituted into the filtering part, we can get the value of $\widetilde{x}'_k$ and $\widetilde{x}''_k$, then substitute the two parameters into the estimating equations to get the next estimated concentration $\widetilde{x}_{k+1/k}$ and the next estimated velocity $\widetilde{x}'_{k+1/k}$, the acceleration $\widetilde{x}''_{k+1/k}$. The three parameters are used to get the filtered concentration, velocity and acceleration. The filter is operating like above. The parameter α is used to describe the ratio of the difference between the measured and estimated concentration which should add to the estimated value to get the filtered concentration; the parameter β is used to filter the estimated velocity as Eq.(7), the parameter γ is used to filter the estimated acceleration as described in Eq.(8).

The sampling periodic time is determined by the system, and after it is determined, the other parameters should be carefully chosen in order to acquire the best filtering function.

3. TDLAS system

TDLAS has been widely employed in detecting atmospheric trace gases due to its high sensitivity, high selectivity, and fast time response. The most important part in a standard TDLAS system is a tunable distributed feedback (DFB) diode laser. The key

features of the DFB lasers are: 1) their very narrow linewidth, typically less than 50MHz, and thus much less than the linewidth of single rotational gas absorption line; 2) the ability to modulate the wavelength of the laser output through the injection current. High sensitivity detection is obtained by wavelength or frequency modulation spectroscopy and by monitoring first, second, or higher order of the modulation frequency in the detected output signal. In addition, increasing the absorption path length by adapting a multi-pass technique could also greatly enhance the detection sensitivity. The laser diode is modulated by a low frequency sawtooth waveform and a high frequency (f) sine waveform, the laser wavelength is slowly scanned across an absorption line by the sawtooth, the signal from the detector is processed by a lock-in amplifier referenced to the modulation frequency (f). The intensity $I_0(v)$ of a laser beam at frequency of ν passes through a cell of length L filled with an absorption gas can be approximated as

$$I(v) = I_0(v)[1 - \alpha(v)CL], \tag{9}$$

where $I_0(v)$ and $I(v)$ are the laser beam intensities before and after passing through the absorption gas respectively, $\alpha(v)$ is the absorption coefficient of the gas at frequency of v, when the wavelength emitted at the center frequency of the absorption line, $\alpha(v) = \alpha_0$, α_0 is the maximum of $\alpha(v)$, C is the concentration of the absorption gas. For harmonic detection one is only concerned with weak absorption lines: i.e., we can assume that the value of $\alpha_0 L$ is confined to $\alpha_0 L \ll 0.05$. The second harmonic signal obtained by demodulation could be expressed as

$$I_{2f} \propto I_0(v)\alpha_0 CL. \tag{10}$$

The experimental apparatus employed for the measurements is a portable ground-based TDLAS system developed by our group specifically for ambient methane detection. The diode laser employed for this study is a commercially available near-infrared DFB laser from NEL NTT Electronic Corporation. The diode laser is driven by a current controller and a temperature controller. These controllers are made by ILX Lightwave. The laser output wavelength can be tuned coarsely by the temperature controller and tuned finely by the current controller. In order to achieve the expected sensitivity a double modulation was applied to the laser diode. The laser wavelength is slowly scanned through the absorption line from 1653.61 nm to 1653.83 nm by a sawtooth waveform at frequency of 50Hz and simultaneously modulated by a sinusoidal waveform at frequency of 5 kHz. A multi-pass white cell with base length of 0.22 m is used to lower the detection limit. The total path length is 24m. The picture of the system and its schematic diagram are shown in Fig.2. The laser beam is transferred to the multi-pass cell through a standard single-mode optical fibre with a self-focusing lens at the end, after multiple reflections in the cell the laser beam passes

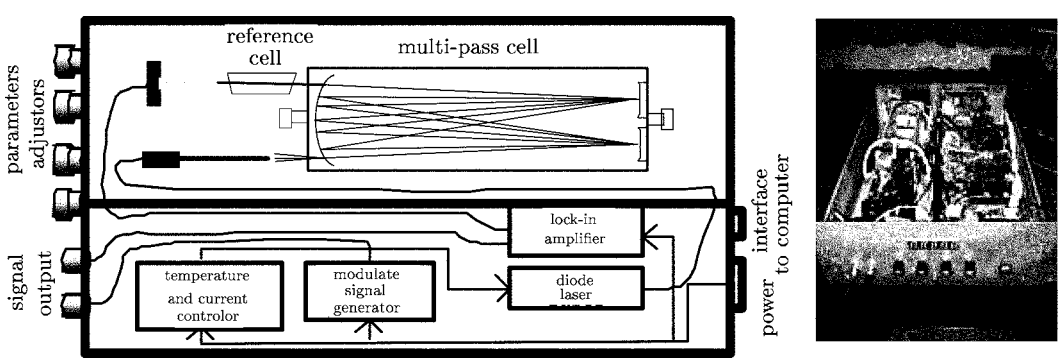


Fig.2. Diode-laser-based methane sensor configuration and its photo for continuous measurement.

through the reference cell which is used to calibrate the trace gas concentration, then it is focused onto a detector. The harmonic detection technique is used in this TDLAS system. The modulation signal to the laser and the reference signal to the lock-in amplifier are produced by a signal generator. The optical output from the reference cell after passing through the detector is then sent to the lock-in amplifier to get the $2f$ absorption signal. The data acquisition and processing system is used to collect the $2f$ signal from the

lock-in amplifiers, and process the signal which will be described in Section 4 in detail. The ambient air is pumped through the multi-pass cell by a sampling pump.

4. Experimental results and discussion

The filtering technique is investigated by using the TDLAS system described above for atmospheric methane detection and quantification.

After optimizing the parameters of the filter, we get the better group parameters and test the filter as below. The gas sealed in the multi-pass cell is the air pumped from the outside, and its concentration is measured for more than 700 s, the unfiltered data and filtered data are shown in Fig.3. In order to estimate

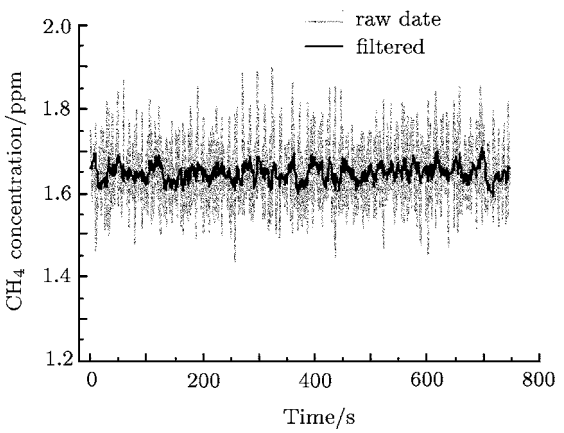


Fig.3. Estimate of the effectiveness of the α–β–γ filter in ambient methane concentration short-time measurements.

the effectiveness of the filter, the standard deviation of the noise fluctuations was estimated. Before the application of the α–β–γ filter, $\sigma^2_{\text{unfiltered}}$=0.085 ppm and after the application of the filter, $\sigma^2_{\text{filtered}}$=0.020 ppm. As there was no reduction in the mean signal amplitude, this result corresponds to a signal noise rate enhancement of a factor of 4.25 in the 750 seconds measurements. After the short time test this filter technique was used for a long time methane concentration measurement, the comparison between a α–β–γ filter solution and a moving average technique is also shown in Fig.4. We measured the outside methane concentration at Kexue Dao in Hefei for 16 h with a concentration value per three seconds and the trace gas level is shown below.

In Fig.4, it is obviously that the signal noise ratio was improved, and the filtered data makes it easy to analyse the methane concentration change. In the raw data there are two spike, this phenomenon also

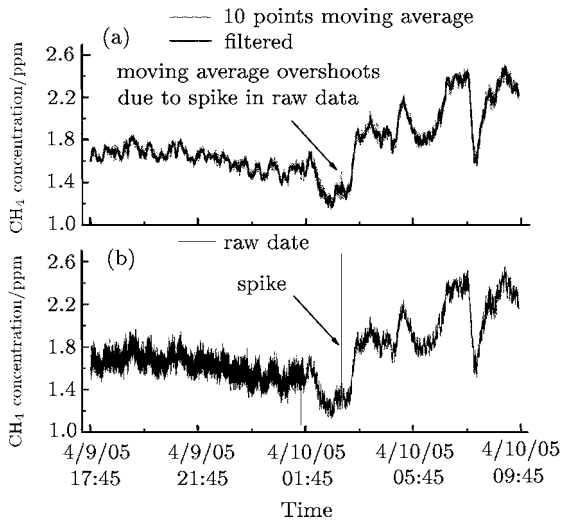


Fig.4. Methane measurement and α–β–γ filter results and the comparison between two techniques.

appeared in Ref.[8]. When abnormally large spikes are generated by the system, the filter shows superiority to the moving average. For instance at 4/10/05 3:03 in Fig.4(b), a spike of 2.6 ppm was generated. Observing surrounding data, we find that the 'real' concentration of 2.6 ppm seems unlikely because the methane concentration in the ambient air will not change so quickly. So after the data processing, this feint should be removed. This value estimated filter technique is useful to remove this influence as shown by the black curve in Fig.4(a), but another simple data processing technique—moving average—cannot remove the influence of this large spike though it can remove the small spike at 4/10/05 1:34 in Fig.4(b); this comparison is shown in Fig.4(a). Increasing the number of points in the moving average will deal with these spikes well, but will bring another problem—-lagging behind the data change as described in Ref.[8]—and it also needs much data to be saved in the memory.

5. Conclusion

In summary, use of α–β–γ filter significantly improved the detection sensitivity of the diode-laser-based trace gas sensor by a factor of four in methane measurements by estimating the true concentration to reduce the variability. The filter technique discussed in this article is suitable for slow changing signals measurements, especially for the ambient trace gas measurements such as CO, CH_4, CO_2, and NO_2 and so

on. In these measurements, it will result in a large signal to noise enhancement with a group of appropriate parameters.

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