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A Coherence-Based Off-Axis Laser Beam Detection System

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Abstract

We describe a concept of a system for detecting laser radiation in the presence of other (background) radiation sources. Unlike most existent laser-warning methods, which detect laser beams based on their intensity and monochromaticity, the proposed approach uses a high degree of *coherence* as the distinguishing property of laser radiation. Further, in contrast to previously considered coherence detection systems, based on amplitude interferometry (AI), we propose to utilize intensity interferometry (II), pioneered by Hanbury Brown and Twiss and originally applied to thermal radiation sources, but here generalized to coexisting high- and low-coherence radiation.
In this contribution we concentrate on a possible application of the proposed system in detection of off-axis laser beam radiation scattered on atmospheric medium particles (water droplets and aerosols, especially dust). A particular design, which may operate in the visible and infrared regions, utilizes a small array of photodetectors (such as PIN photodiodes) and electronic correlator circuits identifying correlations in photocurrent fluctuations of neighboring detectors. It is shown that the normalized cross-correlation coefficients will be significant, even in the presence of a strong incoherent (e.g., solar radiation) background, provided the coherent radiation degeneracy parameter (number of photoelectrons generated by the detector during the coherence-time interval) exceeds the ratio of the background to signal intensities. This condition, which should not be difficult to achieve in realistic situations, ensures that the coherent signal is larger than the shot noise due to the background.

1 Introduction

Laser radiation detection is a long-standing problem in military applications, where laser technology is widely used in support of other weapons, mostly as laser range-finders (LRFs), laser target-designators (LTDs), and laser beam-riders (LBRs), all of them being pulsed lasers. In the recent years, improvised continuous-wave (CW) laser threats have also become a more common concern in civil aviation.

Detection of direct radiation of LRFs and LTDs is relatively straightforward, given their very high instantaneous irradiation ($\sim 10^7\,\mathrm{W/m^2}$) within the beam cone. However, since LRF and LTD beams are very narrow (their typical beam divergence angles may be of the order of $\theta_\mathrm{B} = 0.5\,\mathrm{mrad}$), direct beam detection is possible only at small distances off the axis (such as $5\,\mathrm{m}$ at the distance $R = 1\,\mathrm{km}$). That capability, offered by a single laser warning receiver (LWR), may be sufficient for protecting aircraft or land vehicles, but not for ships (sizes $\sim 100\,\mathrm{m}$). Port-scattering (imperfections of laser output optics) and beam scattering on atmospheric haze and aerosols, cause angular radiation spread and allow its observation at significantly larger off-axis angles (~ 5 to $10\,\mathrm{mrad}$) [1, 2, 3]. The irradiance at such angles, however, may be many orders of magnitude lower than the direct irradiance, typically below $1\,\mathrm{W/m^2}$, and thus has to compete with natural solar background radiation.

In this situation it becomes essential to devise detection techniques which would facilitate discrimination between laser and background sources. One characteristic feature of laser sources – high transverse coherence, hence high collimation and radiation intensity – are already being utilized in the available LWRs, along with identification of pulsed operation (which, however, does not pertain to CW lasers). Another characteristic – high monochromaticity – is not easy to utilize, as the warning systems should be able to detect a wide spectrum of possible laser sources. There remains one critical laser feature – its long coherence time Δt_c and coherence length $\Delta l_\mathrm{c} = c\,\Delta t_\mathrm{c}$, suggesting *coherence detection* as a promising discrimination criterion. Systems based on interferometric detection of laser coherence have been, in fact, considered starting already in 1970s; some more recent examples are [4, 5, 6]. However, to our best knowledge, all these techniques were based on amplitude interferometry (AI) and involved rather complex and fragile electro-optical designs; so far, none of these systems appears to have been realized as a practical LWRs.

In this contribution we propose a concept of a laser coherence detection system utilizing *intensity interferometry* (II), originally developed for the purpose of stellar observations, but here generalized to very different circumstances of coexisting highly coherent laser signal and possibly strong but incoherent background radiation. Our estimates show that the envisaged exceptionally simple and robust device (Fig. 2) should be able to identify the required off-axis laser radiation even in the presence of a full-strength solar background.

2 The theoretical basis of the proposed detection principle

Intensity interferometry (II) has been pioneered in the 1950s by Hanbury Brown and Twiss (HBT) ([7, 8], see also [9]) in a series of experiments culminating in determination of diameters of a number of stars; recent developments in stellar II (SII) are summarized in [10]. II measurements provide the *normalized current correlation coefficient*, i.e., the correlation of current fluctuations $\Delta J_\pm \equiv \Delta J(\pm\boldsymbol{\rho}/2)$ recorded by detectors located at the points $\pm\boldsymbol{\rho}/2$ relative to some reference point, normalized by the product of the current fluctuations of each detector. With the small-ρ approximation $\langle(\Delta J_\pm)^2\rangle \approx \langle(\Delta J(\mathbf{0}))^2\rangle \equiv \langle(\Delta J_0)^2\rangle$, the measured quantity and its value predicted by the theory are

$$C(\boldsymbol{\rho}) := \frac{\langle \Delta J_+ \Delta J_- \rangle}{\langle(\Delta J_0)^2\rangle} = \frac{\widehat{\delta}\, F(\boldsymbol{\rho})}{1+\widehat{\delta}}\,, \tag{1a}$$

where

$$\widehat{\delta} := \alpha(\lambda)\,\frac{A_\mathrm{d}}{\mathrm{m}^2}\,\frac{\Delta t_\mathrm{c}}{\mathrm{ns}}\,\frac{\mathscr{E}}{\mathrm{W/m^2}} \tag{1b}$$

with

$$\alpha(\lambda) = \frac{\lambda}{2hc}\,\mathrm{nJ} \approx 2.5\cdot 10^9\,\frac{\lambda}{\mu\mathrm{m}} \tag{1c}$$

denotes the *(detection) degeneracy parameter*, [1] having the physical meaning of the number of photoelectrons generated by the detector during the coherence time Δt_c; $\eta \lesssim 1$ is the detector's quantum efficiency, $\mathscr{E}$ is the irradiance incident on the detector, and A_d the detector area; finally, the function $F(\boldsymbol{\rho})$ (which could be termed the *degree of intensity correlation*) is normalized to $F(\mathbf{0}) = 1$ and decays to small values for $\rho \gtrsim \Delta\rho$, with the *transverse coherence range* given by

$$\Delta\rho \approx \frac{\lambda R}{\pi D_\mathrm{S}}\,, \tag{2}$$

where λ is the wavelength, D_S is the source size (e.g., the beam waist) and R is the observation distance. For a typical laser-beam detection system we may have $\lambda \sim 1.5\,\mu$m, $D_\mathrm{S} \sim 3\,$cm, $R \sim 1\,$km, hence the detectors should be placed at the distance not exceeding $\Delta\rho \gtrsim 1\,$cm.

Eq. (1) follows from the conventional II theory, describing photodetection by means of a "slow" system, whose response time is long compared to the radiation's coherence time; we have extended the original II approach to radiation that is not strictly thermal, but sufficiently random, being generated by multi-mode pulsed laser and affected by a number of scattering processes (port-scattering, atmospheric particulates and turbulence). A crucially important feature of the formula (1) is the denominator $1+\widehat{\delta}$, in which the term $\widehat{\delta}$ is due to the correlation signal and "1" results from shot noise.

Eq. (1) can be generalized to situations we are interested in, namely coexisting of highly coherent "signal" and incoherent (background) radiation, described by mutually uncorrelated intensities I_s and I_b. The current fluctuations are then sums of mutually uncorrelated signal and background fluctuations, $\Delta J_{\pm,0} = \Delta J^\mathrm{s}_{\pm,0} + \Delta J^\mathrm{b}_{\pm,0}$ and the correlation coefficient (1a) becomes

$$\begin{aligned} C(\boldsymbol{\rho}) &= \frac{\langle \Delta J^\mathrm{s}_+ \Delta J^\mathrm{s}_- \rangle + \langle \Delta J^\mathrm{b}_+ \Delta J^\mathrm{b}_- \rangle}{\langle(\Delta J^\mathrm{s}_0)^2\rangle + \langle(\Delta J^\mathrm{b}_0)^2\rangle} \\ &= \frac{\widehat{\delta}_\mathrm{s}\mathscr{E}_\mathrm{s}F_\mathrm{s}(\boldsymbol{\rho}) + \widehat{\delta}_\mathrm{b}\mathscr{E}_\mathrm{b}F_\mathrm{b}(\boldsymbol{\rho})}{\mathscr{E}_\mathrm{s}(1+\widehat{\delta}_\mathrm{s}) + \mathscr{E}_\mathrm{b}(1+\widehat{\delta}_\mathrm{b})} \approx \frac{\widehat{\delta}_\mathrm{s}\mathscr{E}_\mathrm{s}F_\mathrm{s}(\boldsymbol{\rho})}{\widehat{\delta}_\mathrm{s}\mathscr{E}_\mathrm{s} + \mathscr{E}_\mathrm{b}}\,, \end{aligned} \tag{3}$$

with the parameters $\widehat{\delta}_\mathrm{x}$ and $\mathscr{E}_\mathrm{x}$ pertaining to the coherent signal (x = s) or incoherent background (x = b). The approximate expression in Eq. (3) holds for $\widehat{\delta}_\mathrm{s} > 1$ (typical of laser radiation, due to relatively long coherence time), for $\widehat{\delta}_\mathrm{b} \ll 1$ (typical of background) and for the ratio of the background to signal irradiances does not exceeding the (large) ratio of the coherence coefficients, $\mathscr{E}_\mathrm{b}/\mathscr{E}_\mathrm{s} < \widehat{\delta}_\mathrm{s}/\widehat{\delta}_\mathrm{b} \gg 1$. In addition, the background contribution to the numerator in Eq. (3) is suppressed by $F_\mathrm{b}(\boldsymbol{\rho}) \ll 1$, due to the very small transverse coherence range $\Delta\rho_\mathrm{b}$ of the background radiation. Our expression is in stark contrast with the original HBT and later stellar SII measurements: in those scenarios, even for large detector areas, the degeneracy parameter $\widehat{\delta} \equiv \widehat{\delta}_\mathrm{b}$ is always small, hence $C_\mathrm{SII}(\boldsymbol{\rho}) \approx \widehat{\delta}_\mathrm{b}F_\mathrm{b}(\boldsymbol{\rho}) \ll 1$.

The formula (3) for the correlation coefficient can be now used to assess detectability of the coherent signal in the presence of the low-coherence background. In view of the expression (1b) for the signal degeneracy parameter, we can represent it as

$$C(\boldsymbol{\rho}) \approx \frac{F(\boldsymbol{\rho})}{1 + \dfrac{1}{\alpha(\lambda)}\,\dfrac{\mathrm{m}^2}{\eta A_\mathrm{d}}\,\dfrac{\mathrm{ns}}{\Delta t_\mathrm{s}}\,\dfrac{\mathrm{W}\,\mathscr{E}_\mathrm{b}}{\mathrm{m}^2\,\mathscr{E}_\mathrm{s}^2}}\,. \tag{4}$$

Now, the normalized correlation is not small provided the denominator of Eq. (4) is not large. In other words, for a given wavelength, background irradiance, and the signal coherence time, the lowest detectable signal irradiance is proportional to the square-root of the background irradiance and inversely proportional to the linear detector size $\sqrt{A_\mathrm{d}}$,

$$\mathscr{E}_\mathrm{s\,det} \approx 2{\cdot}10^{-2}\,\frac{\mathrm{mm}}{\sqrt{\eta A_\mathrm{d}}}\sqrt{\frac{\mu\mathrm{m}}{\lambda}}\sqrt{\frac{\mathrm{ns}}{\Delta t_\mathrm{s}}}\sqrt{\frac{\mathscr{E}_\mathrm{b}}{\mathrm{W/m^2}}}\,\frac{\mathrm{W}}{\mathrm{m}^2}\,. \tag{5}$$

3 Beam scattering in atmospheric media and assessment of signal coherence

In analyzing the intensity correlation coefficient (3) we conjectured that small-angle off-axis scattering largely preserves the original beam time coherence. To assess how scattering affects coherence, we consider now the scenario of Fig. 1(a), where the source S at the origin emits a narrow beam in, say, the z-axis direction and the off-axis radiation, due to scattering at random points ζ along the

[1] We add here the designation "detection" in order to avoid ambiguity and confusion with other definitions of the degeneracy parameter δ ([11, 12]).

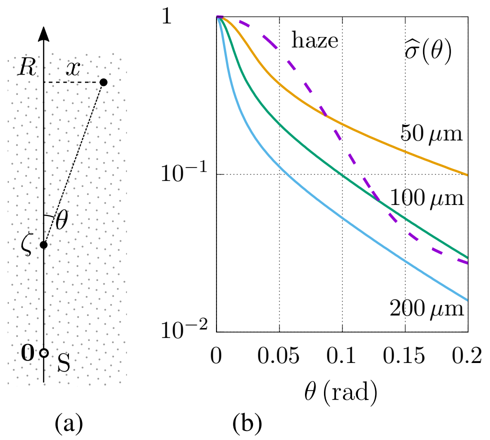

Figure 1. (a) Laser beam propagating along the z axis, scattered off-axis at the point $(0,0,z)$ by the angle θ and observed at the point $(x,0,R)$. (b) Normalized scattering cross-sections averaged over particle size, and normalized to $\widehat{\sigma}(0)=1$, for haze and for three dust models with the indicated maximum grain diameters from $50\,\mu$m to $200\,\mu$m.

beam, is observed at the distance R (typically, a few kilometers) along the axis and at the "miss distance" x (few to few tens of meters) away from the beam. The path length to the observation point is $s(\zeta) := \zeta + \sqrt{(R-\zeta)^2 + x^2} \approx R + x^2/2\,(R-\zeta)$, hence the time difference in the observed field autocorrelation $\langle u(t+\tau/2)\,u^*(t-\tau/2)\rangle$ is given by $\tau + x^2\,(\zeta_1-\zeta_2)/[2c(R-\zeta_1)\,(R-\zeta_2)] \approx \tau + x^2\,(\zeta_1-\zeta_2)/(2cR^2)]$, where relatively small values of ζ_1 and ζ_2 (hence small scattering angles θ) are favored by forward-peaked scattering amplitudes (Fig. 1(b) and the discussion below). As a result of additional cancellations of the random values of ζ_i, path length fluctuations obtained from more detailed calculations are, in typical cases, at most of the order of few centimeters (e.g., about 1.5 cm for $R = 2\,$km and $x = 10\,$m) and do not exceed the expected laser coherence lengths $c\,\Delta t_{\mathrm{c}}$ (see below).

In our modeling of beam scattering in haze we assumed a conventional fairly narrow gamma-distribution [13] of water droplet sizes. Fig. 1(b) shows results for the averaged scattering cross-section, obtained with the shape parameter $\nu = 10$ and the distribution peaked at a relatively large droplet diameter $D = 10\,\mu$m. For comparison, we also considered natural dust media (including the Arizona Road Dust model) characterized by a very different distribution of scatterer sizes, dominated by the smallest grain sizes (e.g., [14, 15, 16]). Results for several choices of parameters, also plotted in Fig. 1(b), show that the average cross-section is dominated by the largest dust particles. The overall behavior of the cross-sections in considered problems is rather similar, which suggests that the proposed off-axis detection approach should be applicable to various atmospheric media.

4 Background irradiance and coherence estimates

As a baseline for our background estimates we simply take the full daylight solar radiation, assuming only that the Sun itself is not in the FoV of the detector, i.e., we consider the indirect (diffuse) irradiance. According to the available data (e.g., [17]), spectral skylight irradiance in the visible and SWIR region of interest does not exceed $800\,\mathrm{W}/(\mathrm{m}^2\,\mu\mathrm{m})$; actually, it is considerably lower in an atmospheric absorption band from about $1.35\,\mu$m to $1.45\,\mu$m. Further, we envisage a system of spectrally complementary (Si- and InGaAs-based) detectors (Sec. 5), each covering the wavelength range of about $0.5\,\mu$m. Therefore, the integrated irradiance will be at most $\mathscr{E} = 800 \cdot 0.5\,\mu\mathrm{m} \cdot \mathrm{W}/(\mathrm{m}^2\mu\mathrm{m}) = 400\,\mathrm{W}/\mathrm{m}^2$. That number represents radiation coming from the 2π solid angle spanned by the sky dome, while the photodetector would cover a smaller FoV solid angle $\Omega = 2\pi\,(1-\cos(\phi/2)) \approx \pi\phi^2/4$, where ϕ is the detector's angle of view (Fig. 2). Thus, as the upper bound on the solar background irradiance seen by the photodiode we can assume

$$\mathscr{E}_{\mathrm{b}}(\phi) \lesssim 50\left(\frac{\phi}{57.3^\circ}\right)^2 \frac{\mathrm{W}}{\mathrm{m}^2}\,; \tag{6}$$

this value would be further reduced by the presence of haze or dust. For $\lambda = 1.54\,\mu$m (erbium fiber laser), $\Delta t_{\mathrm{s}} = 0.1\,$ns (hence $c\,\Delta t_{\mathrm{s}} = 3\,$cm), $\eta = 1$, and $A_{\mathrm{d}} = 4\,\mathrm{mm}^2$, Eq. (5) yields then the minimum detectable laser irradiance $\mathscr{E}_{\mathrm{s\,det}}(\phi) \lesssim 0.1\,(\phi/57.3^\circ)\,\mathrm{W}/\mathrm{m}^2$.

5 The proposed design concept

The proposed detector could be realized as a small array of closely (few millimeters) spaced photodetectors (Fig. 2) measuring short-exposure [2] average values of light intensities, and a fairly simple circuitry which would detect cross-correlations of the photocurrents of the neighboring detectors. The usual discrimination procedure based on signal brightness and its time dependence (short pulses or modulated signals vs. nearly constant background radiation) could be realized in the same way as in the currently available detection systems. Utilizing two of more spectrally complementary types of detectors would also provide additional wavelength-based discrimination. By increasing the number of array elements and reducing thei FoV one could achieve a higher angular resolution and, at the same time, reduce the background (Eq. (6)).

A rather clear choice for photodetectors are Si- and InGaAs-based PIN photodiodes, operating in the complementary visible and SWIR bands, very widely used in optical communication and readily available as common off-the-shelf components.

In the conventional reverse-bias, photoconductive-mode configuration based on an operational amplifier, PIN pho-

[2] The bandwidth of the system could be of the order of $\sim 100\,$MHz.

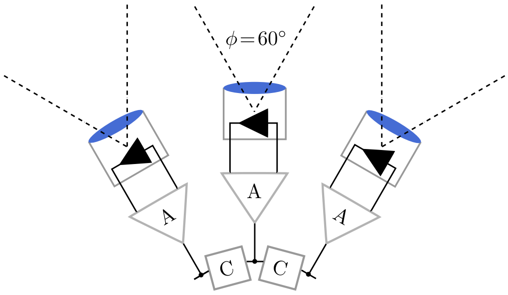

Figure 2. Schematics of a segment of a linear array of photodetectors equipped with lenslets providing a large angle of view, $\phi = 60°$. The triangles marked with "A" are amplifiers (current-to-voltage converters); the boxes indicated by "C" are "correlators" – circuits detecting correlations in voltages generated by the nearest-neighbor photodetectors.

todiodes exhibit well-known advantages of high sensitivity and speed, low dark current, and low noise-equivalent power (NEP) $\sim 10^{-14}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ [18]. In particular, for the desired detector bandwidth $\sim 50\,\mathrm{MHz}$, the minimum detectable irradiance should be $\mathrm{NEP} \cdot \sqrt{50\,\mathrm{MHz}}/\mathrm{mm}^2 \approx 2 \cdot 10^{-5}\,\mathrm{W}/\mathrm{m}^2$, many orders of magnitude below the considered irradiance threshold of $0.1\,\mathrm{W}/\mathrm{m}^2$; this large span of light intensities should not constitute a difficulty, since the PIN photodiodes can handle a large dynamic intensities range, up to 7 orders of magnitude, and are rarely damaged by excessive illumination levels.

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