Calculation of the vision range for light signals from a navigation complex based on scanning electronically pumped semiconductor laser. Part II. Aerosol extinction and calculated results

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Received July 14, 2006

We present numerical results on the vision range for light signals from a navigation complex based on scanning electronically pumped semiconductor laser (SEPSL) under conditions of coastal marine atmosphere. The results are compared with the data of shipborne experiment conducted in the Gulf of Finland near the Shepelevski lighthouse and with the data of airborne experiment carried out with a similar system. The vision range obtained for the SEPSL-based navigation system is $L_{th} \approx (0.5–1)S_m$ for day and night conditions, respectively. The comparison of the calculated and the experimental data shows insignificant discrepancy at small meteorological visual range, S_m. As S_m increases the discrepancy becomes essential.

Introduction

The problem of vision of radiation emitted by a navigation system based on a scanning electronically pumped semiconductor laser (SEPSL), from here on, laser beacon, in the surface layer of the coastal marine atmosphere relates to the radiative transfer theory and is described by the radiative transfer equation (RTE). The complexity of RTE solution is mainly determined by the geometry of the problem and by the regularities in the behavior of the medium characteristics. That is why various approximations are used to solve RTE.[1,2] The application of one or another approximation is determined by the requirement on the accuracy of the results to be obtained with the necessary and sufficient input data characterizing photometric spatial and angular characteristics of radiation, optical properties of the scattering medium, and parameters of a radiation detector.

Below we briefly analyze some approximations of RTE solution as applied to the estimation of the efficiency of a laser beacon with respect to its operation distance. It is currently believed that the radiative transfer theory is developed quite well for the case of isotropic scattering.[2] For anisotropic scattering taking place in the atmosphere, numerical and approximate methods of RTE solution are being developed. The most thoroughly developed numerical methods are the method of characteristics, Monte Carlo technique, and method of spherical harmonics. The main approximations providing for analytical solutions of RTE for laser beams are the small-angle, small-angle diffusion, and diffusion approximations. The first two approximations are mainly used for media with a strongly forward peaked scattering phase function, such as fogs and water suspensions. However, due to low efficiency of optical aids, in particular, laser visual navigation aids (NA), the small-angle approximation is not used for vision in fog. It is now beyond our technical capabilities to provide for the practically acceptable quality of vision in fog.[3] Results of the diffusion approximation refer to isotropic sources and to media with the spherical scattering phase function. In our case, we have a point unidirectional laser source, whose radiation beam propagates through an anisotropically scattering medium.

In general, despite the progress achieved in RTE solution both by numerical methods and within the framework of some approximations, no analytical equations for calculation of the field of radiation of a narrow laser beam, convenient for practical use have been derived so far. Numerical methods are laborious, while approximate ones are presented in the form of integrals of a rather complex form.[2] In addition, approximate analytical equations do not allow one to take into account the microphysical composition of aerosol, its dependence on meteorological parameters, geometry of a problem, and the type of the air mass.

Therefore, to solve the problem of vision of radiation from a laser beacon in the surface layer of the coastal marine atmosphere, we will start from the RTE solution for the intensity of a laser beam in the absence of radiation from other sources in a medium with the use of the Mie theory ideas.

1. Aerosol extinction in the surface layer of the coastal marine atmosphere

1.1. Selection and justification of the calculation technique

The aerosol extinction is known to cause, to a great extent, the main energy losses of an optical signal of the visible spectral region, propagated through the

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surface layer.[4–10] The volume aerosol extinction coefficient $\alpha(\lambda)$ is taken as the basic quantitative characteristic of laser beam extinction in the aerosol atmosphere. This coefficient enters the Bouguer law equation and is equal to the sum of the volume scattering $\alpha_{sc}(\lambda)$ and absorption $\alpha_{abs}(\lambda)$ coefficients. The scattering by aerosol particles makes the main contribution in this case, while the absorbing properties of particles of the coastal aerosol can be neglected. This means that the values of $\alpha(\lambda)$ and $\alpha_{sc}(\lambda)$ nearly coincide for the visible spectral region under hazy conditions. Therefore, only the aerosol extinction is taken into account in this paper in estimating the energy of an optical signal from a laser beacon. Atmospheric haze is taken as a scattering medium, as it is widely known that it is observed in more than 90% of all atmospheric optical situations.

At visual observation of point light sources, such as the source of the laser beacon under consideration, under conditions of coastal marine haze, it can be assumed that the intensity of scattered radiation recorded is low and the changes in the light flux are described by the Bouguer law with the accuracy acceptable in practice.

As known, the correction to the total illumination for multiply scattered radiation depends, to a great extent, on the optical thickness τ and the detector field of view ψ. At ψ equal to several degrees, the correction becomes marked already at $\tau \geq 1$ (see Ref. 2). At ψ equal to several minutes of arc, corresponding to the angular size of an individual light-sensitive cell of the retina, the contribution from the multiple scattering is taken into account starting from $\tau \geq 15$–23 (see Ref. 4). As was already noted in Ref. 11, the threshold conditions for a laser beacon are determined only by three parameters: brightness or illumination at the pupil E, flash duration Δt_{fl}, and brightness of the background B_b, against which the source is observed.

If the pupil illumination at the place of detection exceeds the threshold value, then a point source is visible. In practice, to increase the reliability of detection, the threshold illumination is multiplied by the assurance factor, which can vary widely from one problem to another, achieving 50 (see Ref. 12).

As a consequence of the Bouguer law, the Allard's equation is widely used to calculate the illumination produced by a point source[12,13]:

$$E = \frac{I_0 \cdot 10^{-6}}{L^2} e^{-\alpha(\lambda)L}, \quad (1)$$

where I_0 is the axial radiant intensity, W/sr; L is the distance to an observer, km; $\alpha(\lambda)$ is the aerosol extinction coefficient at the wavelength λ, km^{-1}; $\tau = \alpha(\lambda)L$ is the optical thickness of the aerosol medium.

It should be noted that the use of Eq. (1) is valid under twilight and nighttime conditions of observations. Under daytime and early twilight conditions, it is necessary to take into account the fogging influence of haze determined by the degree of sunlight illumination of the scattering layer in the direction of sighting. With the allowance for the fogging influence of haze, Eq. (1) can be written in the form[13]:

$$E = \frac{\left(I_0 - (B_b - B_b')s\right) \cdot 10^{-6}}{L^2} e^{-\tau}, \quad (2)$$

where B_b is the brightness of the background near the source measured along the line of sighting, W/(sr · m^2); B_b' is the average brightness of the background in the absence of haze, W/(sr · m^2); s is the area of the source emitting surface, m^2.

The product $(B_b - B_b')s$ in Eq. (1) is the additional radiation intensity equivalent to the background brightness due to the haze fogging influence. The temporal and spatial variability of the haze fogging brightness is usually taken into account in calculations through the preset background brightness.[12]

1.2. Selection and justification of a model for calculation of $\alpha(\lambda)$

In calculating the energy of a laser beacon signal, the spectral aerosol extinction coefficient $\alpha(\lambda)$ is one of the key parameters. According to the currently existing ideas about aerosol of the surface layer of the marine and coastal atmosphere, its microphysical and optical characteristics, which determine $\alpha(\lambda)$, significantly depend on humidity, the type of air mass, wind conditions, and wave fetch related with them and have the pronounced vertical profile in a height range from 0 to 30 m. The vertical profile is most pronounced in the mid-IR region in ranges of 3–5 and 8–12 μm (see Refs. 14–17). The influence of chemical composition of aerosol on its microphysical and optical characteristics is not considered in this paper.

Until recently (early 1990s) the main microphysical model describing aerosol of the surface layer of the marine and coastal atmosphere was the NAVY Aerosol Model (NAM) proposed in Ref. 14. The model was based on many-year arrays of experimental data obtained at heights 10 to 12 m above the sea level. Later on many modifications of this model have been produced, and now the sixth version is available. The model predicts quite satisfactorily the extinction of optical radiation under maritime conditions and conditions of open ocean at a height of 10 to 12 m above the sea level.

However, the experimental investigations of the early 1990s have shown a significant discrepancy with NAM predictions of the transmittance at other heights. Thus, the experimental investigations of the particle size distribution as a function of height above the sea level dN/dr (see Refs. 15 and 16) and the experimental investigation of the atmospheric transparency by the transmission method[18,19] within the Electro Optical Propagation Assessment in Coastal Environment (EOPACE) and Rough Evaporation Duct (RED) Programs have demonstrated significant variations of dN/dr with height in the near-surface layer of the marine atmosphere.

To eliminate these discrepancies, NAM was modified, and the new version was called ANAM (Advanced NAVY Aerosol Model).[17] Simultaneously with this, in Ref. 20 a significant dependence of dN/dr on the wave fetch was revealed. This dependence is ignored in ANAM. The fetch is a distance from the shore along the wind direction to the measurement site (in km) in the open water on the windward side.

The fetch is widely used in oceanology in investigations of the influence of waves on a shoreline, in assessments of the protection of shore installations against waves. In our case, it characterizes the size of the area and the intensity of generation of the sea salt aerosol. To find the fetch, it is necessary to have a map of the region of measurements of the proper scale with a grid and to know the wind direction in degrees.

The further development of these investigations has allowed the development of the MEDEX (MEDiterranean Extinction) microphysical model of the coastal aerosol,[21,22] which describes realistically the influence of meteorological parameters, vertical profile, and wind conditions. Through the fetch parameter, this model takes indirectly into account the air mass parameter. The model is based on longer than 17-year arrays of experimental data obtained since 1983 in different seasons for the Baltic, Mediterranean, and North Sea on the microphysical and chemical composition of aerosol in the coastal zone.

There are also some optical models for calculation of $\alpha(\lambda)$ in the surface atmospheric layer. The input parameters of these models are $\alpha(0.55\ \mu\text{m})$ or $\alpha(\lambda_1, \lambda_2)$, humidity, and some empirical coefficients either being functions of the wavelength in the model of the Black Sea coastal haze[6,7] or corresponding to the type of optical weather for a continental environment.[8–10] However, these models ignore the regularities mentioned above. In addition, the use of the continental model[8,10] seems to be difficult, because it corresponds to a different climatic zone. Besides, there is some subjectivity in identification of 10–11 types of optical weather and in consideration of intermediate states of the atmosphere between these types, which may be long and comparable with the main types in duration.

1.3. MaexPro module for calculation of α(λ)

According to known Mie solutions, the aerosol extinction coefficient $\alpha(\lambda)$ is related to the microphysical characteristics of aerosol as[23–25]:

$$\alpha(\lambda) = \int_0^\infty K(\rho, m)\left[\mathrm{d}N/\mathrm{d}r\right]\pi r^2\,\mathrm{d}r, \qquad (3)$$

where dN/dr is the aerosol particle size distribution function, $\text{cm}^{-3}\cdot\mu\text{m}^{-1}$; $K(\rho, m)$ is the Mie coefficient (extinction factor); $\rho = 2\pi r/\lambda$ is the relative size of a particle; m is the complex refractive index; r is the radius of an aerosol particle, μm.

The size distribution function dN/dr was calculated by the last version of the MEDEX microphysical model.[26] The model is characterized by the four-mode particle size distribution function presented as a sum of four lognormal functions:

$$\frac{\mathrm{d}N}{\mathrm{d}r} = \sum_{i=1}^{4}\frac{A_i}{\mathrm{f}}\exp\left\{-C_i(\ln r/\mathrm{f}r_{0i})^2\right\}, \qquad (4)$$

where A_i and C_i are the amplitude and widths of the ith mode; r_{0i} is the modal radius of the ith mode, μm ($r_{01} = 0.03$, $r_{02} = 0.24$, $r_{03} = 2$, $r_{04} = 10$ μm); $\mathrm{f} = \left[((2-S)/6(1-S))\right]^{1/3}$ is the humidity dependent growth function (factor); $S \equiv f/100$ is the saturation index; f is the relative humidity of air, %.

At the relative air humidity $f = 80\%$, the growth function is f = 1. The amplitude and width of different modes are parameterized as functions of the fetch and the wind speed.[21,22]

The model has been developed for particles with radii r from 0.001 to 100 μm and, by now, for a height H range from 0 to 25 m, in which, in our opinion, the microphysical composition varies most strongly. The wind speed U ranges from 3 to 18 m/s; the fetch X varies from 3 to 120 km; and the relative humidity f ranges from 40 to 98%.

As an example, Fig. 1 shows the function dN/dr calculated by the MEDEX model for the most typical input parameters: $f = 80\%$, $U = 3.5$ m/s, $X = 70$ km, and $H = 10$ m.

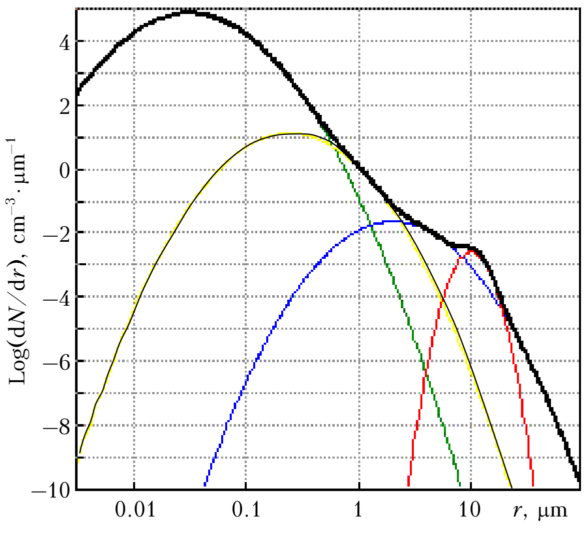

Fig. 1. Particle size distribution function dN/dr at a height of 10 m.

In the MEDEX model, the real and imaginary parts of the complex refractive index for components of the particulate matter were taken from the graphical data of Refs. 27–29 and extrapolated to a wavelength range from 0.2 to 14 μm with a step $\Delta\lambda = 0.0001$ μm. The particulate matter is taken to be a combination of the dry matter, sea salt, and water.[26]

In addition, for calculation of the aerosol extinction coefficient $\alpha(\lambda)$, the following extrapolation related to the vertical profile of the growth function f was used[30]:

$$\left(\frac{\alpha_H}{\alpha_{0\mathrm{m}}}\right) = \left(\frac{0.037}{1.017 - \mathrm{f}_H/100}\right)^{0.84}, \qquad (5)$$

where $\alpha_{0\mathrm{m}}$ is the aerosol extinction coefficient at a height $H_0 = 0$ km^{-1}; f_H is the growth function at a height H.

The vertical profiles of the function f were calculated under the following conditions:

– if 20 m ≤ H ≤ 25 m, then f = $\mathrm{f}_{25\mathrm{m}}$;

– if H ≤ 20 m and f ≤ $\mathrm{f}_{25\mathrm{m}}$, then f = $\mathrm{f}_{25\mathrm{m}}$;

– otherwise, if $H \le 20$ m, then $\mathrm{f} = (\mathrm{f}_{25\mathrm{m}} + 7) \times H^{-0.03}$.

Here $\mathrm{f}_{25\mathrm{m}}$ is the growth function at a height H = 25 m. The extrapolation is valid for f ranging from 40 to 98%.

The MaexPro (Marine aerosol extinction Profile) module (Fig. 2) calculates:

– spectral and vertical profiles of the coefficients $\alpha(\lambda)$ according to Eqs. (3)–(5);

– particle size distribution functions, scattering cross sections, volume distributions;

– spectral profiles of some modes;

– complex refractive indices of the particulate matter.

The input data for the MaexPro module are the following:

– X(70) – fetch, km;

– f(80) – relative humidity, %;

– U(3.5) – wind velocity at a height of 10 m, m/s;

– H(10) – height above the sea surface, m;

– ΔH(1) – height step, m;

– $r_{\min}$(0.001), $r_{\max}$(100), Δr(0.01) – minimal and maximal radii and the corresponding step, μm;

– $\lambda_{\min}$(0.2), $\lambda_{\max}$(40), $\Delta\lambda$(0.0001) – minimum and maximum radiation wavelengths and the corresponding step, μm.

The values in parentheses are the default, most typical values of the input parameters, which can be changed by a user within the ranges acceptable in the model.

The MaexPro module is a permanently upgraded program. It is used to estimate the energy of a signal at a detection site. The key input parameter for this estimation is the fetch.[31,32] Thus, the aerosol extinction can be estimated as a function of standard, readily measurable meteorological parameters, the microphysical composition of aerosol, the detector spectral range, and the observation geometry. The spectral profile of the coefficient $\alpha(\lambda)$ can be presented both graphically and as a table. The module includes the Overplot function for superposition or change of plots. In addition, it includes the functions of the profile interpolation, scaling and tracing, various copy functions, representation of data in the form convenient for entering into the MODTRAN code, etc.

The user interface of the MaexPro module is fully point-and-click controlled. The module can be run on a standard Microsoft Windows PC. The time needed for calculation of the spectral profile $\alpha(\lambda)$ depends on the necessary wavelength resolution, particle radius r, and height H. At the high resolution in these parameters, the computation time does not exceed tens of seconds. Other characteristics, such as the scattering cross section, volume distribution, and spectral profiles of individual modes are calculated nearly immediately.

2. Range program for calculation of the range of visual navigation aids vision

To calculate the energy characteristics of a laser beacon, we used the tentative version of the Range software package, which allows the calculation of the vision range for beacons, coastal navigation lights, floating warning lights with light-optical devices equipped with traditional, LED, and laser light sources.

The Range program (Fig. 3) has a modular structure. The database allows a user to select among different types of navigation aids, radiation sources, and conditions of propagation and detection of an optical signal.

For calculation of the vision range for visual navigation aids, the Range program uses the technique described in Ref. 11 with the allowance for the computational equations from Subsections 1.1–1.3 (see Fig. 4).

In the general form, the algorithm for calculation of the vision range involves the setting of

– energy characteristics of a laser beacon;

– atmospheric parameters;

– threshold vision characteristics.

The energy parameters of a beacon were determined through the input parameters: spectral power and divergence of radiation that were used to calculate the axial luminous intensity of radiation.[11]

Either the meteorological visual range S_{m} or the spectral extinction coefficient $\alpha(\lambda)$ can be used as input parameters of the environment. It should be noted that if the coefficient $\alpha(\lambda)$ is determined or measured under given meteorological conditions and geometry of the site of location of navigation aids, then the values of $\alpha(\lambda)$ can be directly entered into the Range program without using the MaexPro module.

The threshold vision characteristics were specified by the threshold spectral brightness E_{th} and taken from Refs. 11 and 12 taking into account the GUNIO[33] and IALA (International Association of Lighthouse Authorities)[34] recommendations.

The estimation of the vision range of navigation aids reduced to the calculation of the illumination E, produced by the radiation on the observer's pupil and the comparison of the obtained value with the threshold spectral brightness E_{th} taking into account for the corresponding background conditions of the observations.

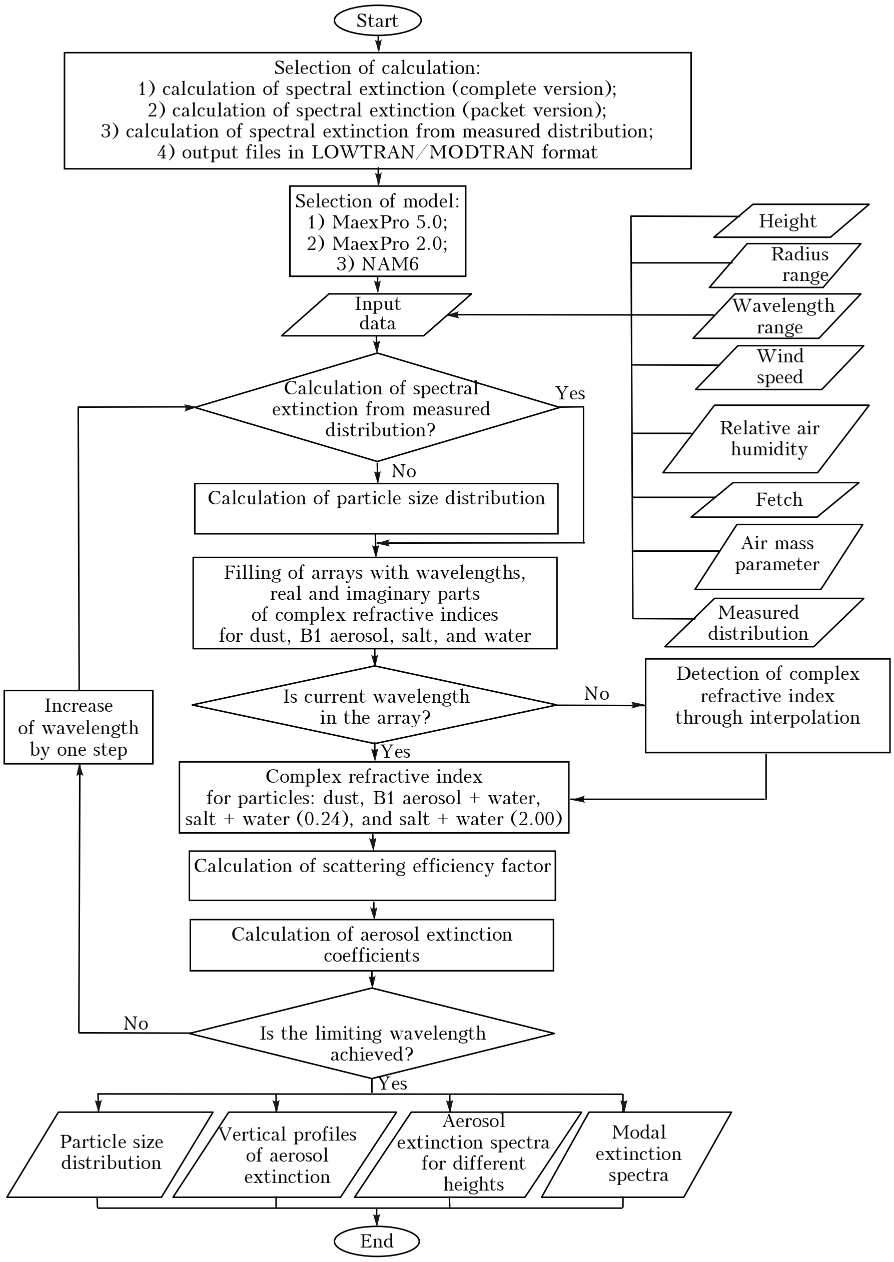

Fig. 2. Structure diagram of the MaexPro module.

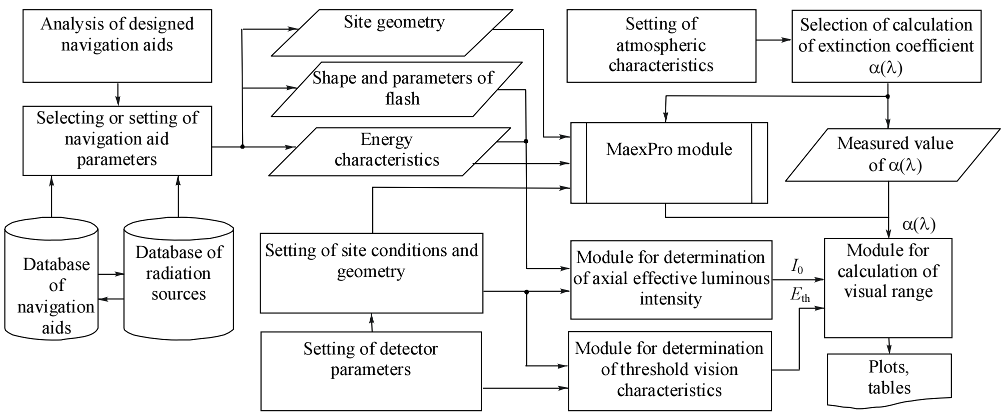

Fig. 3. Functional diagram of the Range program.

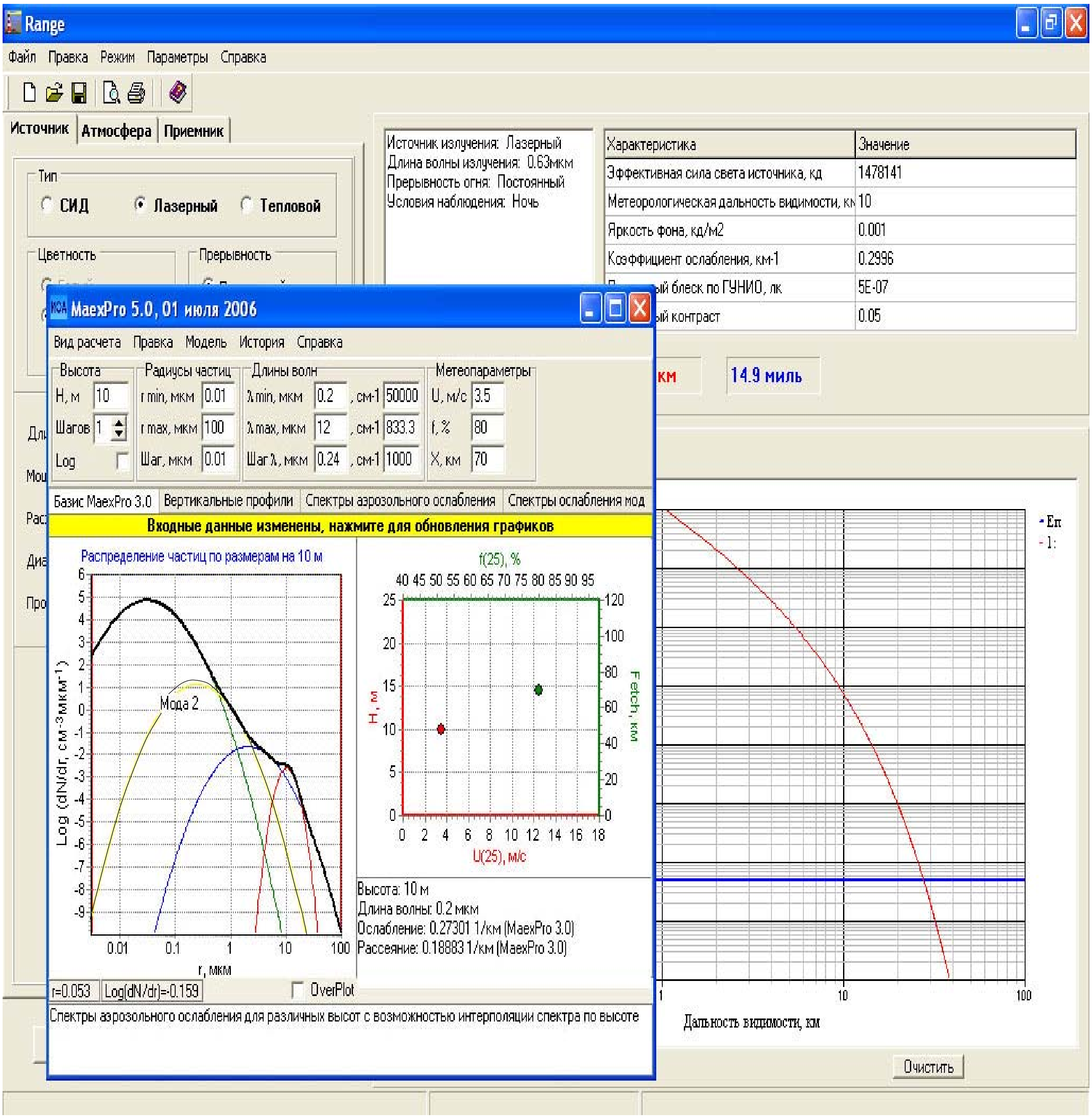

Fig. 4. Interface of the Range program with the MaexPro module.

3. Calculated results

The maximum detectable distance of a laser beacon was calculated based on SEPSL for the conditions summarized in the Table.[35] These conditions were selected to fit the conditions described in the experimental paper[36] and the data of the shipborne experiment conducted in the Gulf of Finland near the Shepelevski lighthouse on June 25–26, 2003.

Since onboard a vessel it was impossible to find the meteorological visual range S_m, the corresponding coefficients $\alpha(\lambda)$ at the wavelength 0.55 μm for all experimental geometries and observation conditions were calculated by the Koschmieder formula:

$$S_m = -\ln(k)/[\alpha(\lambda)], \quad (6)$$

where k is the threshold contrast equal to 0.05 according to regulatory requirements.[33,34] The S_m values calculated by Eq. (6) are summarized in the Table.

The vision range calculated by the Range program is demonstrated in Fig. 5.

Figure 5 shows vision range for night (squares), twilight (circles), and day (diamonds) conditions. Closed signs correspond to threshold values, while open ones correspond to comfort values of the vision range. The values of L in the top part correspond to daytime and twilight conditions, while those in the bottom part correspond to nighttime conditions.

Table. Meteorological visual range S_m and aerosol extinction coefficient α(0.55) calculated at the height of 10 m above the sea level

S_m, km	α(0.55), km^{-1}	Meteorological parameters		
		U, m/s	f, %	Fetch, km
10	0.297	11	81	90
30	0.1	3	65	70

In addition, Figure 5 shows the results of comparison with the experimental data obtained in the Gulf of Finland on June 25–26, 2003, near the Shepelevski lighthouse and in the airborne experiment with the use of a similar system.[36] The airborne experiment was conducted at day and night time at S_m equal to 10 and 20 km. The corresponding values of the vision range are shown in Fig. 5 as horizontal bold (airborne experiment) and gray (shipborne experiment) bars on the top and bottom along the abscissa for day and night, respectively. The shipborne experiment was conducted also for day and night time at S_m equal to 10 and 30 km. In Fig. 5, the left-hand end of a bar corresponds to the light recognition distance, while the right-hand end corresponds to the light detection distance.

As can be seen from Fig. 5, the calculated vision range for lights of a laser navigation system with SEPSL in the coastal marine atmosphere for any observation conditions is always shorter than S_m.

For daytime conditions, the vision range for all the three lights is roughly the same being equal to $L_{th} \approx 3$–4 km at $S_m = 10$ km and $L_{th} \approx 5$–6 km at $S_m = 30$ km. This corresponds to $L_{th} \approx 0.5S_m$.

Under twilight and nighttime conditions, the vision range for the red light is shorter than that for the green and yellow lights. Thus, the vision range for the red light is $L_{th} \approx 4$–5 km under twilight and ≈ 3–4 km at night, while for the green and yellow lights it is roughly the same and equal to $L_{th} \approx 7$–9 km at $S_m = 10$ km and $L_{th} \approx 11$–14 km at $S_m = 30$ km. Thus, vision range for the yellow and green beacon lights is nearly identical under twilight and nighttime observation conditions and $L_{th} \approx S_m$. For the red light, the vision range $L_{th} \approx 0.5S_m$. This value is much shorter than that for leading-type laser beacons, which have $L_{th} \approx 1.5$–$2.5S_m$ at day and night at the wavelength λ = 0.63 μm (see Ref. 32).

For comfort visibility conditions, the similar dependence is observed. At $S_m = 10$ km at night and in twilight, the comfort detectable distance is $L_{comf} \approx 1.3$–2 km for the red light, which corresponds to $L_{th} \approx 0.15S_m$, and for the green and yellow lights $L_{comf} \approx 4$–6 km, corresponding to $L_{th} \approx 0.5S_m$.

The comparison of calculated and experimental data for $S_m = 10$ km demonstrates rather a good agreement.

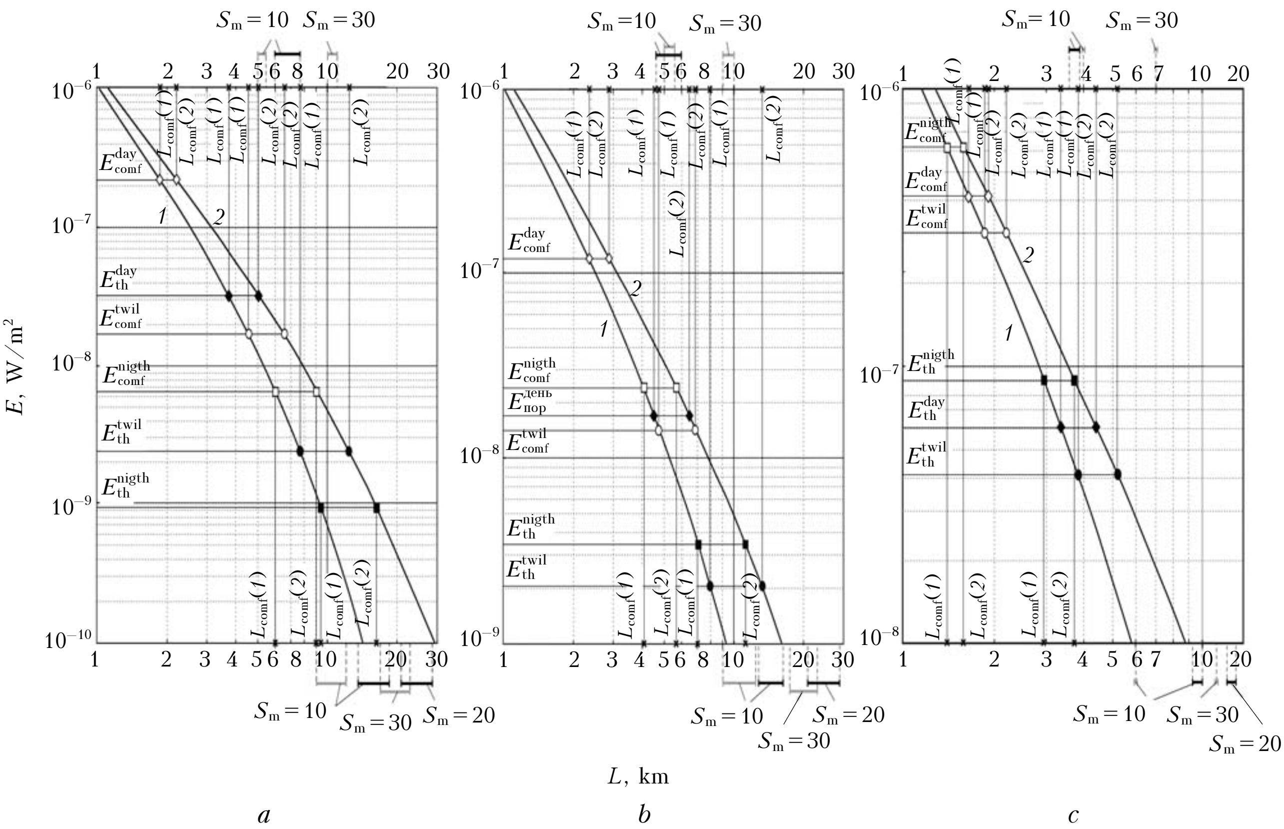

Fig. 5. Illumination E produced by radiation of a navigation system with SEPSL at a distance L at different S_m at wavelengths λ: 0.52 (*a*), 0.57 (*b*), and 0.63 μm (*c*); $S_m = 10$ (curve *1*), 30 km (*2*); L_{comf} (*1*), L_{th} (*1*) for curve *1*; L_{comf} (*2*), L_{th} (*2*) for curve *2*.

At S_m = 30 km, marked discrepancies are observed for both daytime and nighttime conditions. Unfortunately, due to the lack of data on the energy and spatial characteristics of laser beams, observation conditions and geometry taking place in the airborne experiment at mid-latitudes,[36] we failed to perform the detailed comparison with the calculated results.

Conclusions

The calculated vision range for lights of a navigation system with SEPSL is $L_{th} \approx 0.5–1S_m$ for daytime and nighttime conditions.

The comparison with the data of the airborne experiment obtained with the aid of a similar navigation system shows the insignificant discrepancies from the calculated data at small S_m. As S_m increases, the discrepancies become significant. This is likely connected with the specific features of the experiment.

The efficiency in relation to the vision range for a navigation system with SEPSL is much lower than that of leading-type laser beacons, which is explained by the lower energy potential of the system with SEPSL, connected with the principle of formation of the orientation zone. Nevertheless, the system considered meets the requirements to the maximum vision range for navigation aids intended for use in the coastal zones.

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