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Quasi-random Scanning of a Digitally Controlled Spectrometry

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Abstract

A quasi-random method for spectral scanning is proposed to reduce an alias response to a quick change in the source abundance. A direct application is made for an atmospheric methane monitoring with a current-tunable diode laser. Only barrel shift methods are examined being found further vulnerable to drifting etalon fringes.

1. Introduction

Increasing number of measurement apparatuses which are based on spectrum-scanning have been developed, and a spectrometry often finds its application in a continuous monitoring purpose. Also computerized architectures both for controlling and for the data processing are incorporated in order to exploit higher performances.

The authors have developed atmospheric-gas monitors using current tunable diode lasers[1)2)]. A compatibility between locality, real-time measurement, and high sensitivity, as well as portability is achieved. The laser frequency can be controlled as quickly as in 10 microseconds and the spectral scanning is not necessarily in the order of wavelength. A result is given taking a correlation between a prescribed weight spectrum and the measured spectrum. A false response may take place, however, when the gas density changes abruptly on the course of the spectrum scanning. A random scanning of the laser frequency may resolve this problem giving a less singular results aminable to human comprehension.

In this paper a barrel shift method for the quasi random scanning is examined as well as its parasitic response to the etalon fringe noise which is specific to a laser-absorption spectrometry The technique introduced here has wide applications to serial scanning apparatuses for a continuous monitoring purpose.

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2. Serial Spectral Scanning and a Data Processing

In the serial spectral scanning, either a combination of a white light source, a dispersive devise and a photo detector, or a combination of a tunable monochromatic light source and a photodetectors is employed. Since the wavelength that is involved at an instant is only one, a definite time duration is required to aquire the whole spectral information. The object of measurement does, however, not stand still in the period. This is in contrast to an optical multi-channel analyzer where multiple photodetectors are employed. The whole detectors are illuminated simultaneouly and the aquired spectrum therefore stands for the true one at a time instant.

The atmospheric-gas monitor that the authors have developed involves a lead-tin-tellulide diode laser which has an emission band around λ=7.6 μm meeting the ν_4 absorption band of atmospheric methane. An absorption spectrum, though is it the second-derivative spectrum, is scanned in 4.2 second. The response time of laser frequency to a step change of the diode current is about 10 microseconds and the second-derivative spectrometry with source frequency modulation at 7.68 kHz is possible.

Two spectrum S_X and S_R are measured simultaneously. The spectrum S_X is of the open atmosphere of 1 meter pathlength and S^* is of a standard gas contained in a cell of 5 cm long. An adjoint spectrum S^* is created from this reference spectrum S_R after every scanning, and the density of atmospheric methane is calculated by an equation

$$c_X = K \int_{\nu_1}^{\nu_2} S^*(\nu) S(\nu) d\nu \qquad (1)$$

where K is a constant determined by system parameters and [ν_1, ν_2] are the scanning region of the laser freqency.

If the true density of atmospheric methane c keeps still, the equation (1) has no problem. The density may, however, change suddenly on the course of spectral scanning. This may take place when a crowd of thick methane travels across the apparatus. Let the true density at the apparatus changes stepwisely as

$$\delta c(t) = c_0 U(t) \quad , \qquad (2)$$

where $U(t)$ stands for the unit step function and c_0, its amplitude. Substituting Eq.(2) into Eq.(1), we obtain

$$\frac{dc_X}{dt} = -KS^*(\nu) S_R(\nu)\, c_0 \quad . \qquad (3)$$

This effect is well illustrated in Fig. 1, where the change in the measured density is plotted as a function of the time instance when the density change takes place. Here the adjoint spectrum S^* is given by an equation

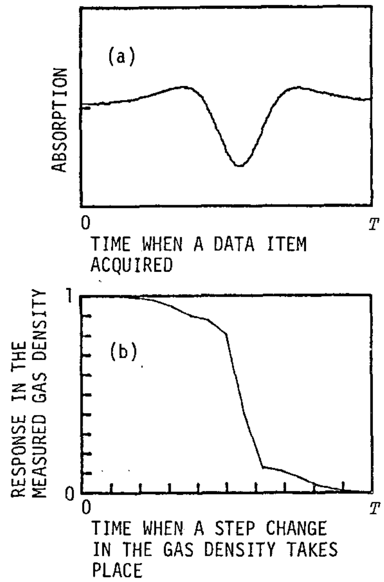


Fig. 1. (a) A methane spectrum involved in a serially scanned spectrometry and (b) a response of the density results subject to a step change in the target gas density. The change is supposed to take place at the time when data item of the spectrum is acquired.

$$S^* = S_R - \bar{S}_R \quad , \tag{4}$$

where $\bar{S}_R$ is the average over the spectum.

The Fig.1(a) was measured by the experimental system for the standard methane gas in a cell and the measured value of c_X for an imaginary step change in c. Results are plotted as a function of the time instance $t=\tau$ when the step change takes place, and the values are normalized by that for $\tau=0$. The value of obtained density value c does not change along with the change of τ but is strongly affected by the spectral profile of Fig. 1(b), as is expected by Eq.(2).

3. Bite-Shuffle Scanning : a quasi-random sequence

In a digitally controlled system, the frequency is once represented by a digital value before is it converted into an analogue voltage or current. A digital signal for a scanning is produced by a counter and its content is implemented to electronic signal with a digital to analog (DA) converter, as illustrated in Fig. 2. The counter and the DA converter is

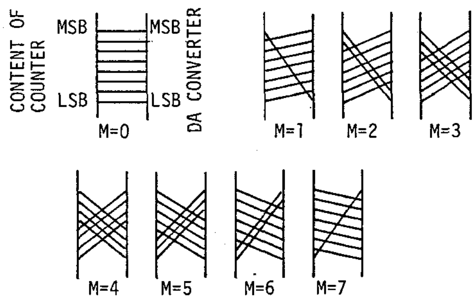


Fig. 2. Connections between the counter and the DA converter. Barrel shift shufflings are shown for shifted numbers M=1∿7.

connected with a bundle of parallel bit wires, the number of which is determined by the width of a word involved in the system.

A quasi-random scanning sequence is achieved by shuffling bit wires from the counter to the DA converter. This technique of scanning is named by the authores as "bite-shuffle scanning". For an 8 bit architecture, 8!=408320 manifold varieties of the shufflings exist. An exhaustive investigation for the best shuffling was abondoned and only barrel-shifts were examined. This method should be called as "barrel-shift scanning". According to the digital control system that the authors are involved, there are 8-fold barrel shifts, each of which is charactorized by the number of shift M as illustrated in Fig.2. Consequent scanning sequences are illustrated in Fig. 3 for three different numbers of shift.

Effects of the shuffling were examined by a computer simulation providing a spectral profile of the target gas of Fig. 1. Figure 4 and 5 give results. According to the number of shifted bits, apparent numbers of spectral lines increase and the consequent response of the calculated gas density as a function of the time instance τ the step change of the object density takes place becomes smoother as had been expected till M=5. However for M=6 and 7, or for M=-2 and -1, number of spectral lines increase but change of the density response becomes not uniform in the period. This is brought by an alias distribution of line intensities. A still existing periodicity in the spectral scanning sequence gives rise to this alias spectrum distribution. A further search for more natural random sequence is therefore desirable to be chosen though, not yet executed.

4. Application to TDL Atmospheric Gas Monitoring

The barrel-shift shuffling technique was applied to the atmospheric methane monitoring that the authors are engaged. A set of spectra of atmospheric methane is scanned over 4.2 seconds and each spectra comprises 256 data items each of which is acquired in 1/60 second.

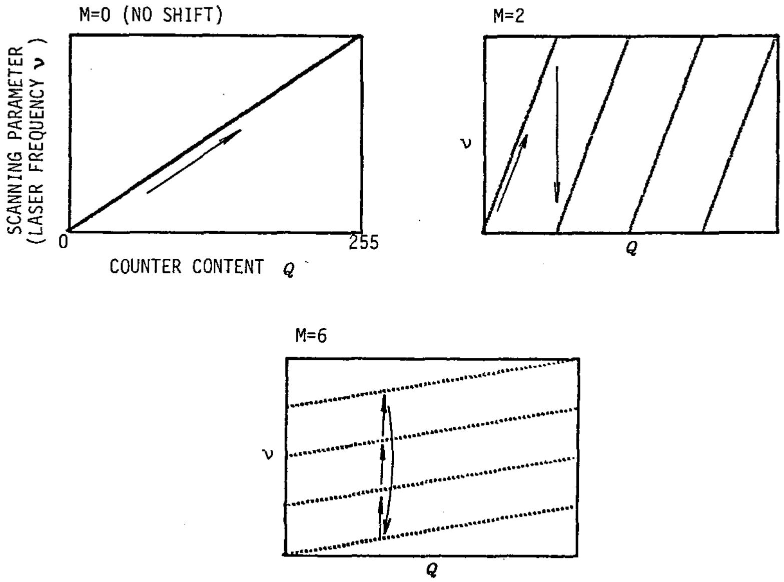


Fig. 3. Temporal sequences of scanning parameter as a function of the counter content for three bite shift shufflings.

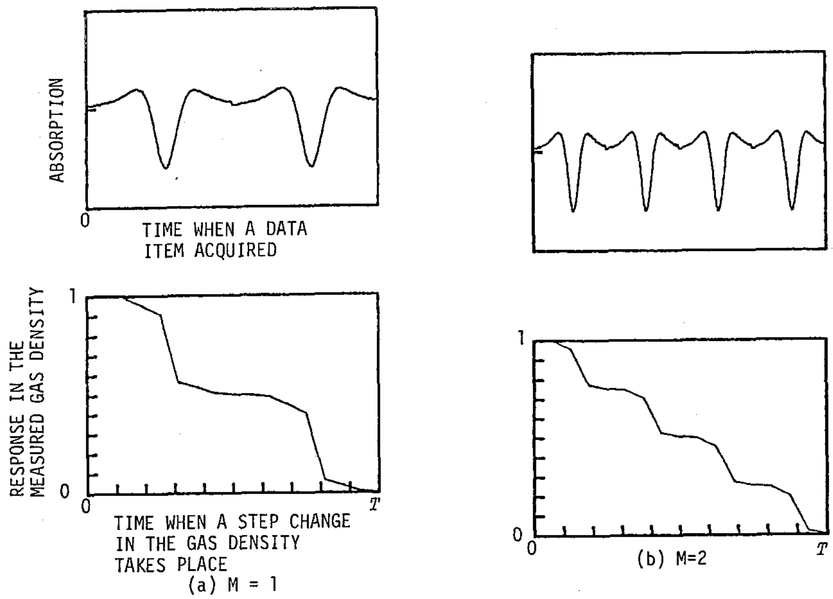


Fig. 4. Results of computer simulation with bite shift shufflings M=1 and 2. A step response becomes closer to the proportional as M increases.

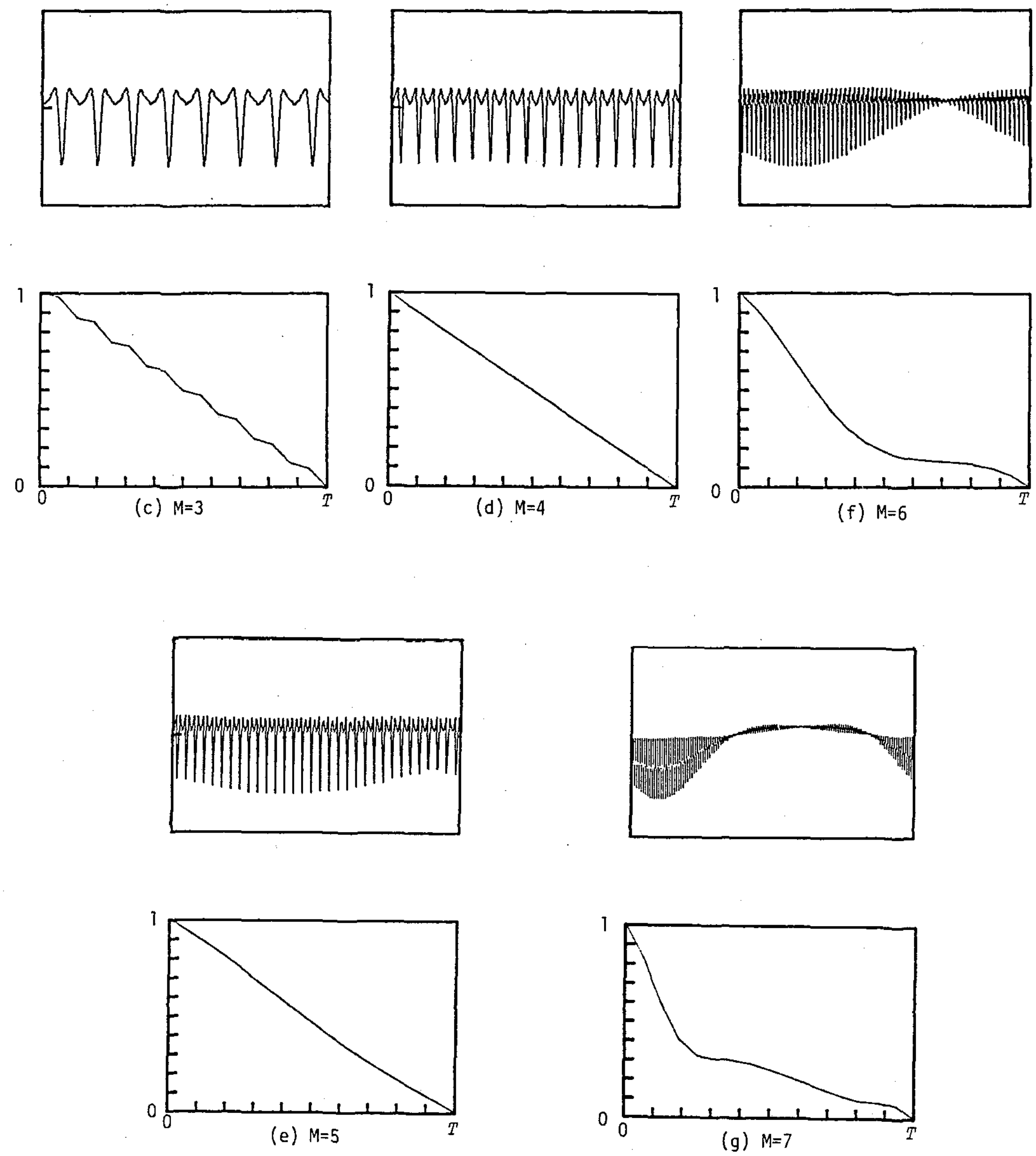


Fig. 5. Results of computer simulation of the spectral scanning and fractional responses of measured values to sep changes in the object gas density for $M=3\sim7$. The response versus the time duration in which the density is increased becomes more closer to be linear as increases till 5. This desirable effect fails for M=6 and 7.

Three different method of shufflings were examined. They are barrel shifts of M=0,2 and 4. Figures 6,7 and 8 give records of the measured density over one hour. The experiments were carried in a laboratory with open window. No distinct change of atmospheric methane was recorded as has been expected from the weather condition on the day. The fluctuation in terms of the relative standard deviation grows bigger as M increases.

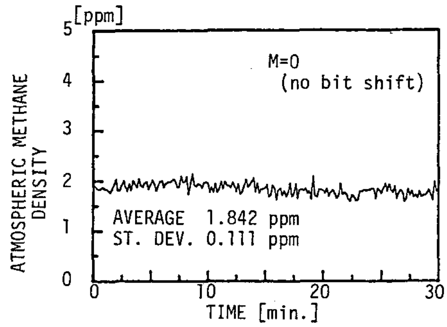


Fig. 6. Temporal trace of atmopheric methane density without the bit shuffling.

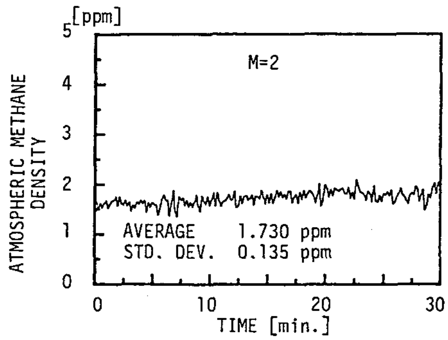


Fig.7. Temporal trace of atmospheric methane density with bite shuffling of M=2.

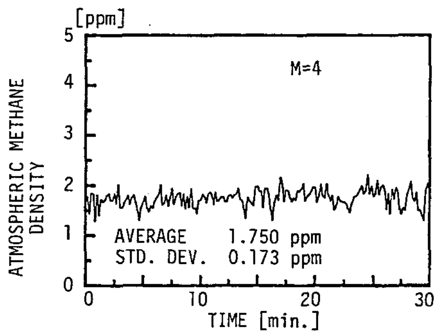


Fig. 8. Temporal trace of atmospheric methane density with bite shuffling of M=4.

5. Alias response to Etalon Fringes

The experimental results were contrary to the author's expectation that fluctuations in the atmospheric methane density on the course of a single spectral scanning is smeared out by the shuffling. After some examinations, this effect is attributed to an interference between an etalon fringe and the periodic quasi-randomisation in the scanning.

Figure 9 is an absorption spectrum of the atmospheric methane of small abundance on the order of 2 ppm•m, and a reference spectrum of stanadard methane gas cell of 500 ppm•m measured on the same scanning. No shuffling is done here. In the spectrum S_X, a fine-pitched periodic constituent is clearly found. This is called as the etalon fringe which takes place because the laser couples with the light reflected back from somewhere of the optical system.[2] This etalon fringe is the dominant noise source of the atmospheric-gas monitoring system and the measuring system is designed to be as least sensitive for these fringe spectra as possible.[3]

Data items composing the spectrum of Fig.10 were rearranged spectrum with the shuffling of $M=4$ into torder of laser frequency. The clear fringe pattern is not found here but the methane spectrum is much distorted. This is considered to be brought by the fringe which has been broken by the shuffled scanning. A beat note between the fringe pitch and that of the bite-shuffled scanning appears here.

In order to confirm this hypothesis, computer simulations were made. At first an etalon fringe spectrum of Fig.11 comprising uqually spaced 256 data items was prepared. The spectrum $S(\nu)$ is expressed as

$$S(\nu) = \sin\{360 \cdot N \cdot \frac{\nu}{255} + f(t)\}$$

$$\nu,\ t = 0,1,\cdots,255 . \tag{5}$$

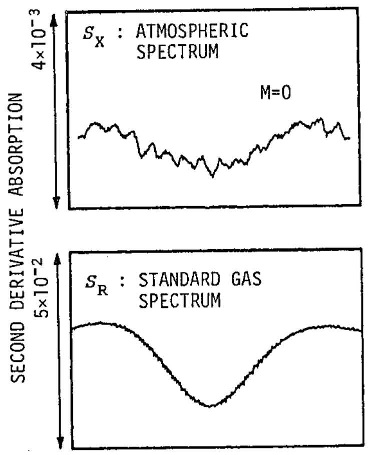


Fig. 9. Spectra of methane without the bite shuffling ($M=0$).

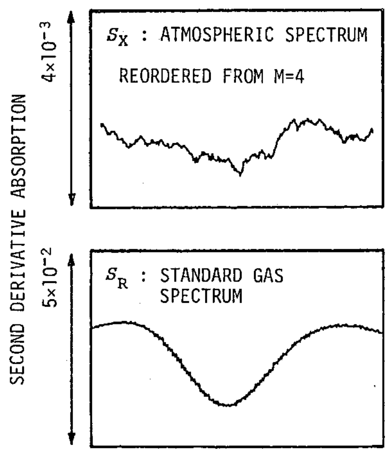


Fig.10. Spectra of methane with the bite shuffling of $M=4$.

This expression stands for a N cycle sinusoidal spectrum with a temporal phase drift of $f(t)$.

Three examples are shown below. For the first case the phase drift of 2π takes place in the period of spectral scanning. Both results with and without the barrel-shifted scanning are shown in Fig. 11a and -b, respectively. The second is for phase drift of -2π. Much difference between Fig.11b and Fig. 12b, though less between Figs. 11a and 12a. The phase lag is taken to be $2\pi \cdot 300/360$ in the third case giving results in Figs. 13a and 13b. An alias response of the measured density value to the drifting etalon fringe is found. Common to these results it is also noted that the amplitude of the parasitic response is limited to that of the source fringe amplitude. The necessity to suppress the amplitude should be therefore stressed.

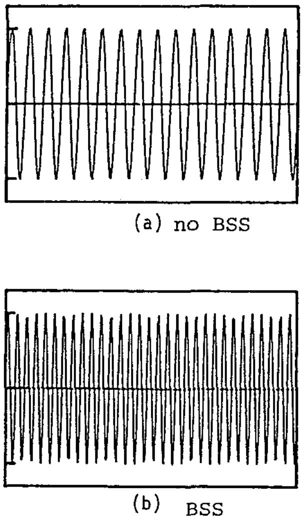


Fig. 11. Computer simulation of the effect of bite shift shuffling (BSS) on a drifting etalon fringe. A fringe phase leads 2π on the scanning period.

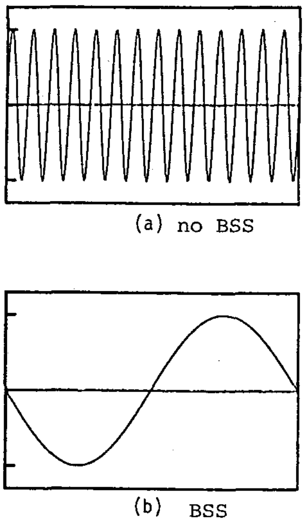
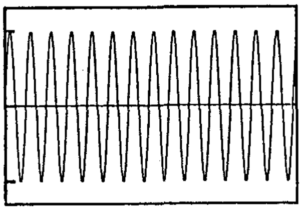


Fig. 12. Computer simulation of the effect of bite-shift shuffling (BSS) on a drifting etalon fringe with 2π lag on the scanning period. The BSS gives an alias spectrum.



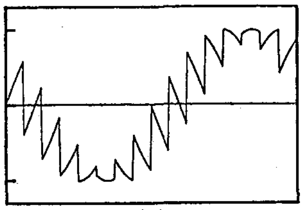


Fig. 13. Computer simulation of the effect of the bite-shift shuffling (BSS) on a drifting etalon fringe with $2\pi \cdot 300/360$ lag. The fringe pattern is transformed to a "noisy" profile.

It is found that the bite shuffled scan with a simple barrel shift is vulnerable to an etalon fringe with a phase drift. A more sophisticated random scanning is necessary and this is still open.

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