

HIGH-PRECISION GROUND-BASED PHOTOMETRIC MONITORING METHOD FOR VALIDATING SATELLITE MONITORING OF ASSOCIATED HYDROCARBON GAS BURNING

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Abstract

The shortcomings of satellite monitoring of associated gas burning in the oil industry have been analyzed. The possibility of performing such monitoring using ground-based photometric devices is indicated. The possibility of compensating for errors of multi-wave solar photometers due to the influence of atmospheric aerosols has been studied. The conducted research allowed to identify redundancy in correction procedures in known three-wave solar photometers. Two new methods for constructing compensated photometers are proposed. In the proposed constructions, the correction procedure is limited to the calculation and installation of one correction factor.

Keywords: photometer, atmosphere. aerosol, error, correction

I. Introduction

It is well known [1] that the Defense Meteorological Satellite Program (DMSP) is used to estimate the volumes of associated gas being flared on a global scale. DMSP satellites have been recording cases of flaring associated gas on a global scale for 16 years. This activity is funded by NOAA and the World Bank in collaboration with the Government of Norway under the Global Gas Flaring Reduction (GGFR) program.

The methodology used in this program to register and evaluate gas flares involves registering the light fluxes coming from associated gas flares, integrating the obtained signal throughout the territory of each individual country, and calibrating these results with official data, which are the most reliable. In particular, as a result of such satellite assessment, Russia was found to be the leader, which before such control was officially in second place after Nigeria [1].

It should be noted that satellite observations of flaring associated with the burning of associated gas are not only carried out in the visible range [1]. Moderate resolution spectrometers MODIS, installed on the TERRA and AQUA satellites, also perform such monitoring. It can be assumed that the desire to neutralize the influence of aerosols - the products of associated gas combustion - prompted NASA to choose the IR range for research. However, the result was clearly opposite. According to [1], in this range, MODIS was unable to register more frequent associated gas burnings of small sizes.

Thus, the above-mentioned unaccounted factors affecting the effectiveness of the overall estimation of the volume of flared associated gas bring to the fore the issues of studying the errors of such systems and optimizing their operation modes. In this regard, the question of using alternative methods and means of ground control over the flaring of associated hydrocarbon gas remains relevant. Such alternative means may include solar photometers, pyranometers, and lidars. However, it should be noted that the most significant factor leading to radiometric distortions in atmospheric photometry in the UV, visible, and initial IR ranges is aerosol. It should be noted that solar radiation is most actively attenuated by soot, which is also subject to dynamic transformation over time. Changes in the optical properties of soot introduce uncertainty into photometric measurements, underscoring the relevance of taking measures to eliminate this uncertainty. This article discusses the possibilities of implementing measures to neutralize the influence of aerosol on the accuracy of photometric devices. First, let us briefly consider the main features and causes of the impact of the temporal instability of aerosol on photometric measurements.

As stated in [2], aging of aerosols is one of the reasons for uncertainty in assessing the direct and indirect impact of aerosols on climate conditions. While fresh aerosol in its initial state is hydrophobic and externally mixed, through mechanisms of coagulation, condensation or photochemical processes, fresh aerosol over time transitions to a state of internal mixing. Such aging processes affect the hygroscopic properties of aerosols, the process of their growth, changes in their optical properties, and the lifetime of aerosol particles. [2] presents some daily and seasonal features of aerosol aging processes. For example, during the summer period, sulfur dioxide plays a dominant role in this process during the daytime, and the aging process lasts 2-8 hours. In winter, these time scales are maintained, but in this case, ammonium nitrate is the dominant factor. During the nighttime, condensation processes weaken, while coagulation serves as the main aging factor, with a time scale of 10-40 hours.

As reported in [3], elemental carbon (EC) is the main component of soot, which absorbs solar radiation and directly heats the air, converting solar radiation into its internal energy (increasing the temperature of soot) and emits thermal infrared radiation. In general, soot particles contribute to the creation of three types of temperature gradients: (1) a temperature gradient that occurs during the day in the presence of soot, resulting in the atmosphere being heated while the Earth cools; (2) a nighttime temperature gradient that occurs in the presence of soot, where both the atmosphere and the Earth are heated; (3) a daytime and nighttime temperature gradient that occurs in the absence of soot, but in the presence of adequately heated air containing soot, resulting in the atmosphere being heated while the Earth's temperature remains unchanged. Thus, soot has a complex meteorological impact and can affect the climate conditions of the planet.

As shown in [4], as a result of aerosol moisture over the ocean, the measured value of aerosol optical density can be 50% higher than that of dry aerosol. Experimental studies have shown that the measured value of aerosol optical density at 85% relative humidity was 30% higher than at 40% relative humidity.

According to [5], hydrophobic soot significantly does not change its optical properties and structure when transitioning from a dry environment to a wet one. However, hydrophilic soot is strongly influenced by water vapor. Hydrophilic soot undergoes thorough restructuring under the influence of humid atmosphere, resulting in significant changes in its optical properties. For instance, according to the data presented in [6], the optical density of highly hydrophilic soot can increase from 0.02 to 0.15 in just 20 minutes under relative humidity increase to 100%.

II. Problem statement

At the same time, atmospheric aerosol has another important property, which consists in the fact that the distribution of the volume concentration of the aerosol has a bimodal character, i.e. the total optical density of the aerosol τ_{Σ} can be represented as a certain combination of the optical densities of fine-dispersed (τ_f) and coarse-dispersed (τ_c) aerosols. It is important to take into account the following properties of the above-mentioned dispersion components:

1. There is practically no statistical correlation between the fine-dispersed and coarse-dispersed components of aerosols.

2. The optical density of the coarse-dispersed component of the aerosol is practically independent of the wavelength, whereas the optical density of the fine-dispersed component strongly depends on the wavelength. This dependence is known in the form of the empirical Angstrom formula, according to which

$$\tau_f = \beta \lambda^{-\alpha} \quad (1)$$

where: $\beta = \tau_f(\lambda = 1 \mu m)$; α - the Angstrom exponent.

Thus, the initial requirements for the development of compensated photometric devices are:

1. The synthesized photometer must neutralize the influence of aging on the measurement result.
2. The synthesized photometer must take into account the dispersion-wave properties of the optical densities of the fractional components of the aerosol mentioned above.

III. Solution

It is easy to show that the three-wavelength photometer model proposed in [6] fully meets these requirements. The intermediate conversion function proposed in this paper has the following form:

$$z = \frac{I_1^{k_1}(\lambda_1) \cdot I_3^{k_3}(\lambda_3)}{I_2^{k_2}(\lambda_2)} \quad (2)$$

Where: $I_i(\lambda_i)$ - the signal at the output of the i^{th} photometer, operating at wavelength λ_i ; k_i - correction coefficients.

For further analysis, we will use the Beer-Lambert law, which has the following form in the wavelength range of 0.3-0.7 μm :

$$I(\lambda) = I_0(\lambda) e^{-m[\tau_{03}(\lambda) + \tau_{pe\lambda}(\lambda) + \tau_{aap}(\lambda)]} \quad (3)$$

Where: $I_0(\lambda)$ - solar constant at wavelength λ ; m - air mass; $\tau_{03}(\lambda)$ - ozone optical density; $\tau_{pe\lambda}(\lambda)$ - Rayleigh scattering optical density; $\tau_{aap}(\lambda)$ - aerosol optical density.

Taking into account (2) and (3), the following conditions for complete separate compensation of the influence of fractional components of aerosol and aging effects can be obtained.

$$k_1 \tau_f(\lambda_1) d_f(t) + k_3 \tau_f(\lambda_3) d_f(t) = k_2 \tau_f(\lambda_2) d_f(t) \quad (4)$$

$$k_1 \tau_c(\lambda_1) d_c(t) + k_3 \tau_c(\lambda_3) d_c(t) = k_2 \tau_c(\lambda_2) d_c(t) \quad (5)$$

Where, $d_f(t)$ and $d_c(t)$ are coefficients that show the change in the optical properties of fine-dispersed and coarse-dispersed aerosols due to aging and hygroscopic growth.

As can be seen from expressions (4) and (5), the factors $d_f(t)$ and $d_c(t)$ cancel out and do not affect the calculation results of the coefficients k_1 and k_3 if we initially take $k_2 = 1$.

However, it can be shown that the three-wavelength photometer with a two-parameter correction proposed in [6] has some redundancy in terms of correction measures. Thus, if we take into account the independence of τ_c from λ , then, with $k_2 = 1$, we have from expression (5):

$$\tau_c(k_1 + k_3) = \tau_c \quad (6)$$

i.e.

$$k_1 + k_3 = 1 \quad (7)$$

Expression (4) with $k_2 = 1$ has the following form:

$$k_1 \cdot \tau_\varphi(\gamma_1) + k_3 \cdot \tau_\varphi(\gamma_3) = \tau_\varphi(\gamma_2) \quad (8)$$

Taking into account (7) and (8), we have

$$\begin{aligned} k_1 \cdot \tau_\varphi(\gamma_1) + k_3 \cdot \tau_\varphi(\gamma_3) &= \tau_\varphi(\gamma_2) \text{ or,} \\ k_1 |\tau_\varphi(\gamma_1) - k_3 \cdot \tau_\varphi(\gamma_3)| &= \tau_\varphi(\gamma_2) \end{aligned} \quad (9)$$

From equation (9) we have

$$k_1 = \frac{\tau_\varphi(\gamma_2) - \tau_\varphi(\gamma_3)}{\tau_\varphi(\gamma_1) - \tau_\varphi(\gamma_3)} \quad (10)$$

The obtained expression (10) provides a basis for assuming that the value of the coefficient k_1 is always less than one if $\lambda_1 < \lambda_2 < \lambda_3$ and $\tau(\lambda_1) > \tau(\lambda_2) > \tau(\lambda_3)$.

IV. Discussion of results

Expression (10) also provides a basis for proposing two new methods for constructing compensated three-wave photometers.

1. The wavelengths λ_1 , λ_2 , and λ_3 are considered as constant values. In this case, the coefficient k_1 is calculated using formula (10).

2. We assume that the parameters k_1 , λ_1 , and λ_3 are constant. In this case, the value of λ_2 can be changed. From expression (10), we have

$$\left. \begin{aligned} \tau_f(\lambda_2) &= k_1 [\tau_f(\lambda_1) - \tau_f(\lambda_3)] + \tau_f(\lambda_3) \\ \lambda_2 &= \tau_f^{-1} \{ k_1 [\tau_f(\lambda_1) - \tau_f(\lambda_3)] + \tau_f(\lambda_3) \} \end{aligned} \right\} \quad (11)$$

Note that both of the above methods are capable of providing the same accuracy in compensating for the influence of aerosol as that provided in a three-wavelength photometer with a two-parameter correction. However, the first of the proposed methods has the advantage over the second in that it provides mutual compensation for instability that may be caused by changes in the coefficient β .

V. Conclusion

Thus, the conducted research has revealed the existing redundancy in the correction procedures of known three-wavelength solar photometers with parametric correction. Two new methods for constructing compensated three-wavelength photometers have been proposed, in which the correction procedure is limited to calculating and setting one correction factor.

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