# OUTGOING SHORTWAVE RADIATION OVER THE ATLANTIC: "INTERCOSMOS–21" SATELLITE DATA MODEL

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*Data on the spectral brightness $B_\lambda$ of the atmosphere-ocean system over the Atlantic are statistically processed, resulting in a statistically significant model of $\bar{B}_\lambda$ us the atmospheric optical mass $m_\odot$. The wavelength dependence of $\bar{B}_\lambda$ is presented for the spectral range 0.4–0.8 μm. The proposed model agrees with the data of other authors.*

In the remote sensing of the Earth and its atmosphere from space it is necessary to have a statistically average model that accounts for the dependence of the observed spectral brightness of the "Earth-atmosphere" system on the solar zenith angle.

In the case of the cloudless atmosphere the authors of Ref. 1 approximated the dependence of the brightness of the "ocean-atmosphere" system on the solar zenith angle $z_\odot$ in the visible range by third-order polynomials. The purpose of the present study is to retrieve such a dependence between the spectral brightness of the "ocean-atmosphere" system $B_\lambda$ and the optical mass of the atmosphere $m_\odot$ in the Earth-Sun direction; under cloudless conditions such a dependence is a function of the solar zenith angle $Z_\odot$.[2]

The present study is based on the results of the statistical processing of one and a half years of accumulated data on $B_\lambda$ (in the range 0.415–0.823 μm) from the multichannel MKS spectrometer[3,4] on board the satellite "Intercosmos-21". The readings were taken during continuous sounding along the flight path with sighting on nadir. The satellite orbited at an altitude of 500–600 km. The field-of-view angle of the spectrometer was ~1°. The "ocean-atmosphere" spectral brightness was obtained from seven spectral channels with half-width $\Delta\lambda = 10$ nm, centered at 0.415, 0.449, 0.483, 0.534, 0.569, 0.621, 0.676 μm, and from six spectral channels of $\Delta\lambda = 0.5$ nm half-width (0.758, 0.761, 0.763, 0.767, 0.794, 0.823 μm). The total measurement error for $B_\lambda$ was about 3%.

In all about 50,000 data points were statistically processed in the 0–30°N latitude belt over the Atlantic. These were grouped by season and five solar zenith angle ranges $Z_\odot$: 0°–60°, 60°–75°, 75°–80°, 80°–85°, and 85°–90°. For all these data sets spectral brightness histograms were plotted, and their statistical characteristics obtained, including the mathematical expectation, the rms error, the asymmetry, and the excess factor. The average values of $B_\lambda$ for various seasons did not differ by more than 30%. In their respective solar zenith angle ranges. This fact made it possible to conclude that there is no seasonal trend in the spectral brightness in the 0°–30°N latitude belt over the Atlantic, so subsequent treatment disregarded time of year.

The complete set of measurement data served as a basis from which to form a set of cloudless flight path segments: analyzing brightness changes along the satellite flight path it was found that segments of cloudless atmosphere and of continuous cloudiness are more homogeneous in comparison with transitional stretches of broken cloudiness in their brightness characteristics. Using a spectral closeness test together with brightness threshold values for flight path segments corresponding to the cloudless atmosphere, such segments were selected from among the totality of data. The total number of cloudless data points in this region of the Atlantic stood at about 10000.

Log-log plots of the average values $\bar{B}_\lambda$ were constructed vs $m_\odot$ and $m_\odot$+1. The linear character of these dependences made it possible to represent them in the form of the following regression relations:

$$\lg \bar{B}_\lambda = \lg \alpha_1 + \beta_1 \lg m_\odot; \tag{1}$$

$$\lg \bar{B}_\lambda = \lg \alpha_2 + \beta_2 \lg (m_\odot + 1), \tag{2}$$

where $\alpha_1$, $\alpha_2$, $\beta_1$, and $\beta_2$ are the regression coefficients. These coefficients were retrieved using the least-squares technique. The calculated correlation coefficients in all the spectral channels appeared to lie within the range from 0.9 to 0.99. The correlation coefficients were tested for statistical significance using the *r*-criterion.[S] An analysis of the variation of the regression coefficients $\beta_1$ and $\beta_2$ in rela-

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tions (1) and (2) showed that these may be taken to be equal to each other, thus: $\beta_1 = \beta_2 = -1$.

Table I presents the relative rms errors $\delta B_\lambda$ of fitting the experimental data by relations (1) and (2) at a significance level of $\alpha = 0.3$. Analysis of these data shows that the accuracy of approximating $B_\lambda(m_\odot)$ by relation (2) is 1.5 to 8 times higher than by relation (1), except at the wavelengths 0.767 and 0.758 μm. At these latter wavelengths both relations yield practically the same accuracy of fit. Using relation (2) the dependence of $B_\lambda$ on $m_\odot$ can by expressed by the following empirical formula:

$$\bar{B}_\lambda = \bar{b}_\lambda S_{\odot\lambda} / (m_\odot + 1), \tag{3}$$

where $E = \pi S_{\odot\lambda}$ is the spectral solar constant[6] and $b_\lambda$ — the brightness coefficient for the “ocean-atmosphere” system.

*TABLE I.*

*Relative rms error of fit. $\delta B_\lambda$ (relations (1) and (2)), spectral brightness variability coefficients $K_\lambda$. Satellite data*

| $\lambda$, μm | 0.415 | 0.449 | 0.483 | 0.534 | 0.569 | 0.621 | 0.676 | 0.758 | 0.761 | 0.763 | 0.767 | 0.794 | 0.823 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma\bar{B}_\lambda^{(1)}$, % | 33 | 38 | 38 | 31 | 24 | 28 | 38 | 28 | 53 | 35 | 24 | 32 | 45 |
| $\sigma\bar{B}_\lambda^{(1)}$, % | 4 | 5 | 6 | 11 | 16 | 17 | 16 | 23 | 23 | 21 | 28 | 22 | 21 |
| $K_\lambda$, % | 17 | 18 | 26 | 31 | 37 | 43 | 48 | 59 | 58 | 59 | 63 | 60 | 54 |

In Ref. 1 experimental dependences of $B_\lambda$ on the solar zenith angle $Z_\odot$ were plotted for $\lambda = 0.5$ μm and $\lambda = 0.7$ μm. We fitted those data by relation (3) in the $30° \le Z_\odot \le 75°$ range, demonstrating that the relative error of such a fit at $\lambda = 0.5$ μm is about 7%, while at $\lambda = 0.7$ μm it reaches approximately 13%. Therefore, the practical applicability of relation (3) is demonstrated for fitting the data obtained in Ref. 1.

Turning now to an analysis of the spectral trend of $B_\lambda$ one should note the considerable increase in the variability coefficients of the measured values of $B_\lambda$ at longer wavelengths (see Table I). The variability of the brightness of the ”ocean-atmosphere” system is related to its dependence on the spectral trend of the underlying surface albedo $q(\lambda)$, the peculiarities of the spectral absorption, the scattering of radiation by the atmospheric aerosol, and also on the presence of absorption bands of molecular oxygen and ozone in the investigated spectral range. The values of $\bar{b}_\lambda$ presented in Table II may be considered as one of the models for the minimal values of the brightness coefficients of the ”ocean-atmosphere” system, if we take into account the following facts:

– the ocean albedo $q(\lambda)$ is minimal. In comparison with the albedo of other types of underlying surface, and is characterized by an insignificant spectral trend;

– the oceanic aerosol number densities in the corresponding size range is minimal in comparison with the number densities of continental aerosols;

– the total ozone in the atmospheric column is minimal in the latitude belt (0°–30° N) under study.

For those wavelengths, where absorption due to ozone and molecular oxygen is absent (0.449, 0.483, 0.676, 0.758, 0.794, 0.823 μm) the model for $b_\lambda$ can take the following form:

$$\bar{b}_\lambda = a/\lambda^4 + d/\lambda^\kappa + c, \tag{4}$$

Here $a$, $d$, $c$, and $\kappa$ are numerical parameters. For low values of the optical mass ($m_\odot < 2.5$) above the ocean surface the single-scattering approximation is quite acceptable. In this саде the term $a/\lambda^4$ in Eq. (4) to a certain degree of accuracy characterizes the molecular scattering of light in the atmosphere.

We determined the value of the parameter a by comparing the spectral brightness values $B_\lambda$ of the ”ocean-atmosphere” system, calculated in Ref. 7 for a purely molecular atmosphere at $m_\odot \le 2.5$ and an underlying surface albedo of $q = 0$, with the values given by the formula $B_{\lambda m} = aS_\lambda / \lambda^4(m_\odot + 1)$. The value of $a$ was found to be $0.0063 \pm 0.0005$. The values of $\kappa$ were assumed to lie within the range $0.8 \le \kappa \le 1.4$ since for $\kappa \le 0.7$, $c$ becomes negative. The parameters $d$ and $c$ were calculated using the nonlinear least squares technique, borrowing $\bar{b}_\lambda$ from Table II and varying $\kappa$ within the range $0.8 \le \kappa \le 1.4$. Analysis of the computational results demonstrates that the minimal rms error of the fit to $b_\lambda$ by relation (4) is attained at $\kappa = 1$, where it does not exceed 3%. The parameters $d$ and $c$ are found to be equal to $0.054 \pm 0.001$ and $0.017 \pm 0.001$, respectively, at a significance level of $\alpha = 0.1$. When calculating the brightness values $B_\lambda$ by relations (3) and (4) in the 0.415, 0.534, 0.569, 0.621, 0.761, 0.763, and 0.767 μm bands. It is necessary to introduce certain additional correction coefficients $r_\lambda$. The values of these coefficients are given in Table II.

*TABLE II.*

*Values of $b_\lambda$, confidence intervals, $|\Delta b_\lambda|$ at $\alpha = 0.1$, and values of $r_\lambda$*

| $\lambda$, μm | 0.415 | 0.449 | 0.483 | 0.534 | 0.569 | 0.621 | 0.676 | 0.758 | 0.761 | 0.763 | 0.767 | 0.794 | 0.823 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\bar{b}_\lambda$, r.u. | 0.311 | 0.294 | 0.24 | 0.181 | 0.135 | 0.124 | 0.13 | 0.105 | 0.03 | 0.049 | 0.079 | 0.1 | 0.095 |
| $\lvert\Delta\bar{b}_\lambda\rvert$ | 0.008 | 0.009 | 0.009 | 0.012 | 0.014 | 0.014 | 0.013 | 0.016 | 0.04 | 0.006 | 0.014 | 0.014 | 0.012 |
| $S_{\odot\lambda}$, mW cm$^2$·μm·sr | 54.78 | 63.28 | 63.28 | 60.1 | 58.66 | 53.79 | 47.4 | 39.63 | 39.15 | 38.93 | 38.36 | 36.92 | 33.9 |
| $r_\lambda$, r.u. | 0.87 | 1.0 | 1.0 | 0.93 | 0.79 | 0.85 | 1.0 | 1.0 | 0.28 | 0.46 | 0.75 | 1.0 | 1.0 |

r.u. — relative units

Thus, as a statistically significant model of the spectral brightness $B_\lambda$ of the "ocean- atmosphere" system in the equatorial Atlantic as a function of the radiation wavelength and the solar zenith angle $Z_\odot$ (or $m_\odot$) we propose the following dependence:

$$\bar{B}_\lambda = \frac{\left[\left[\left(\frac{0.0063}{\lambda^4} + \frac{0.054}{\lambda} + 0.017\right] r_\lambda S_{\odot\lambda}\right]}{(m_\odot + 1)}, \qquad (5)$$

Here $\bar{B}_\lambda$ is expressed in mW/ster · cm$^2$ · μm, and λ in the μm.

The data calculated using relation (5) for $Z_\odot = 57°$ ($m_\odot = 1.84$) were compared with the results from a statistical processing of experimental data for the Pacific (64 realizations).[8] Figure 1 presents the results of such a comparison, which show that the differences in the $0.415 \le \lambda \le 0.676$ μm range do not exceed 18%. Such am agreement can be considered quite satisfactory since different regions of the global ocean far removed from each other were compared.

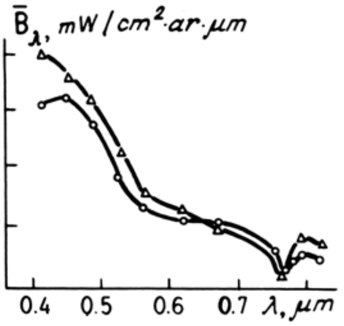

*FIG. 1. Average spectral distribution of brightness in the system "ocean-atmosphere" ($m_\odot = 1.84$): o — the result of calculation according to Eq. (5) for the Atlantic Ocean, Δ— the result of statistical processing of experimental data obtained over Pacific Ocean.[8]*

The results presented in this study demonstrate that

– in the 0°–30°N latitude belt of the Atlantic weak annual variations of the spectral brightness averages $\bar{B}_\lambda$ are observed;

– the $\bar{B}_\lambda$ values display a definite dependence on the solar zenith angle, which may be approximated by relation (5);

– at solar zenith angles $Z_\odot < 20°$ glint reflections from the ocean surface can be observed (depending on the sea roughness).

Thus at such solar zenith angles expression (5) can provide only a rough estimate of $B_\lambda$.

The model proposed in the present article can be recommended for testing the operation of satellite optical instrumentation above the equatorial Atlantic.

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