Stochastic electromagnetic beams for LIDAR systems operating through turbulent atmosphere

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Abstract With the help of the generalized Huygens–Fresnel integral and the ABCD matrix approach a bistatic LIDAR system involving a rough target at a distant location in a turbulent atmosphere is modeled. The system operates by means of an optical beam which has arbitrary spectral composition, and states of coherence and polarization. The rough target is modeled as a combination of a Gaussian mirror and a thin phase screen which induces phase perturbations of the components of the electric field. The analytical form of the cross-spectral density matrix of the returned beam is determined, from which the effect of the rough target on the spectral density (intensity) and polarization of the returned wave is analyzed.

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1 General description of the LIDAR system

The description of an active LIDAR system operating in a turbulent atmosphere involves several interactions of the electromagnetic radiation with random media, namely propagation of the illumination wave from the transmitter to the target surface through a turbulent channel, scattering of the illumination wave from the surface of the target and propagation of the scattered wave from the target back to the receiver ([1], Chap. 13). A schematic diagram illustrating the propagation channel of the LIDAR system is given in Fig. 1. In this ‘unfolded’ version of the system ‘transmission through’ the surface of the target is equivalent to ‘reflection from’ it. We will restrict ourselves to the case of the bistatic propagation scenario, i.e. we assume that the transmitter and the receiver are sufficiently separated and therefore weak localization effects, e.g. enhanced backscattering ([1], p. 535), do not appear. Also, it will be assumed that the propagation paths are horizontal, located in the boundary layer of the atmosphere, with constant \( C_{n2} \) along the path, which releases the dependence of the shape of the atmospheric power spectrum on the path.

Propagation of light beams in the atmosphere through the radar system of interest was first investigated by Banakh and Mironov [2] and the subject is reviewed there. However, in those studies the scalar treatment was employed and the target was modeled as a Gaussian mirror with perfect reflectivity. The extension of Banakh and Mironov’s work to the case of a target with arbitrary surface roughness was later made in Refs. [3–5] (see also [1], Chap. 13) but again was restricted to scalar beams. The effects of the atmospheric power spectrum and LIDAR operation in various regimes of atmospheric fluctuations (weak, moderate and strong) have also been addressed and summarized in Ref. [6]. It is also worth mentioning that previously the beam was always assumed to be quasi-monochromatic.

In this paper we generalize the previous analysis to the case when the beam is stochastic, electromagnetic and can...
have any spectral composition and states of spectral coherence and spectral polarization (i.e. coherence and polarization properties depend on oscillation frequency). Such analysis is largely based on the recently formulated unified theory of coherence and polarization by Wolf [7]. Following the discussion of Ref. [7], Chap. 9 about propagation of stochastic electromagnetic fields in linear media we suppose that the propagating field remains highly directional everywhere in the system and has two transverse polarization components which may be coupled (correlated) only once, at the transmitter. Atmospheric turbulence is assumed to be homogeneous and isotropic and it, therefore, acts on the electric field components independently and in the same manner. The rough isotropic surface of the target will be modeled as the combination of a perfectly reflecting, convex mirror, a phase screen with a given correlation function and an aperture mask, accounting for the size of the target (see Refs. [2–4], where such a model is introduced). Both cases of a resolved target, i.e. when the spread of the illumination beam is larger than the effective size of the target, and of an unresolved target (otherwise) will be considered.

We will describe the second-order statistical properties of a propagating radiation field with the help of a sequence of the $2 \times 2$ cross-spectral density matrices of the beam [7] (see Fig. 1). In order to distinguish between the matrices at different transverse planes we will simply use different symbols to denote transverse position vectors: $W(r)$ will characterize the beam in the source plane, $W(t)$ after passing through the atmosphere and the Gaussian lens (mirror), $W(v)$ after the scattering from the target surface and propagating through the atmosphere up to the collecting lens (pupil plane) and $W(\rho)$ after being focused by the collecting lens and on the surface of the detector (image plane). Here and everywhere below we will omit the frequency dependence of the cross-spectral density. It will also be assumed that no atmosphere exists between the collecting lens and the detector.

Interaction of the cross-spectral density matrices with ABCD optical systems operating in any linear, possibly random, media may be treated with the help of the tensor method developed and applied to various systems in Refs. [8–10]. In the following section we will apply this method for the system in Fig. 1. In particular, we will apply the ABCD matrix approach to a special but wide class of random electromagnetic beams, called elsewhere the electromagnetic Gaussian Schell model (EGSM) beams ([11], see also [7]), for propagation in the LIDAR system. A similar analysis was performed in Ref. [12] but was restricted to mirror targets and pupil plane analysis only. We finally note that our results are valid for ABCD matrices with complex values, i.e. systems with inherent apertures.

2 Derivation of the propagation laws for the cross-spectral density matrix of the beam

In this section we will derive the propagation laws for the cross-spectral density matrix in four stages: (1) propagation from the source plane to plane 1 (including the target lens); (2) interaction with the surface of the target; (3) propagation from the target plane to plane 2 (excluding collecting lens); (4) propagation from plane 2 to the output plane.

2.1 Propagation from the source plane to plane 1 (including the target lens)

We begin by describing the illumination beam in the plane of the transmitter. We assume that, in general, it is a stochastic, statistically stationary electromagnetic beam-like field of the Gaussian Schell-model type. The second-order field properties can be characterized with the help of the matrix [12]