SYNTHESIS OF MULTIWAVELENGTH METERS OF ATMOSPHERIC LOW GASES AND AEROSOL

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In the paper “Synthesis of multi-wavelengths corrected meters of atmospheric low gases and aerosol” the possibility for synthesis of corrected three – wavelengths meters of low gas components in atmosphere on the basis of development the mathematical model and the classification table is considered, The carried out synthesis allows to reveal some new variants for development of three – wavelengths meters of low gas components in atmosphere. The possibility of combining of DOAS meters with three wavelengths devices with two-parametric correction is also considered. It is shown, that such a combination of two well – known methods makes it possible to obtain more accurate estimates of total amount of ozone in on – earth layer of atmosphere.

I. Introduction

The carrying out of spectral measurements in UV band is one of high priority spheres of atmospheric researches, because the results of these measurements may be used both for assessment of some low components of atmosphere (aerosol, ozone, etc.) and the level of effect of harmful spectral part of solar UV radiation.

The basic method in this sphere of atmospheric measurements is two-wavelengths method of Dobson, which till now is used in modern spectrometers designated for measurements of total ozone content. Recently proposed three–wavelengths method of measurements [1] differs from the Dobson method in principle and featured with its wide functional possibilities for measurements and carrying out of different corrections. Despite presence of sufficient number of publications on this theme, the questions on synthesis of possible variants for construction of three–wavelengths meters and classification of latter’s, embracing various forms for correction of measurement’s error are not considered.

The purpose of this article is carrying out of synthesis of all possible variants for construction of three – wavelengths meters on the basis of development the mathematical model of corrected meters, making – up of classification table of synthesis on the basis of revealed classification signs, and also analysis of possibility for combining the two-parametrical corrected meters with DOAS type remote gas analyzers.

It should be noted, that the three-wavelengths method of measurements is based on Bouger’s low, which in common case may be formulated as follows:

$$I_1 = I_0\, e^{-[\alpha_\lambda \mu X + \beta_1 m_1 + \delta_\lambda m_2]}, \tag{1}$$

where I_1 is intensity of solar radiation at the level of ground, I_0 is solar constant; α_λ is ozone’s absorption index; μ is optical mass of ozone; X is total amount of ozone in atmosphere; $\beta_\lambda, \delta_\lambda$ are appropriately optical depths of Rayleigh scattering and aerosol; m_1, m_2 are appropriately optical masses of Rayleigh scattering and aerosol.

From view–point of metrology and accuracy characteristics of remote atmospheric measurements the most representative parameter of atmospheric instability is aerosol.

It should be noted, that the atmospheric aerosol is characterized by bimodal type of distribution function of dependence of volume depth from particles’ size [2, 3], which is physically explained with presence in atmosphere the strictly discernable fine and coarse fractions of aerosol. These fractions have different sources of their origin. The correlation existing between them is so weak, that it is impossible to reveal any deviation of Angstrom parameter of fine aerosol fraction in dependence from the same parameter of coarse fraction [2]. Such a situation allows us to describe the optical depth of atmospheric aerosol δ_λ as a linear sum of two non–correlated components:

$$\delta_\lambda = \delta_{\lambda f} + \delta_{\lambda c}, \tag{2}$$

where $\delta_{\lambda f}$ - optical depth of fine fraction of aerosol; $\delta_{\lambda c}$ - optical depth of coarse fraction of aerosol.

Thus, from view–point of increasing the accuracy of atmospheric measurements, consideration of correlation dependences may be limited only with consideration of correlations between internal parts of fractions for each selected fraction. The practical benefit from aforesaid physical feature of atmospheric aerosol is possibility of separate statistical compensation of effect of aerosol to the accuracy of measurements. It is obvious, that in order to reach mathematical conditions of compensation of effects of said fractions, the individual weight coefficients of compensation for measuring channels involved to joint measurements should be applied.

2.1 General solution of the problem

The conceptual block–diagram of multi–channel meter of atmospheric components with separated application of correction coefficients is shown in fig. 1, where assigned numbers mean following: 1is block of opto–electronic meters $f_i(\lambda_i)$, carrying out measurements at the wavelength λ_i; 2 is block of correcting units; 3 is block of intermediate transformation; 4 is block of control and computing of output parameter.

The relevant mathematical model of multi-channel compensated meter consists of three equations:

1. Equation of transformation of the single measurement channel:

$$I_i = f_i\left[I_0(\lambda_i), X, \mu, m, m_1, \delta_f(\lambda_i), \delta_c(\lambda_i), \beta(\lambda_i), \alpha(\lambda_i)\right],\ i = \overline{1,n}. \tag{3}$$

2. Equation of intermediate transformation of output signals of channels:

$$z=\varphi\left\{f_i(\lambda_i),k_i,\rho_1\left[\delta_f(\lambda_i),\delta_f(\lambda_j)\right],\ \rho_2\left[\delta_c(\lambda_i),\delta_c(\lambda_j)\right]\right\},\ i,j=\overline{1,n}\ , \qquad (4)$$

where ρ - coefficient of correlation between the relevant parameters.

3. Equation for computing X.

$$X=\varphi^{-1}(I_i,z);\ i=\overline{1,\ n}\ . \qquad (5)$$

4. Therefore, abovementioned equations (3)–(5) represent the mathematical model of corrected meter of low gas components of atmosphere in UV band.

As an example of realization of three wavelengths meter we consider the variant of construction, where the equation of intermediate transformation is as follows:

$$z=\frac{I_1^{1/k_1}\cdot I_3^{1/k_2}}{I_2} \qquad (6)$$

Taking into consideration formulas (1), (2) and (6) we can obtain following system of equations, characterizing conditions of separate compensation of fine coarse fractions.

$$\begin{cases}\dfrac{\delta_{\lambda_1 c}}{k_1}+\dfrac{\delta_{\lambda_3,c}}{k_2}=\delta_{\lambda_2,c}\\[2ex]\dfrac{\delta_{\lambda_1 f}}{k_1}+\dfrac{\delta_{\lambda_3,f}}{k_2}=\delta_{\lambda_2,f}\end{cases}. \qquad (7)$$

Solution of system (7) regarding k_1 and k_2 allows to find out factual meaning of correcting coefficients, making it possible to carry out full separated compensation of two fractions of atmospheric aerosol.

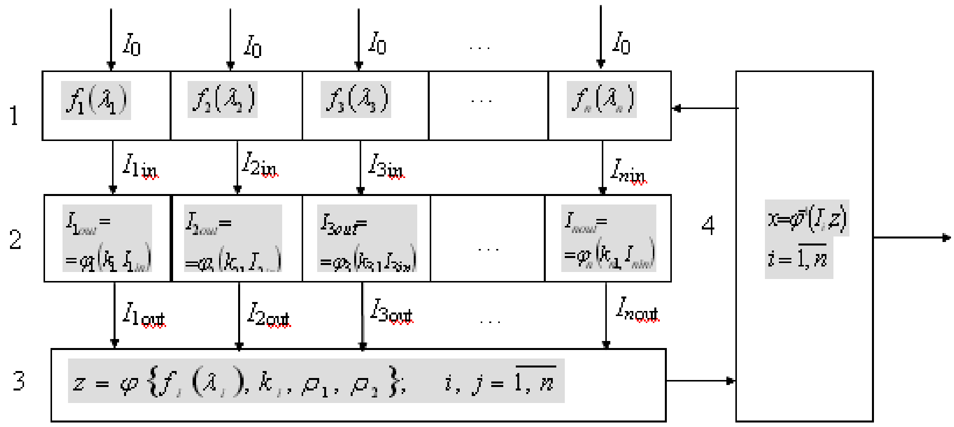

Fig. 1. Block – diagram of multichannel corrected atmospheric measurements device.

2.2. Table type synthesis of corrected meters

Now we consider another possible method for synthesis of corrected three – wavelengths meters based on identification of major classification signs of correction and composing of classification table. Major classification signs are following:

1. Realization of multi–component or mono–component correction:
   - multi–component correction;
   - mono–component correction.
2. Types of mono–component interfractional correction:
   - separated correction of effect of fractions;
   - absence of separated correction of effect of fractions.
3. Quantity of used parameters of correction:
   - mono–parametric correction;
   - multi–parametric correction.

Aforesaid classification parameter allows to develop the classification table and therefore to carry out table type synthesis of all possible variants of development of three – wavelengths meters (table 1).

Table 1

Sign 3. Amount of correcting parameters	Sign 1. Multi–component or mono–component correction		
	Multi–component correction	Sign 2. Separated interfractional compensation	
		Separated compensation on fractions	Non–compensation on fractions
Multi-parametric	M1	M2	M3
Mono-parametric	M4	M5	M6

Now we can characterize the possible models of constructions of corrected three–wavelength meters, according to models M1-M6.

It should be noted that models M4 and M6 are described in detail in [1]. The model M2 is considered above, The model M3 possesses surplus elements and is non–practical.

The models M1 and M5 represents some interest for further research.

The analysis of conditions of full correction of effect of separate components may be carried out as it was done for M2. Model M5 is of special interest, where using only one correcting parameter, the separated correction on fractions is envisaged.

But researches of possibility of technical realization of these models in detail are out of purpose of this article.

Let us consider the peculiarities of combining of synthesized two-parametrical three – wavelengths meter with spectrometer of DOAS type, designated for measurements of on – earth ozone.

3. Combining of three – wavelengths corrected meter with DOAS type device.

3.1. Using of DOAS for ecological purposes

It is well – known, that the stratospheric ozone fulfils protection function in regard of all live organisms, due to strong absorption of biologically harmful part of solar UV radiation. At the same time it should be taken into account, that ozone itself is dangerous pollutant of troposphere and toxically effects to all live organisms. As it is shown in [4], upon meeting of some conditions, as a result of chemical transformation of nitrogen's oxides, the accumulation of ozone in the on – earth layer of atmosphere may take place, which represents serious danger for life of humans. More appropriate for measurements of on – earth ozone now are meters developed on the basis of principle of differential optical absorption spectroscopy DOAS.

Basic principle of DOAS meters is removal of low – frequency or continual component of spectrum of absorption of emitted reference radiation. The way of realization of this principle may be various.

For example, there is construction of DOAS meter [5], where low – frequency continual components of absorption spectrum in UV band are removed by special algorithmic processing of signal of receiver in the form of array of photosensitive elements. In another variant of realization of DOAS principle [6], the aforesaid low frequency continual signal are partly removed by organization of two – step procedure of measurements, upon which the researched route and the reference route should be measured sequentially. Further differential processing of two signals allows us to calculate the total amount of researched gas along the route. Each of aforesaid realizations of principle of differential spectroscopy has its own shortages.

The shortage of the first realization is that full and high accuracy electronic filtration of low–frequency signal of linear type photoreceiver is impossible, and the second one is high sizes of construction and effect of non – identity of conditions of measurements during two – stage measurements procedure. But if we intent install the stationary points of local ecological control over accumulation of on – earth ozone near the loaded city main roads the factor of big sizes is not so important. This negative feature may be easily compensated with such positive feature of the second realization of DOAS principle as possibility of physical modeling of reference route, and also possibility of carrying out of comparative measurements on heavy and low polluted routes.

Carrying out of comparative measurements using the first realization of DOAS in complicated by such factor, that using of filtration of low – frequency components may lead to various comparative estimates of condition of pollution on two fixed heavy and low polluted routes. Aforesaid conditions mainly determine choosing of second realization of DOAS for ecological control of level of accumulation of on – earth ozone near the main roads.

3.2. Analysis of accuracy of combined device

Further in this paper we shell consider the possibility of increasing of accuracy of estimates of measurement results of DOAS of the second realization using combination of original DOAS principle with two-parametric modification of recently suggested principle of three–wavelength measurements [1].

Preliminarily we should note the approximate character of analyses done in [3] due to following reasons.

1. In the band 280–300 nm the aerosol optical depth is principally non–linear and depends on wavelength.

2. In the noted spectral band the optical depth of Rayleigh scattering is also non–linear, depends from wavelength of optical radiation and has a significant value in order to be considered as one of factors leading to forming of error of ozonometric measurements.

Now we would show, that combination of the DOAS principle with two-parametric modification of three–wavelengths principle allows us to remove fully the effect of two above said factors to accuracy of measurements.

The simplified scheme of measurements on the basis of DOAS principle is shown on figure 2, where numbers mean following: 1 is reflective fixed mirror; 2 is researched object; 3 is movable mirror; 4 is photoreceiver; 5 is source of radiation, Similar to [5], the value of signal, registered at the input of photo receiver 4 may be calculated as:

$$S_\lambda = g\,\gamma_\lambda R_\lambda I_\lambda \,exp\left(-\tau_\lambda\right), \tag{8}$$

where g is geometric factor of passing of optical beam, not depending from wavelength; γ_λ is spectral sensitivity; R_λ is coefficient of reflection of mirror; τ_λ is total optical depth, determined as

$$\tau_\lambda = \tau_{oz}(\lambda) + \tau_{mol}(\lambda) + \tau_{aer}(\lambda), \tag{9}$$

where $\tau_{oz}(\lambda)$ is optical depth of ozone on route; $\tau_{mol}(\lambda)$ is optical depth of Reyleigh scattering; $\tau_{aer}(\lambda)$ is optical depth of aerosol.

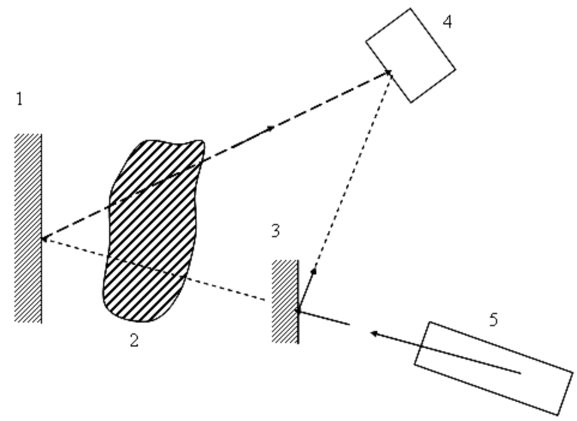

Fig. 2. Simplified scheme of measurements on DOAS principle.

Assume, that we carry out three wavelength measurements of total of ozone on horizontal route. Basic equation for these measurements is Bouger–Beer formula (1).

The common function of three – wavelength measurements may be written as

$$I(\lambda_i)=I_0(\lambda_i)exp\{-[X\cdot\sigma(\lambda_i)+\beta(\lambda_i)+\delta(\lambda_i)]\}, \quad (10)$$

The common function of three–wavelength measurements may be written as

$$F[I(\lambda_1),I(\lambda_2),I(\lambda_3)]=\frac{I(\lambda_1)^{k_1}\cdot I(\lambda_3)^{k_2}}{I(\lambda_2)}. \quad (11)$$

Taking into consideration (1) and (11) we obtain

$$\begin{aligned}F[I(\lambda_1),I(\lambda_2),I(\lambda_3)]=&\frac{I_0(\lambda_1)^{k_1}\cdot I_0(\lambda_3)^{k_2}}{I_0(\lambda_2)}\cdot exp\,\{-[k_1[X\sigma(\lambda_1)+\beta(\lambda_1)+\delta(\lambda_1)]+\\&+k_2[X\sigma(\lambda_3)+\beta(\lambda_3)+\delta(\lambda_3)]-[X\sigma(\lambda_2)+\beta(\lambda_2)+\delta(\lambda_2)]]\}\end{aligned}. \quad (12)$$

From last equation we find condition for full separate removal of $\beta(\lambda_1)$ and $\delta(\lambda_i)$, $i=\overline{1,3}$:

$$k_1\beta(\lambda_1)+k_2\beta(\lambda_3)=\beta(\lambda_2), \quad (13)$$

$$k_1\delta(\lambda_1)+k_2\,\delta(\lambda_3)=\delta(\lambda_2). \quad (14)$$

Joint solution of (13) and (14) gives us the values of k_1 and k_2, upon which the influence of molecular scattering and aerosol is fully compensated.

Joint solution of (13) and (14) gives following values of k_1 and k_2,

$$k_2=\frac{\beta(\lambda_1)\cdot\delta(\lambda_2)-\beta(\lambda_2)\cdot\delta(\lambda_1)}{\delta(\lambda_3)\cdot\beta(\lambda_1)-\beta(\lambda_3)\cdot\delta(\lambda_1)}, \quad (15)$$

$$k_1=\frac{\beta(\lambda_2)\cdot\delta(\lambda_3)-\beta(\lambda_3)\cdot\delta(\lambda_2)}{\delta(\lambda_3)\cdot\beta(\lambda_1)-\beta(\lambda_3)\cdot\delta(\lambda_1)}. \quad (16)$$

Taking into consideration the strong separate correlation between adjacent of values of $\beta(\lambda)$ and $\delta(\lambda)$ on λ upon low differences between λ_1,λ_2 and λ_3, we can conclude, that parameters k_1 and k_2, are constants, not depending from variations of β and δ.

Taking into consideration equations (13) and (14) the formula (12) may be written as

$$F(I_1,I_2,I_3)=I_э(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)\cdot exp[-X\,\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)], \quad (17)$$

where

$$I_э(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)=\frac{I_0(\lambda_1)^{k_1}\cdot I_0(\lambda_3)^{k_2}}{I_0(\lambda_2)}. \quad (18)$$

$$\Delta\alpha=k_1\alpha(\lambda_1)+k_2\alpha(\lambda_3)-\alpha(\lambda_2). \quad (19)$$

Taking into consideration the formula (8), the value of signal from the route at the output of photo receiver may be calculated as follows:

$$S_\lambda=g_l\,\gamma_\lambda\,R_\lambda I_э(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)\cdot exp[-X_l\,\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)]. \quad (20)$$

Value of signal from the reference route, at the output of photo receiver may be calculated as follows:

$$S_{\lambda_0}=g_0\,\gamma_\lambda\,R_\lambda I_э(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)\cdot exp[-X_0\,\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)]. \quad (21)$$

Then we should calculate $\frac{S_{\lambda_l}}{S_{\lambda_0}}$:

$$\frac{S_{\lambda_l}}{S_{\lambda_0}}=\frac{g_l}{g_0}\cdot exp[-(X_l-X_0)\cdot\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2)]. \quad (22)$$

Taking the logarithm from (22), we obtain:

$$ln\,S_{\lambda_l}-ln\,S_{\lambda_0}=ln\frac{g_l}{g_0}-\Delta X\cdot\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2). \quad (23)$$

using following indications:

$$S_{\lambda_0}-S_{\lambda_l}=z;$$

$$ln\frac{g_0}{g_l}=G$$

we have

$$z=G+\Delta X\,\Delta\alpha(\lambda_1,\lambda_2,\lambda_3,k_1,k_2). \quad (24)$$

The most non–stable parameters in equation (24) are G and ΔX.

In order to minimize the effect of non–stability of G and ΔX to result of measurements, we can suggest, similar to [2], carrying out of multi–wavelengths measurements and further calculation of ΔX using procedure of least squares.

Using of method of least squares allows to obtain following estimates for ΔX and G:

$$\Delta X=D_{z,\Delta\alpha}/D_{\Delta\alpha,\Delta\alpha},$$

$$G=\bar{z}-\overline{\Delta\alpha}\cdot\Delta X,$$

where

$$D_{z,\Delta\alpha}=\overline{(z-\bar{z})\cdot(\Delta\alpha-\overline{\Delta\alpha})}.$$

Conclusion.

Above mentioned mechanism of application of two-parametrical correction is a universal principle and may be used also in the bands of visible and infrared wavelengths by the aim to neutralize the effect of various continual lines of absorption.

Joining of three–wave and multi–wavelengths methods in this realization of measurements scheme does not lead to increase of number of held measurements in comparison with the same parameter in [2], because the three wavelengths method uses triads $\left(\lambda_{i-1}, \lambda_i, \lambda_{i+1}\right)$ of wavelengths, elements of which are also elements of set of wavelengths method of measurements.

As a conclusion, we should note, that the three–wavelengths principle of two-parametrical correction of measurements also may be used in DOAS meters with electronic filtration of low frequency components, which indicate the universal character of proposed modification of DOAS technology.

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ATMOSFERDƏ OLAN KİÇİK QAZ KOMPONENTLƏRİNİN VƏ AEROZOLUN ÜÇDALĞALI TƏSHİH EDİLMİŞ ÖLÇMƏ QURĞULARININ SİNTEZİ

Məqalədə riyazi modelin yaradılması və təsnifat cədvəlinin tərtib edilməsi yolu ilə atmosferdə olan kiçik qaz komponentlərini və aerozolun təshih edilmiş üçdalğalı ölçmə qurğularının sintezi mümkünlüyü nəzərdən keçirilmişdir.

Bu cür sintez atmosferin kiçik qaz komponentləri və aerozolun üçdalğalı ölçmə qurğularının bir neçə yeni variantlarının yaradılması mümkünlüyünü göstərmişdir.

Həmçinin məlum "Differensial Optik Absorbsion Spektrometriya" metodunun üçdalğalı ölçmə metodu ilə kombinasiyası imkanı nəzərdən keçirilmişdir. Göstərilmişdir ki, iki metodun kombinasiyası şəhər mühitində olan yerüstü ozonun ümumi miqdarını daha dəqiq müəyyənləşdirməyə imkan verir.

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СИНТЕЗ ТРЕХВОЛНОВЫХ СКОРРЕКТИРОВАННЫХ ИЗМЕРИТЕЛЕЙ МАЛЫХ ГАЗОВЫХ КОМПОНЕНТ И АЭРОЗОЛЯ АТМОСФЕРЫ

В статье «Синтез трехволновых скорректированных измерителей малых компонент и аэрозоля атмосферы» рассмотрена возможность синтеза скорректированных трехволновых измерителей малых компонент атмосферы на основе создания математической модели, а также составления классификационной таблицы. Осуществленный синтез позволяет выявить ряд новых вариантов построения трехволновых измерителей малых газовых компонентов атмосферы. Также рассмотрена возможность комбинирования ДОАС (дифференциальная оптическая абсорбционная спектрометрия) измерителя с трехволновым измерителем двухпараметрической коррекцией. Показано, что такое комбинирование двух известных методов позволяет получить более точные оценки общего количества озона в приземном слое атмосферы.

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