Atmospheric channel for bistatic optical communication: Simulation algorithms

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ABSTRACT

Three algorithms of statistical simulation of the impulse response (IR) for the atmospheric optical communication channel are considered, including algorithms of local estimate and double local estimate and the algorithm suggested by us. On the example of a homogeneous molecular atmosphere it is demonstrated that algorithms of double local estimate and the suggested algorithm are more efficient than the algorithm of local estimate. For small optical path length, the proposed algorithm is more efficient, and for large optical path length, the algorithm of double local estimate is more efficient. Using the proposed algorithm, the communication quality is estimated for a particular case of the atmospheric channel under conditions of intermediate turbidity. The communication quality is characterized by the maximum IR, time of maximum IR, integral IR, and bandwidth of the communication channel. Calculations of these criteria demonstrated that communication is most efficient when the point of intersection of the directions toward the source and the receiver is most close to the source point.

Keywords: Monte Carlo method, non-line-of-site atmospheric optical communication, impulse response of the atmospheric communication channel.

1. INTRODUCTION

One of the methods of information transfer through an open atmospheric or underwater channel is laser optical communication. Systems of laser optical communication are developed in two directions. The first of them is formed by line-of-sight communication systems (for example, see [1–2]). The second direction is formed by non-line-of-sight communication systems. The line-of-sight communication systems allow more information to be transmitted per unit time, but communication becomes impossible in the presence of an obstacle on the radiation propagation path. The non-line-of-sight communication systems are more flexible, because in the case of an obstacle, they can be adapted by changing the geometry of the optical channel. In addition, the non-line-of sight optical communication is less sensitive to turbulent pulsations.

The creation of the non-line-of sight communication systems was started in [3–6]. However, insufficient power of laser radiation sources and insufficient sensitivity of receiving systems did not allow an efficient communication system to be developed at that time. At present such possibility has appeared. Investigations of the bistatic optical communication can be subdivided into:

1) Communication systems in the far-UV range with small source-receiver base [7–14].
2) Communication systems in the near-UV and visible ranges with large bases [15–19].

Experimental and theoretical investigations of the line-of-sight communication systems in the visible range for extended communication channels have been performed at the IAO SB RAS since 2011. In [16] the first results of experiments on optical communication using reflected and scattered radiation for small base (2 m) were presented. In [17] results of successful experiments on optical communication using radiation scattered from clouds and aerosol were performed with base of about 10 km. The analysis demonstrated that in many cases, communication was almost ideal, but in some cases the probability of errors was noticeably greater. No significant correlation between the probability of errors and atmospheric meteorological and optical parameters has been revealed. This is most likely due to the simultaneous influence of a great number of factors. In that work it was confirmed that the communication quality was influenced by the PMT cooling temperature. At present, experiments on the underwater optical communication are performed.

In parallel with this, theoretical studies are carried out aimed at simulation of the transfer properties of the communication channels. In [16] an algorithm of statistical simulation of impulse response of the atmospheric communication channel with local estimates at each collision point was considered. Computations demonstrated its low

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efficiency. Therefore, a new algorithm has been developed. It is described below together with results of its testing for the impulse response calculated by three competing algorithms of statistical simulation. Using the developed algorithm for situations close to the field experiments, the most efficient communication schemes are analyzed.

2. PROBLEM FORMULATION

To estimate the communication quality for transmission of any arbitrary signal, it is suffice to know the response of the atmospheric channel to the input δ-pulse, that is, the impulse response (IR). The IR was simulated for the following problem formulation (Fig. 1). Let the optical properties of the model inhomogeneous plain stratified scattering and absorbing atmosphere be assigned. That is, the aerosol and molecular scattering phase functions g_a and g_m are assigned together with the coefficients of the aerosol and molecular scattering and extinction $\sigma_{s,a}$, $\sigma_{s,m}$, $\sigma_{t,a}$, and $\sigma_{t,m}$. Let a laser $\delta(t)$ pulse with angular divergence ν_0 be radiated from the point (0, 0, 0) of the Cartesian coordinate system. The optical beam axis lies in the $Y0Z$ plane and is specified by the angle θ_0. At a certain distance Y_N (called the base) from the source, the receiving optical system is situated whose optical axis is also located in the $Y0Z$ plane and is oriented in the direction θ_d and receives radiation within the field-of-view angle v_d. Let the distance from the source to the point of intersection of source and receiver axes be equal to D_{SI}. Let time be counted from the moment $t_0 = c \times Y_N$ (c is the velocity of light), and the IR be determined in the time interval [0, t_{max}], where $t_{max} = c \times (Y_N + l_{max})$. We now subdivide the observation region into the near time zone (Fig. 1) N_1, intermediate time zone N_2, and far time zone N_3 with identical time intervals within each zone (but different from each other).

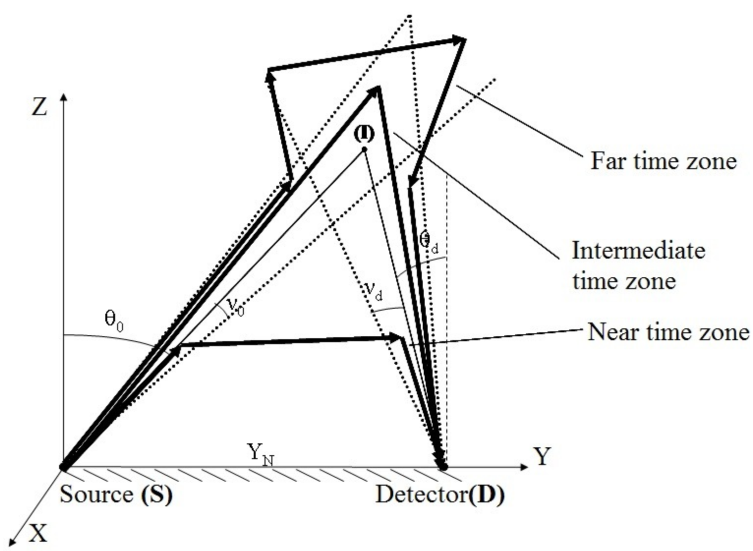

Figure 1. Geometry of the problem.

3. METHODS OF STATISTICAL SIMULATION OF THE IMPULSE RESPONSE

To calculate the impulse response of the communication channel, three algorithms of statistical simulation were used: 1) algorithm of local estimate described in [16] and based on ([20], P. 38), 2) algorithm of double local estimate based on ([20], P. 39), and 3) new algorithm proposed by us. Below we briefly consider each of these algorithms.

1. Algorithm of local estimate (loc)

This algorithm of the Monte Carlo method is implemented by simulation of photon tracing in the medium ([20], P. 10). For each collision point M lying within the field-of-view angle v_d, the local estimate is performed in the corresponding time interval of the function h(t).

2. Classical algorithm of double local estimate (double)

This algorithm is also implemented by simulation of photon tracing ([20], P. 10). For each collision point M, 1 fictitious collision point N is simulated in the field of view, and double local estimate in the corresponding time interval is performed.

At present, there exist several modifications of the algorithm of double local estimate. For example, in [21] the algorithm of accelerated calculations using several double local estimates is suggested.

3. New algorithm of modified double local estimate (new)

In the new algorithm, unlike the classical double local estimate, it is suggested to simulate fictitious collision points N_j for each collision point M in each examined time interval and to perform double local estimates in several time intervals at once. This will considerably increase the efficiency of application of each photon trajectory.

4. COMPARISON OF ERRORS OF THE EXAMINED ALGORITHMS

To compare three algorithms of calculation of the impulse response, we performed calculations of multiply scattered IR components for the homogeneous molecular medium without absorption and with the molecular scattering coefficient $\sigma_{s,m}$ = 0.02, 0.1, and 2 km^{-1}. Calculations were carried out for the following parameters: source zenith angle θ_0 = 45°, zenith angle of the optical axis of the receiving system θ_d = 75.96°, base Y_N = 3 km, angle of source divergence ν_0 = 10°, and field-of-view angle of the receiving system ν_d = 10°. For the given scattering coefficients, the optical length of the source – intermediate zone –receiver (S-I-D) path (Fig. 1) was τ_{SID} = 0.0664, 0.332, and 6.64. The function $h(t)$ was performed for 5 time intervals in the near time zone, 5 intervals in the intermediate time zone, and 15 intervals in the far time zone. In calculations we restricted ourselves with the maximum length of the trajectory minus the base in the local (or double local) estimate by l_{max} = 15 km. The number of trajectories for each algorithm was set so that the calculation time on the PC with test Lin-X 30 GFlops was 1 h (±5 min).

An example of comparison of the results of calculations for $\sigma_{s,m}$ = 0.1 km^{-1} is shown in Fig. 2. Table 1 compares the standard deviations of the results obtained using three algorithms. The comparison demonstrates that the error of the new algorithm for small optical thickness of the S-I-D path is on average by a factor of 1.6–5.6 smaller than of the algorithm of classical double local estimate.

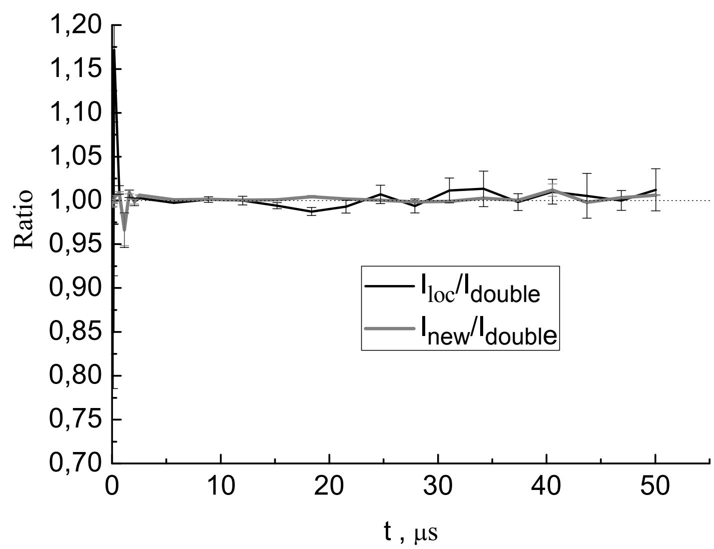

Figure 2. Ratio of the results of calculations of the multiply scattered IR components using three algorithms for $\sigma_{s,m}$ = 0.1 km^{-1}.

For large optical thickness, the error of the algorithm of double local estimate for identical times of calculation was by a factor of 2.7 smaller than of the new algorithm. This is due to the fact that for the same time period, the number of trajectories simulated by the new algorithm for small optical thickness was 1–2 times less, but for large optical thickness, it was 4 and more times less compared to the classical algorithm of double local estimate. A comparison with the algorithm of local estimate demonstrates that the error of the new algorithm is by a factor of 1.6–55.6 smaller.

Table 1. Standard deviations of the calculated multiply scattered component *h*(t) using three algorithms for the molecular homogeneous medium. In the table max indicates a maximum value, aver indicates a component averaged over time intervals, $M\xi$ is the estimated mathematical expectation of the of sought-after value, and $D\xi$ is its variance.

Algorithm	$\left(\sqrt{D\xi}/M\xi\right)_{\max}$	$\left(\sqrt{D\xi}/M\xi\right)_{aver}$	$\frac{\left(\sqrt{D\xi}/M\xi\right)_{\max}}{\left(\sqrt{D\xi}/M\xi\right)_{\max,new}}$	$\frac{\left(\sqrt{D\xi}/M\xi\right)_{aver}}{\left(\sqrt{D\xi}/M\xi\right)_{aver,new}}$
$\sigma_{s,m} = 0.02,\ \tau_{SID} = 0.0664$				
New	1.20E-02	1.55E-03	1	1
Double local estimate	5.80E-02	8.77E-03	4.83E+00	5.66E+00
Local estimate	9.83E-01	8.63E-02	8.19E+01	5.56E+01
$\sigma_{s,m} = 0.1,\ \tau_{SID} = 0.332$				
New	8.88E-03	2.16E-03	1	1
Double local estimate	2.20E-02	3.35E-03	2.48E+00	1.55E+00
Local estimate	3.15E-01	3.87E-02	3.55E+01	1.79E+01
$\sigma_{s,m} = 2,\ \tau_{SID} = 6.64$				
New	4.23E-01	4.37E-02	1	1
Double local estimate	7.99E-02	1.60E-02	1.89E-01	3.66E-01
Local estimate	6.44E-01	7.02E-02	1.52E+00	1.60E+00

5. QUALITY OF THE BISTATIC ATMOSPHERIC OPTICAL COMMUNICATION CHANNELS

The quality of the communication channels is suggested to be characterized by the following criteria: 1) maximum impulse response $h_{\max}$, 2) time of maximum occurrence counted from the beginning of signal registration $t_{\max}$, 3) integral impulse response H, and 4) bandwidth of the atmospheric channel ω_*.

The maximum of the impulse response $h_{\max}$ characterizes the maximum power in the received signal. It is determined as follows:

$$h_{\max} = \max_{i=1,..,N}\left(h_i\right), \tag{1}$$

where N is the number of time intervals, h_i is the IR value in the time interval $\left[t_{i-1}, t_i\right]$.

The time of occurrence of the maximum $t_{\max}$ characterizes as quickly from the beginning of signal reception the received radiation power reaches maximum. It is determined as the upper limit of the time interval corresponding to $h_{\max}$.

The integral impulse response H characterizes what portion of energy of the transmitted impulse is received. It is determined as follows:

$$H = \int_0^{t_{\max}} h(t)dt = \sum_{i=1}^{N} h_i\left(t_i - t_{i-1}\right). \tag{2}$$

The passband ω_* characterizes the volume of information that can be transmitted through the communication channel. It is determined as follows:

$$\omega_* : \frac{|F[h(t)](\omega)|}{|F[h(t)](0)|} \equiv \frac{|F[h(t)](\omega)|}{H} = 0.5\,, \tag{3}$$

where $F[h(t)]$ is the Fourier transform of the IR.

Using the new algorithm of IR calculation, simulation was performed for the following initial parameters: wavelength $\lambda = 0.51$ μm, meteorological range of visibility $S_M = 10$ km, $\theta_0 = 60°$, $\nu_0 = 0.0034°$, $\nu_d = 2°$, $Y_N = 1, 2, \ldots, 10$ km, and $D_{SI} = 0.2, 0.4, 1, 2, 3, 4$ km. The received IR was used to determine the criteria describing the communication quality. Results of calculations are shown in Figs. 3–6. From the figures it can be seen that for the same base Y_N the communication quality will be better for minimal D_{SI}, since for it h_{max}, H, and ω_* values will be greater and t_{max} will be smaller. From Fig. 6 it can be seen that when Y_N increases from 1 to 10 km, the number of transmitted information decreases by more than 10 times.

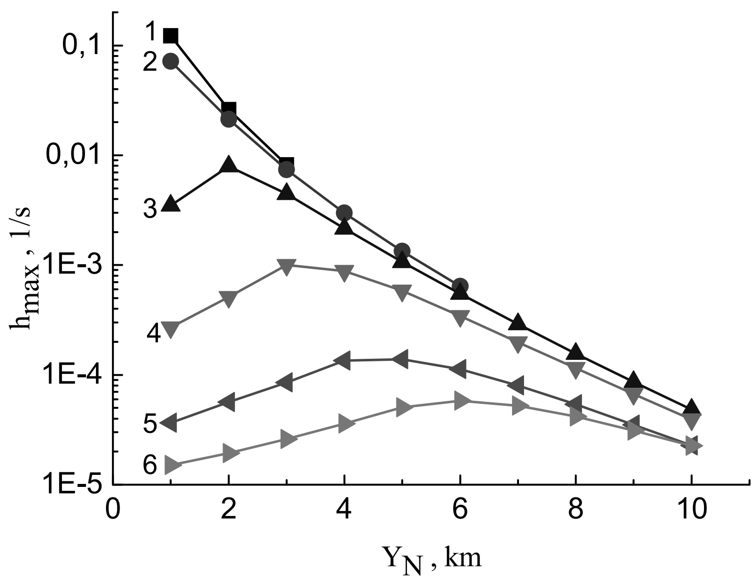

Figure 3. Dependence of h_{max} on Y_N for $D_{SI} = 0.2$ (curve 1), 0.4 (curve 2), 1 (curve 3), 2 (curve 4), 3 (curve 5), and 4 km (curve 6).

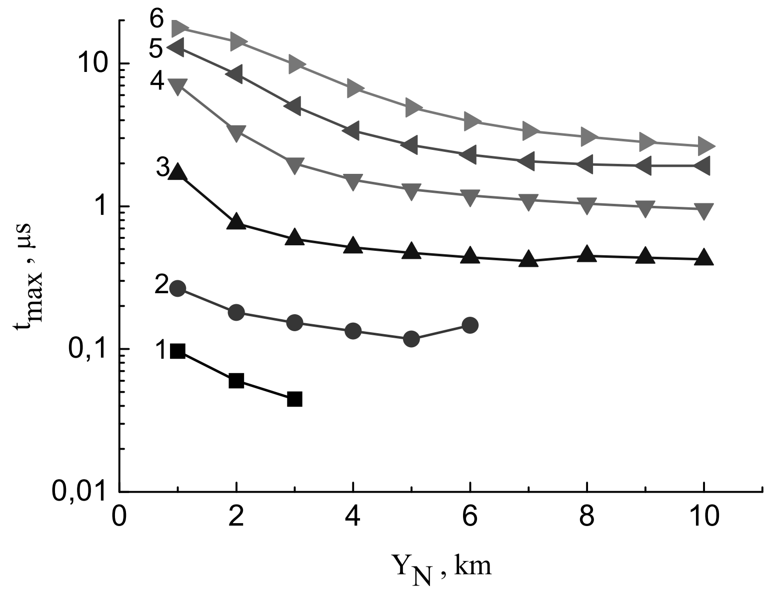

Figure 4. Dependence of $t_{\max}$ on Y_N for the D_{SI} values the same as in Fig. 3.

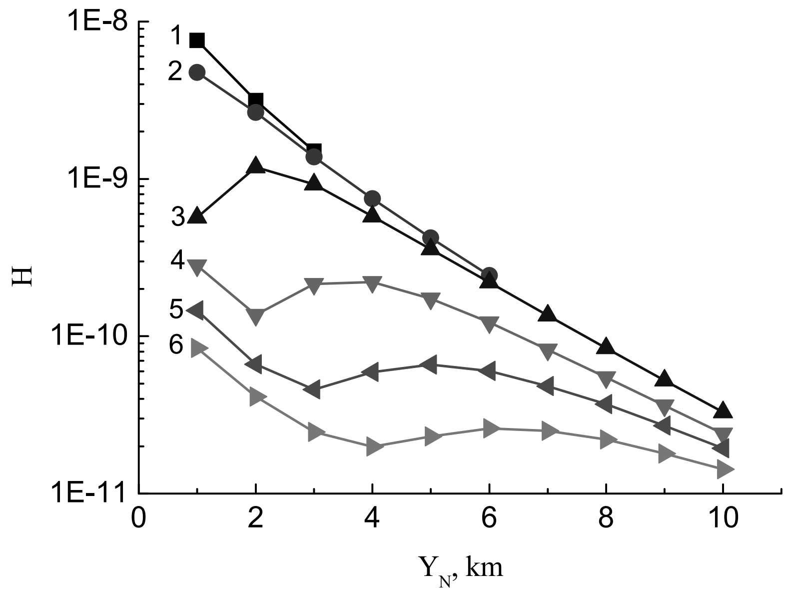

Figure 5. Dependence of H on Y_N for the D_{SI} values the same as in Fig. 3.

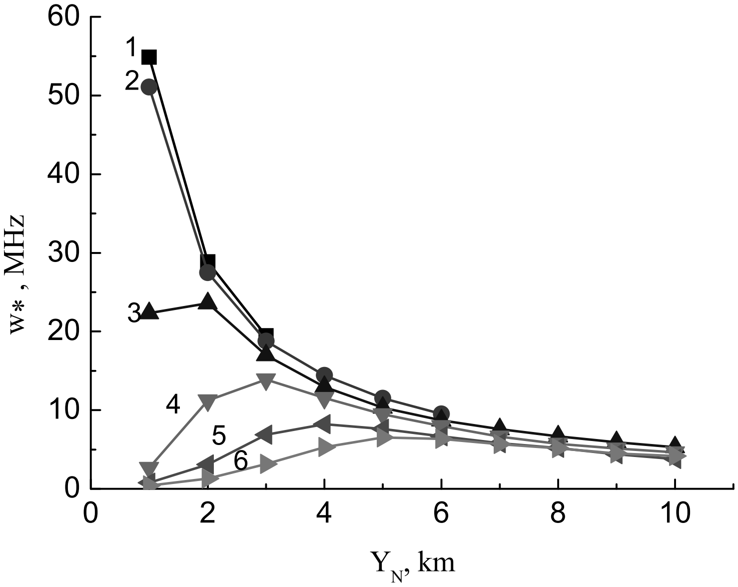

Figure 6. Dependence ω_* on Y_N for D_{SI} values the same as in Fig. 3.

6. CONCLUSIONS

The software implementing three algorithms of statistical simulation of the IR has been developed: local estimate, double local estimate, and modified double local estimate in each time interval. Test comparisons demonstrated that the algorithm of local estimate is least efficient in all cases. The new algorithm was more efficient under conditions of low turbidity and when the volume forming the received signal was large. In other cases, the algorithm of double local estimate was slightly more efficient.

Using the suggested algorithm, the criteria characterizing the communication quality for the special case of intermediate turbidity of the medium were calculated. Results of calculations demonstrated that for fixed base, the best communication quality was provided when the source and receiver axis were intersected as close as possible to the signal source. When the base increased from 1 to 10 km for the examined special case, the maximum volume of the transmitted information decreased 10 times since the bandwidth ω_* decreased from $1\,5.5\cdot10^7$ 1/s to $1\,5\cdot10^6$ 1/s.

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