A DATA ACQUISITION AND PROCESSING SYSTEM FOR LIDAR MONITORING OF THE ATMOSPHERIC CONTAMINANTS

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A problem of determining the atmospheric contaminant concentrations using a DIAL technique is considered in this paper. An analysis of a complex multidimentional nonlinear system allows one to make its serial–parallel decomposition into simpler components and for each of them to construct an optimal reduction transformation chain from a linear to a series of simple nonlinear and finally to a spatially invariant measuring system.

INTRODUCTION

The problem of interpreting results of lidar measurements is one of the most important problems in the atmospheric studies. It is considered to be solved when one obtains from lidar sensing data sufficiently accurate estimates of the atmospheric parameters of interest like, e.g., distributions of densities or concentrations of atmospheric contaminants along the sounding path.[1,2,3]

In practice, of complex measurements like, e.g., lidar sensing of the atmosphere, direct interpretation of measurement results is too problematic. However, if a mathematical model relating the properties of an object under study and measurement results can be constructed, a whole spectrum of processing techniques can be suggested that could fit the interpretation task.[4]

As a rule, lidar measurements follow one and the same routine: a laser pulse is sent into the atmosphere (to reach a remote topographic target), and backscattered radiation is detected. Then the atmospheric parameters sought (concentrations or size spectrum of contaminants), should be estimated using an optimal technique for processing the received signals (spectra).

The present paper discusses the task of designing a computerized measuring system[1] of the highest possible sensitivity or resolution (CMS SHR) for a lidar measurement system (MS) available. Generally speaking a design of an optimal computational component of the CMS (an optimal processing algorithm) needs for an accurate information about the model of measurements.

A lidar measurement system is in general a complex nonlinear system of large dimensionality, admitting however, a serial–parallel decomposition into simple components; a linear one, a series of simple parallel nonlinear ones, and a multidimensional linear spatially invariant MS for each component an optimal computational algorithm can be constructed.[4,5] The entire processing algorithm (the computational component of the CMS) is then presented as a serial–sequential composition of corresponding algorithms.

The computational component of such a lidar CMS performs a complex optimal transformation of a signal, adequately accounting for the spectral intensity distribution of a laser emission (i.e., for its nonmonochromaticity), for standard absorption spectra of different pollutants, and for *a priori* information about pollutants or the particle size spectra that would allow the final estimation of the sought parameters to be made.

THE LIDAR MEASUREMENT SYSTEM

In a long path absorption lidar measurement arrangement, a laser pulse is sent to a remote topographic target in the atmosphere and a portion of the laser pulse power reflected backward by the target is detected. The measurement algorithm can be given in the following form:

$$\xi(\nu_0) = \frac{B\int a(\nu,\ \nu_0)\ \exp\left(-2R\sum\limits_{i=1}^{k} N_i\sigma_i(\nu)\right)\mathrm{d}\nu}{\int a(\nu,\ \nu_0)\mathrm{d}\nu} + \eta\ , \qquad (1)$$

where $\xi(\nu_o)$ is the measured power of a spectrum within some frequency interval; ν_o is the coordinate in the laser emission tuning range, (note that the measured spectrum has the dimensionality of K, and k pollutants affect the measurement result), $a(\nu, \nu_o)$ is the spectral characteristic of the output laser radiation at the frequency ν_o (it is usually assumed Gaussian, with the half–width γ_λ); B is the factor depending on the area of the receiving optics, on the reflection coefficient of a topographic target, on the efficiency of the receiving system (i.e., on its optical losses), and on the volume losses along the sounding path, i.e., on R^{-2}; η is the noise; k is the number of absorbing components in the atmosphere; N_i is the concentration of the ith component; R is the path length; $\sigma_i(\nu)$ is the function describing the absorption by the ith component (its absorption cross section), which is usually given in the form of a linear superposition of individual absorption lines of a fixed shape, as

$$\sigma_i(\nu) = \frac{\sum\limits_{j=1}^{m_i} S_{0j}^{(i)}}{\left\{1 + \left(\dfrac{\nu - \nu_{0j}^{(i)}}{\gamma_{0j}^{(i)}}\right)^2\right\}}\ ,$$

where m_i is the number of absorption lines in the ith standard spectrum; $S_{0j}^{(i)}$, $\nu_{0j}^{(i)}$, and $\gamma_{0j}^{(i)}$, are the intensity, central frequency, and half–width of the ith line of the jth component, respectively.

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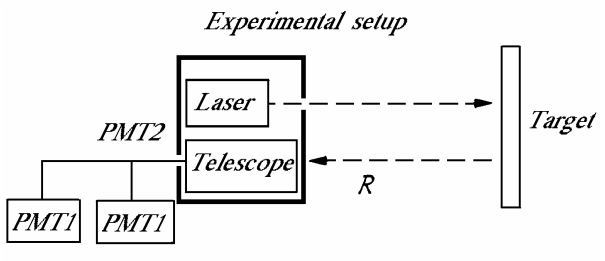

FIG. 1.

Since the measurement system remains spatially invariant (it is invariant with respect to the frequency shift) measurement scheme (1) may be described within the above problem, as follows[2]:

$$\xi(\nu_0) = \int I(\nu) \exp\left\{-2R \sum_{i=1}^{k} N_i \sigma_i(\nu)\right\} a(\nu - \nu_0) d\nu + \eta \ . \quad (2)$$

Here $a(\nu - \nu_0)$ describes the line shape, since the laser tuned to the frequency ν_0 emits radiation in a certain frequency interval following the function $a(\nu - \nu_0)$; $I(\nu)$ is the spectral power of laser radiation.

SERIAL–PARALLEL DECOMPOSITION OF THE MEASURING SYSTEM

Scheme of measurements (2) aimed at determination of number densities of absorbing contaminants by a differential absorption technique is a nonlinear measuring algorithm of large dimensionality, and therefore the reconstruction of the initial signal from data of measurements is not a trivial problem.

To solve this problem let us present the lidar measurement procedure as a sequence of three "mathematical" measurements. The linear measurement *1* is a transformation of the vector of concentrations $\mathbf{N} = (N_1, \ldots, N_k)^*$ of dimensionality k to a multi–dimensional signal $S(\nu) = 2R \sum_{i=1}^{k} N_i \sigma_i(\nu)$ which is the resulting spectrum, either the absorption or the transmission one.

The measurement *2* is the decomposition into K nonlinear one–dimensional measurements $g(\nu) = I(\nu)\exp(-S(\nu))$, where $g(\nu)$ is the intensity of radiation which would be detected at a frequency provided that the radiation is purely monochromatic with the intensity $I(\nu)$. The frequency dependence of the receiving channel B = const.

Measurement *3* is the spatially invariant measurement system in which a multidimensional signal $\xi(\nu_0) = \int a(\nu - \nu_0) g(\nu) d\nu$ is obtained. The laser tuned to the frequency ν_0, in fact emits the radiation within a certain frequency band, described by the function $a(\nu - \nu_0)$.

Thus, the total measurement scheme may be represented as a series of three "mathematical" measurements.

SYNTHESIZING THE MEASURING–COMPUTATIONAL SYSTEM

Mathematically the problem of interpreting experimental data involves obtaining an estimate **N** of concentrations from measurement results $\xi(\nu_0)$, i.e., it is the problem on constructing an algorithm, which would optimally transform $\xi(\nu)$ into the estimate **N** and which adequately accounts for the measurement errors. It should be especially noted that this algorithm theoretically guarantees certain error of reduction (i.e., an error in determining **N**).

The reduction problem is solved step by step. At the first step g is optimally retrieved from the measurement result ξ and all specific features of the 3–rd measurement, i.e., the scanning nature of measurements and their invariance with respect to the frequency shift are accounted for.[5]

At the second stage the components S are optimally retrieved in parallel from all of the g components. At the third stage the vector of concentrations **N** is also optimally retrieved from S.

Since ξ is known with an error that has certain stochastic characteristics, g is optimally retrieved to a certain controllable error, the estimates of S and, consequently, of **N**, will also be obtained with some controllable error.

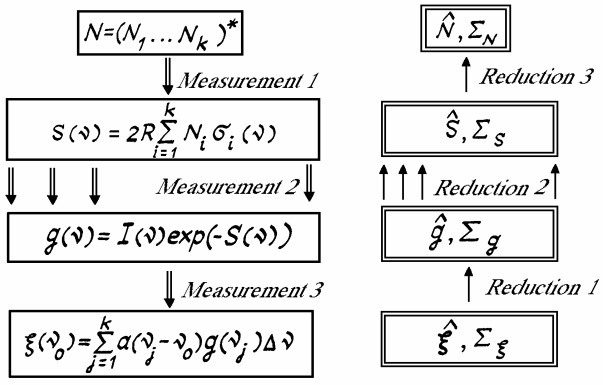

FIG. 2.

Thus, the complete measurement and reduction schemes will have the structure shown in Fig. 2. The scheme involves only two types of measurements: the linear and the simple nonlinear (exponential).

A LINEAR MEASURING SYSTEM

Let a measurement be described by a linear stochastic measurement scheme with an additive noise.[4]

$$\zeta = Az + \mu,$$

where z is a random vector with the known covariance operator F; vectors μ and ζ are the random error with a zero mean value and the correlation operator Σ and the measurement result, respectively; and, A is the linear operator. Let the vector Uz (U is the linear operator) is estimated using the transformation R (the reduction operator[4]). The quality of the operator R is usually described by the rms error of the estimate

$$h(R, A) = \mathbf{E}\,||R\zeta - Uz||^2 \ .$$

It is natural in this case that the operator R_A, such as

$$h(R_A, A) = \min\{h(R, A) \ | R: \tilde{\mathbf{R}} \to \mathbf{U}\} \ ,$$

is optimal.

Then the solution of the problem of reduction has the form:

$$R_A = UFA^*(AFA^* + \Sigma)^{-1},$$

$$h(R_A, A) = \mathrm{tr}(UFU^* - UFA^*(AFA^* + \Sigma)^{-1}AFU^*) .$$

For the reduction *1* this means that

$$g = R\xi , \ \Sigma_g = UGU^* - UGA^*(AGA^* + \Sigma)^{-1}AGU^*, \text{ and } \Sigma_g = \Sigma.$$

As to the reduction *3*, its solution is constructed in a similar way.

A NONLINEAR MEASURING SYSTEM

Let us consider a nonlinear measurement scheme[6]

$$\zeta = a(z) + \mu .$$

The task of reduction is then formulated as follows. First such a reduction transformation r is constructed that minimizes the rms error

$$h = \mathbf{E}\,||\, r(\zeta) - U(z)||^2 \to \min .$$

In our case an individual measurement is simple (contains an exponential dependence) and an analytical solution may be constructed from it. Indeed, let us consider the measurement scheme:

$$\zeta = \exp(-z) + \mu .$$

If one assumes that z is uniformly distributed over the interval $[0, z_{\max}]$ (what agrees with the natural situation), and the noise μ is uniformly distributed over the interval $[-\delta, \delta]$, then $r(\zeta)$ will be the sought–after reduction transformation (see Fig. 3.). Such a measurement scheme is used in the reduction *2*.

CONCLUSION

The described concept has been developed for some problems of lidar sensing (e.g., on determination of concentrations of atmospheric pollutants using a DIAL technique). The construction of a measuring and computational system, that is synthesizing an optimal algorithm for processing lidar measurement data makes it possible to calculate the parameters of spectral lines from tan experimentally measured spectrum on a real time scale and at a controlled level of uncertainty.

The principles of serial–parallel decomposition of the described–above measurement systems may be used to solve the problems of analysis and interpretation of experimental data in various problems of lidar sensing.

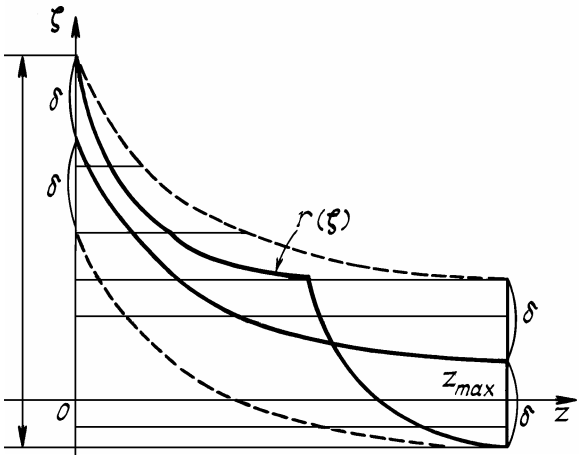

FIG. 3.

REFERENCES

1. P.V. Golubtsov, A.A. Kozlov, Yu.P. Put'ev, S.A. Filatova, and A.I. Chulichkov, Proc., ITTIAPR'90, USSR, Lviv (1990), P. 2, pp. 34–38.
2. S.A. Filatova, Yu.P. Put'ev, P.V. Golubtsov, A.V. Curbatov, and A.V. Migulin, in: Ann. Geophys. Supp., **9**, 565 (1991).
3. P.V. Golubtsov, A.V. Migulin, Yu.P. Put'ev, and S.A. Filatova, in: *Abstracts of Reports at the 15th International Laser Radar Conference,* Tomsk, USSR (1990), Pt. 2, pp. 205–207.
4. Yu.P. Pyt'ev, *Mathematical Techniques of Interpreting Experimental Results* (Moscow, Vys'shaya Shkola, 1989).
5. P.V. Golubtsov and S.A. Filatova, Mat. Modelirovani **2** No. 10 (1990).
6. Yu.P. Pyt'ev, Mat. Modelirovani. **1** No. 5 (1989).