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# Aerosol optical thickness over the coastal area of the southern Baltic Sea

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The aerosol component of extinction in the marine boundary layer over coastal areas can be determined by using the lidar method and through the application of the Mie's theory to derive the aerosol concentration and size distribution. This can be done for the various meteorological conditions and at various altitudes above the sea surface.

## 1. Introduction

In order to apply satellite generated data to oceanological studies, various types of disturbances resulting from signal passage through the atmosphere must be separated from relevant information which reaches the sensor [1], [2]. This task is specially difficult when investigating optically active sea water components [3], [4]. The main problem faced in such investigation is concerned with the necessity of applying visible light which penetrates water, depending on the water type [5], at depths from several up to 100 meters. In the VIS spectrum range the contribution of radiation from over the water surface compared to the total radiation which reaches the satellite is relatively small. The ratio of useful radiation, which carries relevant information about the environment, to the total amount of radiation which reaches the satellite is also small. Therefore, the problem of how to properly correct the atmospheric impact on the registered signal becomes significant [1], [3], [4]. In the various atmospheric models, particular emphasis is put on detailed description of the aerosol impact on signal, *i.e.*, determination of the aerosol component in radiation [6]. This is especially important in coastal, strongly urbanized and industrialized areas, such as the Baltic [7]. Over the Baltic Sea the spectra of aerosol optical thickness strongly differ from the Angström approximation which is generally accepted in descriptions of the various marine (oceanic) areas [8]. These spectra vary diurnally and strongly depend on the advection of clean polar sea air from the Arctic. They also depend on aerosol concentration at sea level and on particle size distribution. Therefore, the problem of determining the aerosol component in radiation can be solved by modelling both variables for a particular area [9], [10] or by the direct measurement of these parameters [11].

Lidar methods are especially useful as they quickly measure the optical properties of marine aerosols over distances greater than the limits of the surf

zone. By employing several wavelengths, the lidar gives very accurate information about the size distribution of aerosol particles as well as their concentrations under various weather conditions and at different altitudes above the sea surface. This work presents the possibilities of utilizing the lidar method to determine the aerosol optical thickness in the marine atmosphere as functions of wind speed and direction.

## 2. Experimental site and instrumentation

Since 1996 measurements have been carried out in different seasons in the coastal areas of the southern Baltic Sea (17–19° E and 54.4–55° N). Wind speed and direction as well as wet and dry bulb temperatures were recorded along with other supporting information. The air temperature varied from 275 K to 296 K, the air pressure ranged from 990 hPa to 1018 hPa, relative humidity from 65% to 96% and wind speed fluctuated from 0 m/s to 10 m/s.

The lidar system FLS-12 used in aerosol concentration measurements was installed in a van and stationed on the top of the dunes at a fixed distance from the sea [12]. Sounding the marine boundary layer at various altitudes was possible due to the easily adjustable inclination of the lidar.

The measurements were carried out using two wavelenghts, $\lambda = 443$ and 566 nm, which were generated by a dye laser employing Coumarin 120 ($\lambda = 443$ nm) and Rhodamine 110 ($\lambda = 566$ nm) dyes.

The FLS-12 is a tunable laser system designed for remote sensing of the air in the VIS spectrum range (400–670 nm). The backscattered energy from various distances is collected by a Cassegranian configured telescope, which has a 280 mm diameter primary mirror, and is registered by the separate channels of an 8 channel photoreceiver. The backscattered signal was registered, every 50 ns, *i.e.*, every 7.5 m, on the optical path. The useful part of the optical path was between 60 and 2,000 m and altitudes up to 500 m were sounded. The backscattered signal values for all wavelengths served as the basis for the determination of the size distribution of aerosol particles and their concentrations at particular altitudes.

Lidar measurements were calibrated by simultaneous measurements with six stage cascade impactors and a laser particle counter (PMS – Particle Measurement System).

## 3. Theory

The comparative method introdued by POTTER [13] was used to derive the optical parameters of aerosols at every point on the sensing path. It was assumed that aerosols are composed of optically homogeneous, non-absorbing, spherical water droplets. Thus, the size distribution of marine aerosols can be described as follows [14]:

$$n(r) = ar^2 \exp(-br) \tag{1}$$

where: $a$, $b > 0$ are distribution parameters.

Non-linear minimization was used to determine distribution parameters $a$ and $b$, which, in turn, determine the size distribution and concentration of aerosols at particular altitudes (for $r \in [0.5\ \mu m;\ 5\ \mu m]$) as follows:

$$N_c(z_i, h_i) = \int_{0.5}^{r} n_r \, dr = \frac{a(z_i, h_i)}{b^2(z_i, h_i)} e^{[-0.5b(z_i, h_i)]}, \tag{2}$$

$$N_r(z_i, h_i) = N_c(z_i, h_i) f(r), \tag{3}$$

$f(r)$ is a normalized size distribution function,

$$f(r) = be^{[-b(z_i, r_i)r]} \tag{4}$$

where: $z_i$ – arbitrary point on the sensing path, $h_i$ – altitude, $r$ – particle radius. The value of the extinction coefficient $\alpha_{ij}$ at an arbitrary point $z_i$ and wavelength $\lambda_j$ is described by the following formula:

$$\alpha_{ij}(z_i, \lambda_j) = \pi \int_{r_1}^{r_2} r^2 Q(r, \lambda_j) n(r) dr \tag{5}$$

where: $r$ is the particle radius and $Q(r, \lambda_j)$ is the dimensionless extinction coefficient in the Mie's theory. The coefficient $Q(r, \lambda_j)$ for non-absorbing spheres which scatter light can be derived from the model developed by KRÓL [15]. The extinction value obtained from formula (5) allows horizontal visibility to be determined as follows:

$$V = \frac{3.912}{\alpha(0, \lambda)}. \tag{6}$$

Using the definition of optical thickness in the form

$$r = \int_{h_0}^{H} \alpha dh, \tag{7}$$

for the aerosol component (with $h_0 = 0$), the aerosol optical thickness $\tau_A$ can be determined as a function of visibility in the analytical form [3]

$$\tau_A(\alpha, \lambda) = \left(\frac{3.912}{V} - 0.0116\right)\left(\frac{0.55}{\lambda}\right)^{\beta}\left[H_1\left(1 - \exp\left(-\frac{5.5}{H_1}\right)\right) + 12.5\exp\left(-\frac{5.5}{H_1}\right) + H_2\exp\left(-\frac{5.5}{H_1}\right)\right] \tag{8}$$

where: $H_1 = 0.886 + 0.0222 \times V$ [km] and $H_2 = 3.77$ km.

Based on the size distribution function $f(r)$ and aerosol concentration $N_c$ are the sea surface obtained from the above procedure, it is possible to determine the aerosol optical thickness in the atmosphere $\tau_A$ as a function of wind speed and direction. The analysis of the variations of this parameter along with variations of wind conditions was carried out for the average values of the Mie coefficients, which are described

as follows:

$$\langle Q(\lambda) \rangle = \frac{\int_{r_1}^{r_2} Q(r,\lambda) f(r) \mathrm{d}r}{\int_{r_1}^{r_2} f(r) \mathrm{d}r}. \tag{9}$$

Parameter $\beta$ from formula (8) was derived theoretically as follows:

$$\beta = \frac{\log \dfrac{\langle Q(\lambda = 0.55) \rangle}{\langle Q(\lambda) \rangle}}{\log \dfrac{0.55}{\lambda}}. \tag{10}$$

## 4. Results

Aerosol concentrations derived as a function of wind speed and direction at an altitude of 4 m over the sea surface are presented in Fig. 1. The aerosol concentrations increase with an increase of wind speed. However, for southerly winds these concentrations are 2–2.5 times higher in comparison with those of

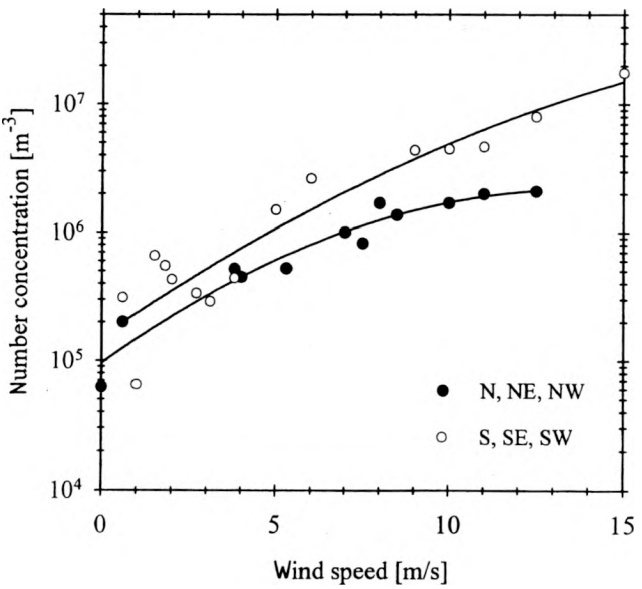


Fig. 1. Variations of aerosol concentration with wind speed and direction at an altitude of 4 m above the sea surface.

northerly winds of the same or similar speed. In the case of northerly winds, *i.e.*, on-shore, the aerosol ensemble was comprised mainly of particles of marine origin (salt and water droplets), while with southerly winds, *i.e.*, off-shore, the aerosol

ensemble was composed of both natural and anthropogenic material. Additionally, in both cases, the optical properties of the aerosols are different. It can be assumed that the light absorption coefficient in the VIS spectrum range of marine aerosols is close to zero; thus, marine aerosols have scattering properties only in the VIS range of spectrum. The same cannot be assumed about a mixture of marine and land aerosols. The light attenuation function shows two tendencies: it increases for marine aerosols and decreases for mixed aerosols along with an increase in light wavelength. The remainder of the paper addresses only cases of marine aerosols (northerly winds).

The relation between the extinction coefficient and the number of particles at sea level is linear ($\alpha = N_c Q$). So, for a given wavelength, it depends mainly on the value of $N_c$. The lidar method provides information about aerosol concentrations from size range $r \in (0.5\ \mu m, 5\mu m)$. The question arises whether the aerosol concentration derived within the lidar measurements is correct. In order to solve this problem it is necessary to verify the shape of function $Qf(r)$ in formula (9).

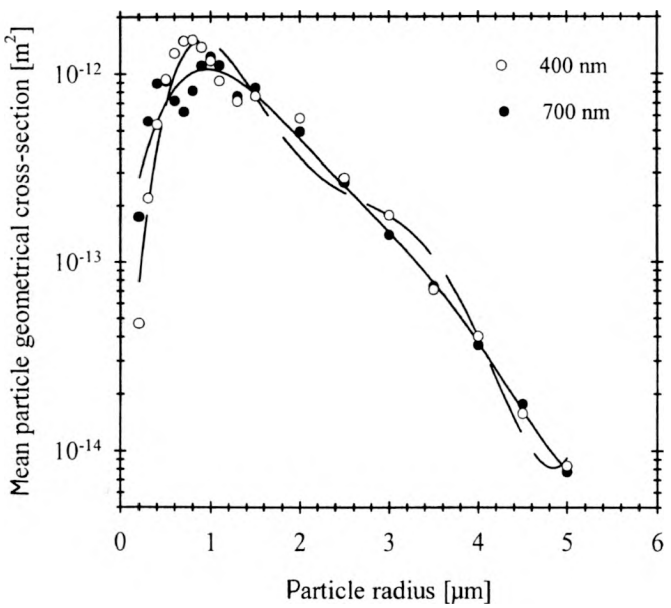


Fig. 2. Theoretically derived variations of mean particle geometrical cross-section with particle radii for two light wavelengths.

Assuming that parameter $b$ of the size distribution function is independent of wind speed and direction, or, if such dependences are negligible, the function $Qf(r)$ was derived for various values of $r$. The results of these calculations are presented in Fig. 2. For the derived marine aerosol size distribution function ($b = 2$), particles of a radius close to 1 μm play the greatest role in light scattering in the VIS spectrum range. This is due to the maximum values of the light scattering coefficient. Particles with radii $r < 0.5$ μm have very little impact, especially on light of $\lambda = 400$ nm (about

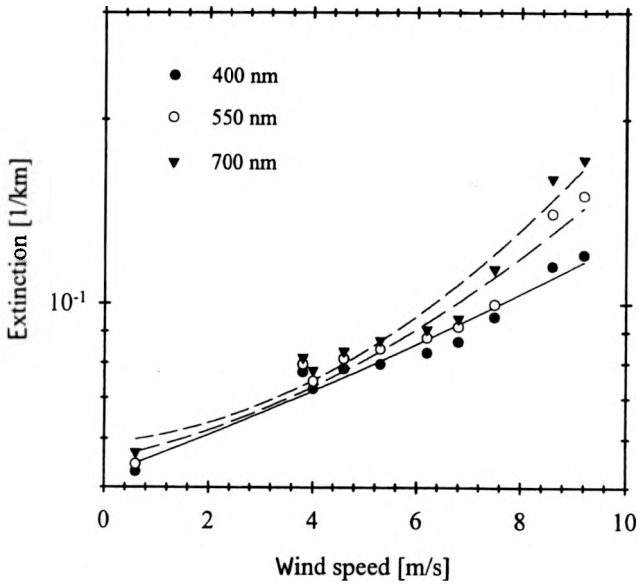


Fig. 3. Variations of extinction with wind speed for three light wavelengths.

2%). As there are very few particles of radii $r > 5$ μm their impact on scattering is insignificant (about 1%). Therefore, the marine aerosol concentrations derived by means of the lidar method for particles of radii $r \in (0.5\ \mu m, 5\ \mu m)$ are accurate and loaded with small error which has very little impact on the derived values of the extinction coefficient. The variations of the extinction coefficient for three wavelength, $\lambda = 400$, 550, 700 nm, with wind speed are presented in Fig. 3.

As expected, the extinction coefficient increases along with scattered light wavelength and wind speed (increase of concentration). Knowing the extinction coefficient and using formulae (7) and (10), formula (8) can be used to derive the aerosol optical thickness in the atmosphere. The values of coefficient $\beta$ from formula (8) are given in the Table. The variations of aerosol optical thickness in the atmosphere for three light wavelengths, $\lambda = 400$, 550, 700 nm, as a function of wind speed are presented in Fig. 4.

Table. Variations of coefficient $\beta$ (formula (8)) with light wavelength.

| $\lambda$ [nm] | 400 | 450 | 500 | 550 | 600 | 700 |
|---|---|---|---|---|---|---|
| $\beta$ | −0.2298 | −0.2568 | −0.128 | 0 | −0.00213 | −0.0926 |

The aerosol optical thicknesses obtained by the lidar method are comparable to those obtained from simultaneous measurements of the total and diffusive illumination [16]. Similar to the extinction coefficient, aerosol optical thickness increases with light wavelength and wind speed. The direction of variations is uniform for all wind speeds, as shown in Fig. 5. For wind speed of 3.8 and 9.2 m/s,

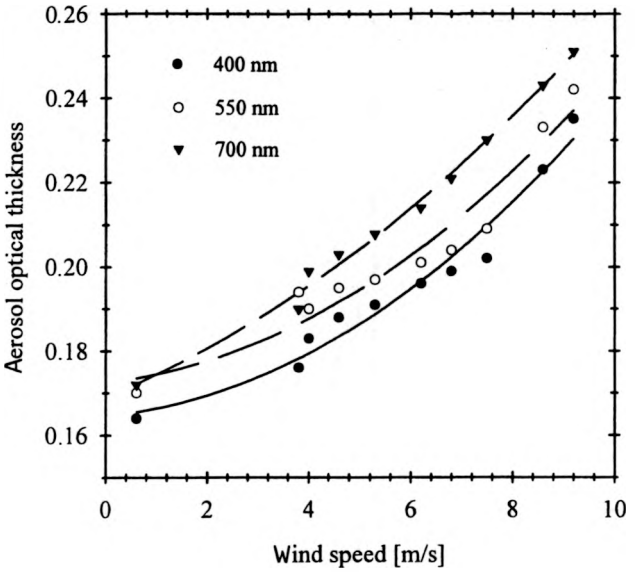


Fig. 4. Variations of aerosol optical thickness with wind speed for three light wavelengths.

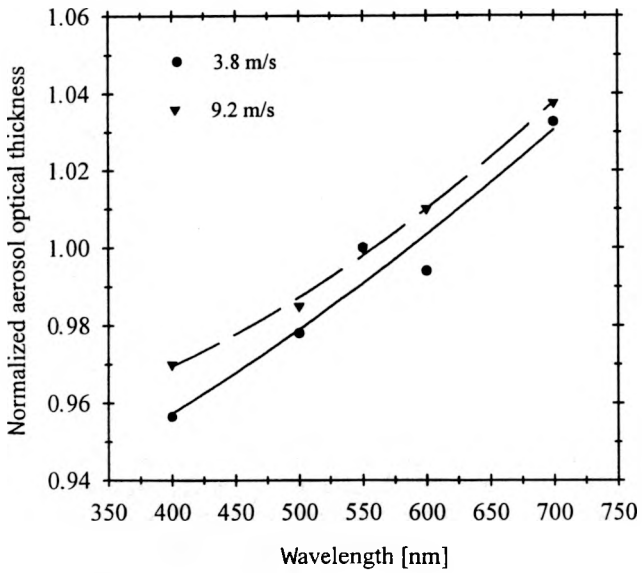


Fig. 5. Variations of normalized aerosol optical thickness with light wavelengths for two wind speeds.

the reduced values of aerosol optical thickness $\tau_\lambda/\tau_{550}$ are presented as a function of wavelength. This figure reveals that with the increase of wavelength the value of the aerosol optical thickness increases, while the variations concerned with the increase of wind speed are less apparent. This results from the fact that marine aerosol concentration depends on wind speed and when derived by the lidar method it

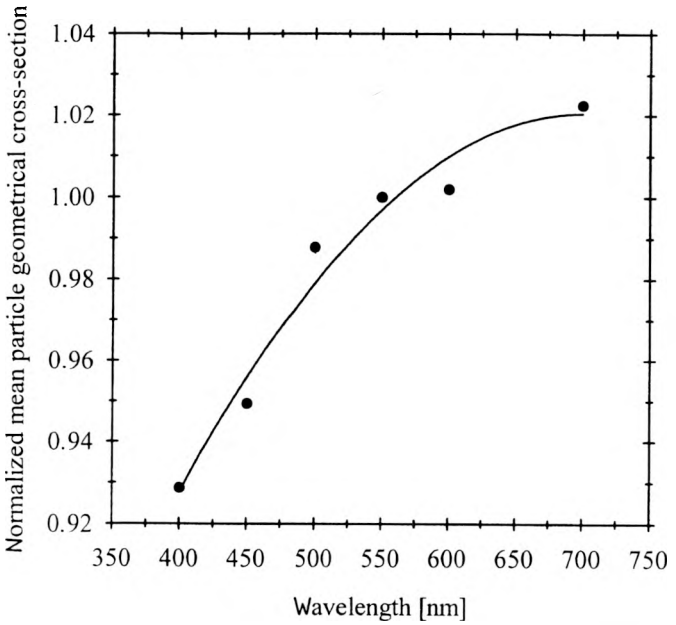


Fig. 6. Theoretically derived variations of normalized mean aerosol geometrical cross-section with light wavelengths.

is constant in the whole VIS spectrum range. Therefore, the values of the ratio $\tau_\lambda/\tau_{550}$ should change like the values of $\langle Q(\lambda,r)\rangle/\langle Q(\lambda=550,r)\rangle$ presented in Fig. 6, which were derived theoretically for a given size distribution function $f(r)$.

The comparison of the graphs in Figs. 5 and 6 reveals the existing differences for wavelengths $\lambda = 400$ and 700 nm. These differences are concerned with changes of parameter $b$ which occurs in the size distribution function. As presented by ZIELIŃSKI *et al.* [17] the values of parameter $b$ increase with wind speed and depend on the sea bottom slope in the surf area.

## References

[1] ROBINSON J.S., *Satellite Oceanography*, Ellis Horwood Ltd., Chichester 1985.
[2] STEWART R.H., *Methods of Satellite Oceanography*, University of California Press, 1985.
[3] STURM B., *The atmospheric correction of remotely sensed data and the quantitative determination of suspended matter in marine surface layers*, [In] *Remote Sensing in Meteorology, Oceanography and Hydrology*, [Ed.] A.P Crocknell, Ellis Horwood Ltd., Chichester 1981, pp. 163–197.
[4] GORDON H.R., *A preliminary assessment of the Nimbus-7 CZCS atmospheric correction algorithm in a horizontally inhomogeneous atmosphere*, [In] *Oceanography from Space*, [Ed.] J.F.R Gower, Plenum Press, New York, London 1981.
[5] JERLOV N.G., *Marine Optics*, Elsevier, Amsterdam 1976.
[6] GORDON H.R., Appl. Opt. **29** (1990), 3228.
[7] KUŚMIERCZYK-MICHULEC J., Oceanologia **36** (1994), 3.
[8] WELLER M., LEITERER V., Beitr. Phys. Atmosph. **61** (1988), 1.
[9] VAN EIJK A., DE LEEUW G., J. Geophys. Res. **97** (1992), 14417.
[10] GONG L.S., BARRIE A.L., BLANCHET P.J., J. Geophys. Res. **102** (1997), 3805.

[11] ZIELIŃSKI A., PISKOZUB J., ZIELIŃSKI T., Bull. Pol. Acad. Sci., Earth Sci., **42** (1994), 77.
[12] ZIELIŃSKI T., PISKOZUB J., ZIELIŃSKI A., Bull. Pol. Acad. Sci., Earth Sci., **41** (1993), 161.
[13] POTTER J., Appl. Opt. **26** (1987), 120.
[14] *A preliminary cloudless standard atmosphere for radiation computation*, International Association for Meteorology and Atmospheric Physics, Radiation Commission, Boulder, Colorado, USA, 1984, pp. 9–10.
[15] KRÓL T., Studia i Materiały Oceanologiczne **49** (1985), 43 (in Polish).
[16] KUŚMIERCZYK-MICHULEC J., DARECKI M., Oceanologia **38** (1996), 423.
[17] ZIELIŃSKI A., ZIELIŃSKI T., PISKOZUB J., J. Aerosol. Sci. **28**, Suppl. 1, (1997), 41.

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