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AN ANALYSIS OF THE EFFICIENCY OF SOME LASER SYSTEMS USED IN DIFFICULT AMBIENT CONDITIONS

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Abstract : *The paper presents the assessment of how the main hostile ambient conditions (atmospheric turbulence and diffusion) influence the efficiency of reception of LASER radiation by the warning systems type LWS (LASER Warning System) used for the detection of intruders from the ground or from air. We analyzed several specific types of installation of LWS systems on platforms having different precisions of stabilization to vibrations*.

Keywords: LASER Warning System, Atmospheric turbulence, Atmospheric diffusion, Vibrations, Signal-to-noise ratio (SNR), the Probability of detection / False alarm

1. Introduction

LASER Warning System (LWS) systems are tools to alert the intruders (terrestrial or aerial) in real time to their surveillance area, intruders using LASER (continuous or pulsed) light sources for detecting objects (or objectives) of interest. After the rapid detection of intruder LASER irradiation, the LWS system issues commands to take protection counters (eg, by targeting interest objects with smoke curtains or by moving the object of interest to the initial position). In this way, the intensity of the LASER signal on the object to be highlighted by illumination decreases significantly and the intruder detection optoelectronic system will become inefficient [1-3]. The paper presents the assessment of how the main hostile ambient conditions (atmospheric turbulence and diffusion) influence the efficiency of reception of LASER radiation by the warning systems type LWS used for the detection of intruders from the ground or from air. We analyzed several specific types of installation of LWS systems on platforms having different precisions of stabilization to vibrations.

2. Basic aspects

General configuration of using LWS systems on fixed (left) or mobile (right) platform [4-7, 17] is given in figure 1 and the variation of the LASER signal relative to the relative displacement speed between the intruder's LASER emitter and the object of interest is prezented in figure 2 [8-10].

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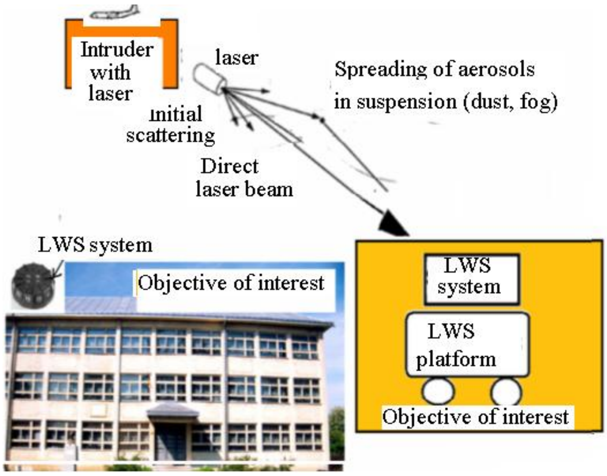

Fig. 1. Examples of using LWS systems on fixed (left) or mobile (right) platform.

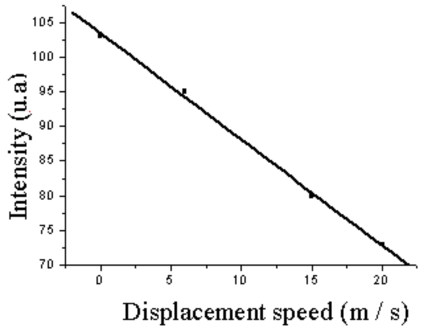

Fig. 2. Variation of the LASER signal relative to the relative displacement speed between the intruder's LASER emitter and the object of interest. The higher the speed of movement, the signal intensity (expressed in u.a, arbitrary units) is lower.

The LWS warning when sensing a LASER beam / pulse length wavelength is made with one or more blocks of min. 4 detectors / sensors placed on the surveillance lens so as to cover as much detection angle as possible (Fig. 3).

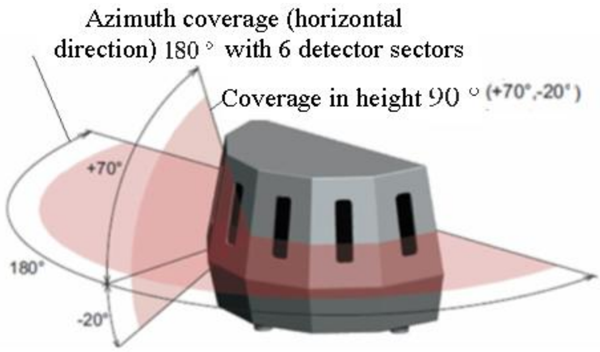

Fig. 3. Example of a 6-sensor LASER block in a LWS
that provides a horizontal (azimuth) 180 ° and 90 ° vertical detection angle.

The LWS efficiency is defined by the capability of its sensor system to detect a distance signal R (distance between the LASER emitter and the LWS receiver) with probability P_d of detection, typically> 95%, under difficult ambient conditions. Severe weather conditions affect LWS performance in a negative way.

For example, at an 80 ^{0}C increase in ambient temperature, the photonic noise of the LWS sensors is doubled and consequently decreases the P_d and SNR, as shown below. As a result, in the summer and in dry areas of the plain, many false alarms appear, because the temperature, the sun's irradiation, the dust and the humidity are high. Thus, for example, if under normal circumstances an intruder's detection is 5.5 km, the summer is reduced to 4.5 km.

False alarm is a decision to detect non-existent objects, noise-generated detection or signal interference that exceeds the threshold detection limit.

It is very important to be able to assess early on the effectiveness of an LWS system under different conditions of use, especially in those conditions where possible threats of unwanted intrusions become current and the environment limits their operability.

One way of evaluating is to determine the likelihood of detecting the threat (or LASER signal) and its simulation under turbulent conditions or stressed mechanical stresses (eg. mechanical vibrations) by highlighting the influence factors [11-13].

The main issues contributing to the LWS vulnerability depend on the efficiency with which it receives the LASER radiation emitted by the intruder and are related to:

A. False intruders (artificial radiant objects, flares, lightning, etc.);
B. Errors of appreciation of the irradiation direction received from the intruder's LASER source;
C. Not sensing or lowering the level of LASER radiation encountered.

The three suspected vulnerabilities (A, B and C) are influenced by:
a) external disturbing factors such as:
• environmental changes (atmospheric transmission, atmospheric turbulence);
• changes in mechanical stability (shocks, vibrations, etc.), with immediate effect on the uncertainty of determining the direction of the source of the threat;
b) Internal disturbance factors of detection efficiency:
• partial or total beam movement from the initial direction;
• jitter changes, which increase the diameter of the LASER beam at the target, exceeding its size, or moving the LASER beam out of the intruder.
Jitter represents a deviation from the LASER pulse frequency (through amplitude, phase, or frequency variation).

In hostile environments (difficult incidents of incidence of incident LASER radiation) objects or targets to be protected become vulnerable.

The hostile environments considered in this paper were [14-18]:

• diffusion and atmospheric turbulence;
• LWS platform vibrations and intruder displacement.

LASER Warning systems must:

• detect the threat, type and direction of the LASER irradiation threat with a probability of min. 95% for singular pulses, of min. 99% for repetitive pulses and in a very short time;
• ensure detection of simultaneous threats;
• not react to lightning impacts or reflections from nearby objects;
• have a low probability of false alarms (P_{fa}).

The smallest detection distances are at atmospheric attenuation = 1, turbulence $C_n^2 = 10^{-12}[m^{-2/3}]$ and strong solar irradiation.

The magnitude of C_n^2 $[m^{-2/3}]$ is the refractive index describing the atmospheric turbulence between the transmitter and the detector.

The main performance characteristics and conditions of use (LWS, atmospheric transmission, turbulence, vibrations) are characterized by:

• ensuring the detection of LASER signals in the 550 - 1650 nm band;
• ensuring the detection of LASER signals with powers starting from 0.3 μWatt / cm^2;
• detection of pulse type signals with a minimum duration of 5 ns;
• determination of repeat patterns for pulse trains with a minimum duration of 5 ns and frequencies of repetition between 2 Hz and 70 kHz.

Typically, the power density on the LWS detector is between 3750÷375000 [nW/cm^2].

The characteristics of the LWS detectors and the intruder LASER beam are multiple dependent.

A significant example is illustrated in figure 4, which is the influence of the frequency band B on the false alarm probability.

According to this dependence, LWS sensitivity depends on NEP (noise-equivalent power) and increases by reducing the bandwidth. The lower the NEP, the higher the LWS efficiency. Noise-equivalent power (NEP) is a measure of the sensitivity of a LWS detector and it is defined as the signal power that gives a signal-to-noise ratio of one, in one hertz output bandwidth.

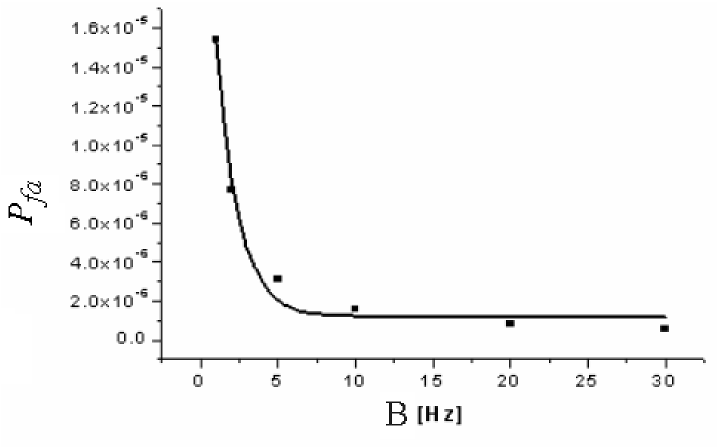

Fig. 4. Variation of false alarm probability P_{fa} with frequency band B to LWS in the range 2÷ 30 [Hz] for τ = 5 [ns].

Another example in the same sense is illustrated in figure 5, which highlights the influence of the signal emitted by the intruder LASER

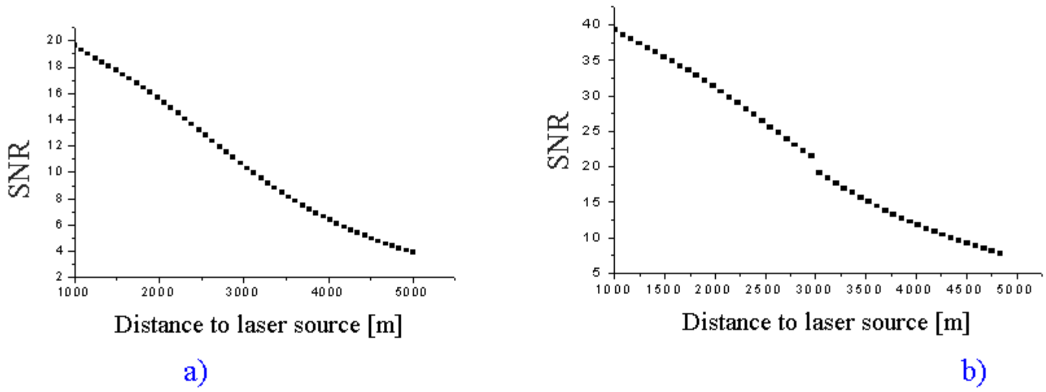

Fig. 5. Variation of SNR on a LWS detector for different distances between the transmitter and receiver (1-5 km) at normal atmospheric transmission (a), at doubling the signal power emitted by the intruder LASER for the same normal atmospheric transmission (b).

Typical LASER emitting systems used by intruders are characterized by [2, 19-24]:

• powers ranging from 20÷100 [W];
• power density or sensitivity (threshold value of discrimination between two levels of input power) of 1W/[cm^2]÷10 [μW/cm^2];
• LASER beam divergence of approx. 1000 [μrad];
• false alarm rate (FAR) > 1/24 [h^{-1}];
• response time τ <0.2 [s];
• optical power of 0.÷÷2 [MW] use at a distance of 5.000 [m].

All these make the used LWS photodiodes, usually with an active surface of approx. 1 [mm^2] to be sensitive to a LASER power of 0.01 [W].

3. Effects of the environment (atmosphere, support platform) on LWS systems

Atmospheric disturbances (such as the diffusion due to aerosol particles and atmospheric turbulence), on the one hand, and mechanical disturbances (such as vibration or relative displacements between the emitter and the detector), on the other hand, diminish the efficiency of receiving LASER radiation from LWS systems (Fig. 6).

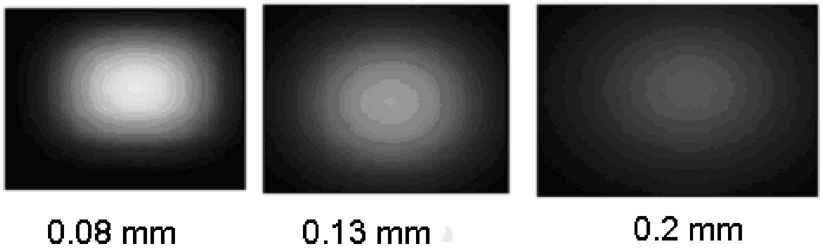

Fig. 6. Examples of increase in LASER beam diameter due to increased vibration amplitude from 0.08 mm to 0.2 mm.

An empirical expression for spectral atmospheric transmission τ at distance *R* [km] depending on wavelength, aerosol diffusion (expressed by aerosol size), *R* distance and atmospheric optical visibility *V* is the following [25-27]:

$$\tau(\lambda) = \exp\left[\frac{-3{,}91}{V} \cdot \left(\frac{\lambda}{0{,}55}\right)^{-q} \cdot R\right]$$

where *q* depends on the particle size of the aerosol particles in the atmosphere. Typical values are:

• 1.6 for high visibility (V> 50 km);
• 1.3 for medium visibility (6 km <V <50 km);
• 0.16V + 0.34 or fog visibility (1 km <V <6 km);
• V-0.5 for visibility (0.5 km <V <1 km);
• 0 for visibility (V <0.5 km).

The turbulence is due to the variation of the atmospheric refraction index along the distance from the LASER emitter (located on the intruder) to the detector. These variations are the result of inhomogeneities in the atmosphere, inhomogeneities due to differences of the temperature between the moving air layers (wind). By turbulence, the intensity of the LASER beam decreases as its diameter increases. A minimum C_n^2 [$m^{-2/3}$] value occurs when the heat transfer between the earth and the atmosphere is minimal. These points are called "thermal passages" because at these times of the day the air temperature and the temperature of the Earth interpenetrate.

4. Results on the detection probability and false alarm probability

The paper considered as relevant the probability of detecting the threat of P_d data from the LASER signal, the false alarm probability P_{fa} on the existence of a threat, the noise signal ratio in the receiver at different R_2 distances between the LASER source and the object of interest.

The characteristics of the emitters and detectors envisaged in the present study were related to the duration of the LASER pulse (for the emission source), the frequency band, the equivalent noise power

In the papers [1-3] there were highlighted image analyzes obtained by simulation from EO/IR sensor systems located on vibrated platforms and operating in hostile environment.

However, the behaviours of single-ray irradiated LASER beams have not been analyzed.

Entry data and working procedure

For this paper, the following explanations are made:

• Consideration was given to:

A) LASER receivers with NEP comprised in the range of 0.01 nW÷100 nW;
B) pulsed LASER sources: τ = 5 [ns] and τ = 100 [ns].

• Influence of atmospheric severity was quantified by:

A) variations of turbulence in a wide and commonly encountered range, ranging from 10^{-12} (very high turbulence) to 10^{-15} (very low turbulence);
B) variation of atmospheric transmission by the coefficient of attenuation σ in a wide and commonly encountered range, ranging between σ = 0,2 [km^{-1}] (very good atmospheric transmission) to 0,7 [km^{-1}] (extremely low atmospheric transmission);

• The influence of severity of mechanical stresses was quantified by the magnitude of vertical vibrations, with common values ranging from 300-1000 [µrad], vibration of the LASER source or LASER receiver that are located on a platform with different degrees of stabilization;

• Existing computations of MAVIISS 1.5, SSCAM, NVThermIP2009, C_n^2 and NVLASERD softwares were used;
• Threat distances ranging from 500-10 000 [m].

The working procedure used was the following:

A) The operational and system characteristics of the LWS have been defined as follows:

• For LWS receiver: equivalent noise power (NEP), detector diameter, quantum efficiency);
• For the LASER emitter that poses a threat to the LWS system: LWS LASER pulse energy, impulse duration, wavelength, quantum yield, beam divergence, alignment error, mechanical stabilization precision.

B) To determine the probability of detection, the false alarm probability P_{fa} or the false alarm rate (FAR) proceed as follows:

1. Determine SNR based on distance, weather conditions, threatening type of LASER, and detector used (defined by NEP and LASER pulse duration τ);

2. Determine P_{fa} by the desired P_d;

3. Determine FAR based on P_{fa};

4. Determine the distance range ΔR from the relation:

$$\Delta R[m] = 3 \cdot 10^8 [m/s] \cdot \frac{P_{fa}}{FAR[s^{-1}]};$$

Results obtained by simulation

Influence of atmosphere (diffusion and atmospheric turbulence) is manifested by:

• Decreasing the probability of detecting the incident LASER beam (Figs. 7- 9);
• Decrease SNR (Fig. 10).

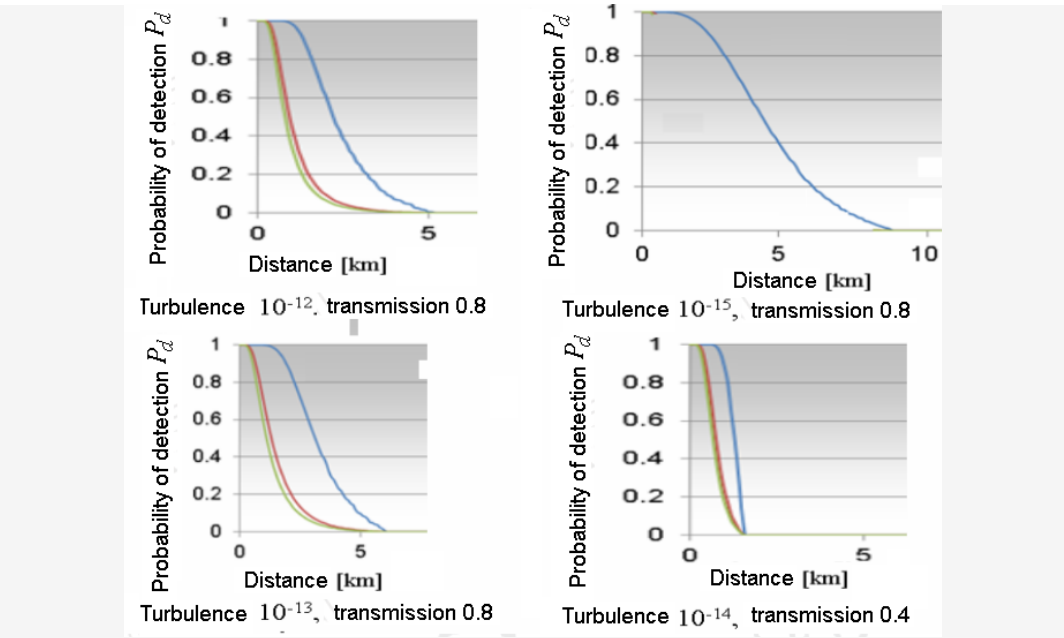

Fig. 7. Variation of probability of detection according to transmission and atmospheric turbulence.

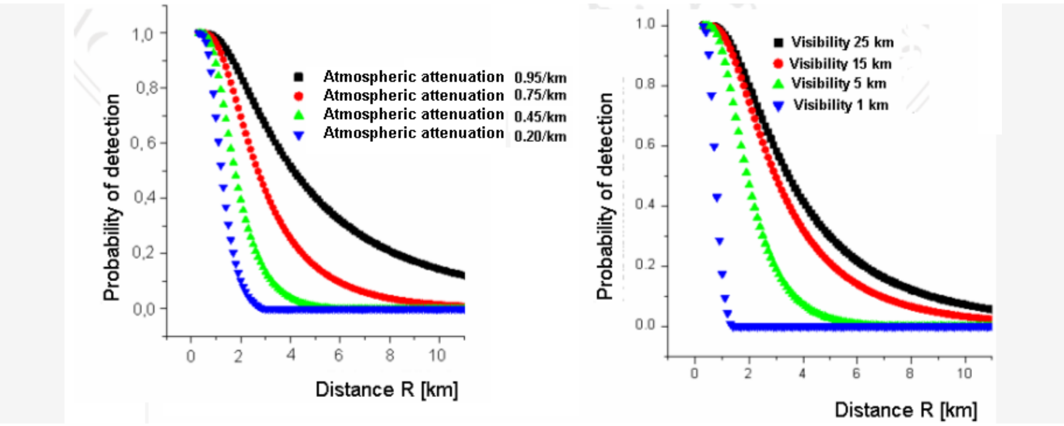

Fig. 8. Dependence of probability of distance detection and atmospheric attenuation (left) or meteorological visibility (right).

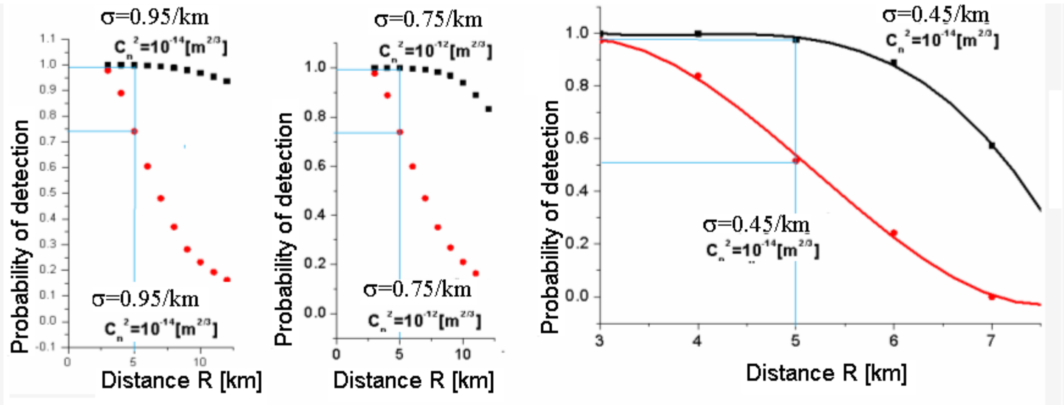

Fig. 9. Variation of probability of detection according to the distance between intruder and LWS at different turbulence and atmospheric attenuation values. It is found that the influence of turbulence decreases as the atmospheric attenuation increases.

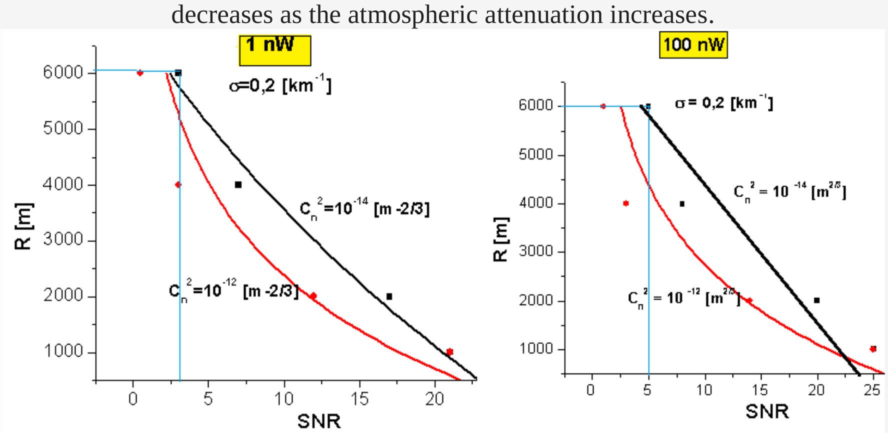

Fig. 10. Variance of SNR with different atmospheric attenuation and different atmospheric turbulences for NEP = 1 nW and 100 nW. The turbulence influence on SNR decreases with NEP increase: it is lower for NEP = 100 [nW] than for NEP = 1 [nW]. Example: at NEP = 1 [nW] results SNR = 2.6; at NEP = 100 [nW] results SNR = 5.

Influence of mechanical stress on the stabilization of LWS platforms.

It is manifested by:

• Increasing the deviation of the beam leaves the initial direction (Fig.11);
• Decreasing power on detector P (Fig. 12);
• Decreasing the probability of detecting P_d of the incident LASER beam (Figs. 13, 14 and 15);
• decrease SNR signal ratio (Figs.16 and 17).

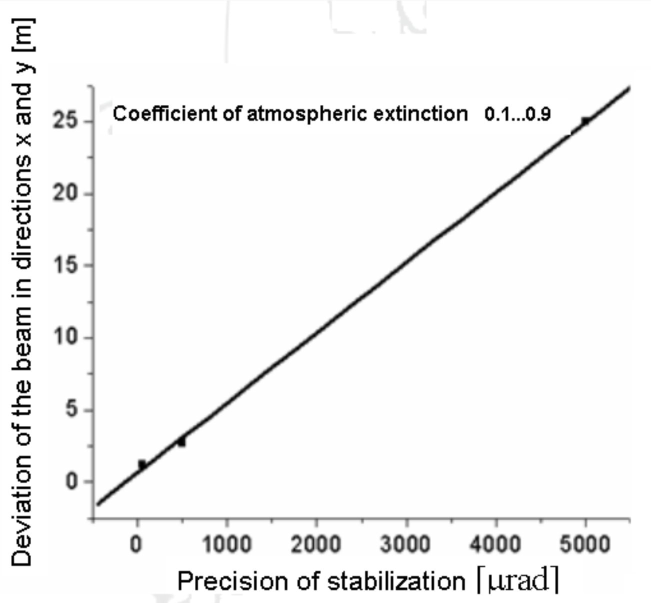

Fig. 11. Influence of the stabilization precision of the LWS platform on LASER beam deviation.

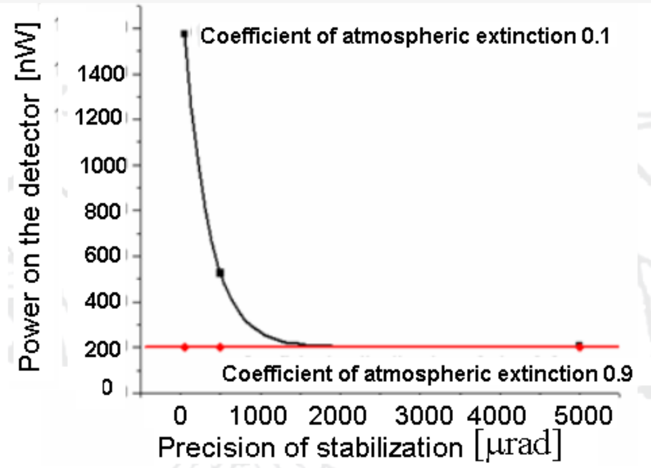

Fig. 12. Influence of the LWS platform's precision on the power of the detector on two extreme atmospheric transmissions for a stabilization of 50 and 5000 microns of the LWS platform.

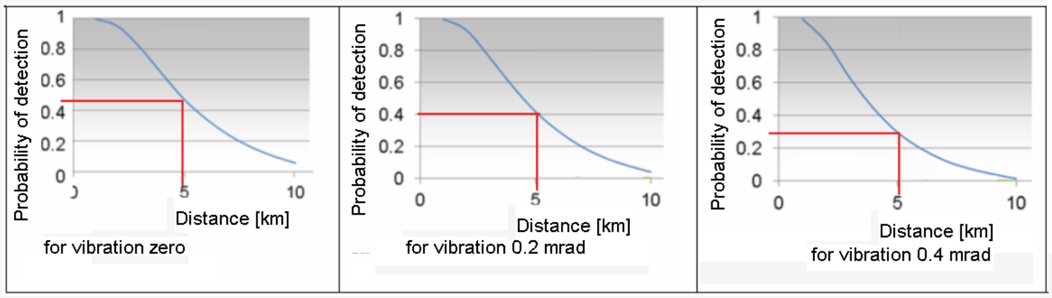

Fig. 13. Variability of probability of detection at different vibrations without LWS on the stabilized platform.

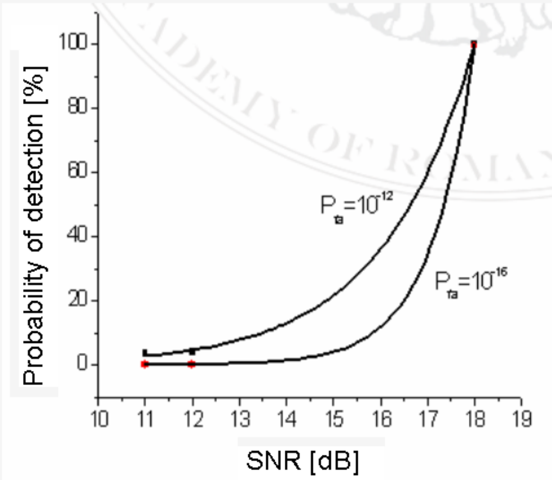

Fig. 14. Variation of detection probability for two false alarms probability values: $P_{fa}=10^{-16}$ (at 6,000 m distance), respectively $P_{fa}=10^{-12}$ (at a distance of 10,000 m), for a stabilization of 1.

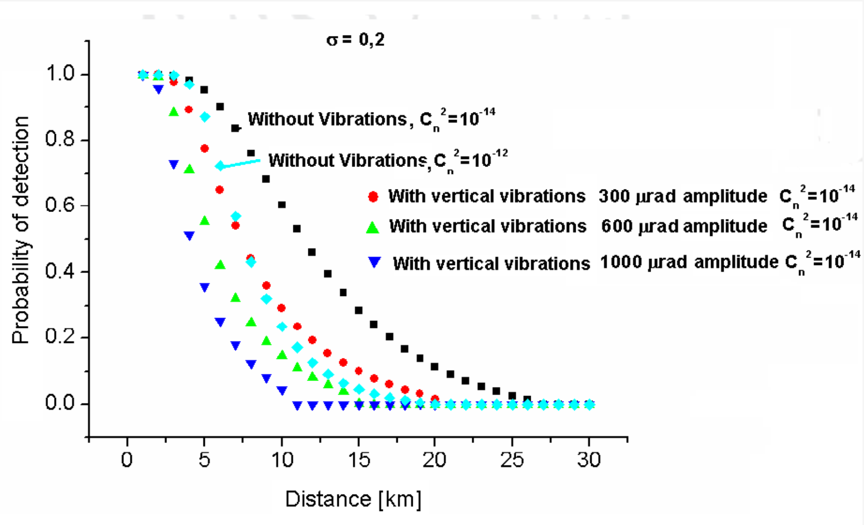

Fig. 15. The combined influence of vibrations and turbulence on the probability of detection.

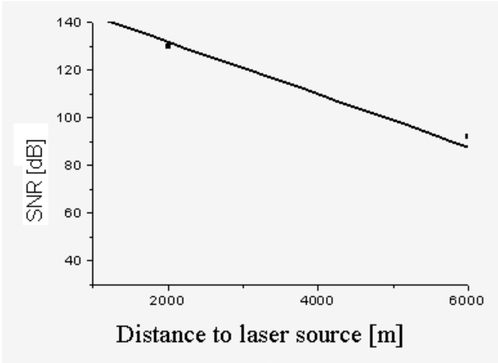

Fig. 16. SNR variation vs R distance to LASER threat source, for a stabilization of 1000 microns.

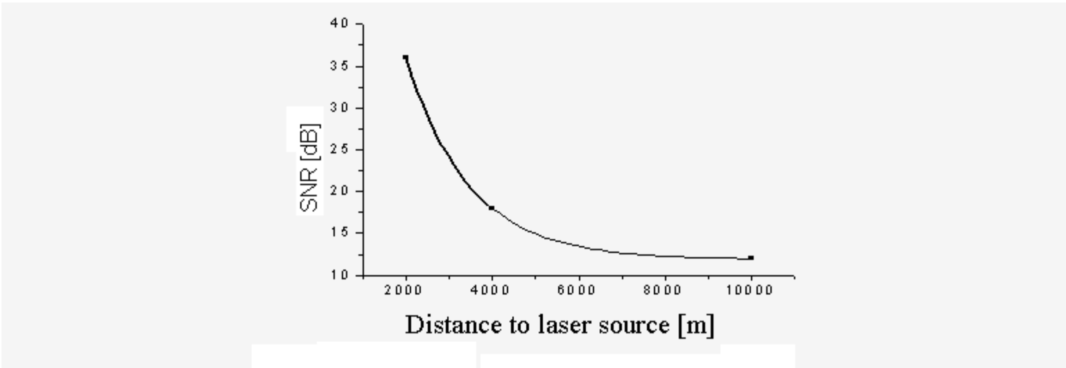

Fig. 17. SNR variation vs. R distance to LASER threat source for a stabilization of 1 [mrad].

5. Preliminary experiments

These experiments allow:

- verification of the correlation between the results of the simulation of the quantitative characterization modes of the influence of the analyzed difficult conditions and the parameters of the LWS on the probability of detection and the signal / noise ratio (SNR) with the real behaviour in the field, highlighting how these parameters are interrelated and what their weight is;

- characterizing the operation of LWS systems, the results found useful in design.

Using the specifics of the studied assembly by locations at different distances of the LWS system and in conditions of different weather conditions or mechanical displacements of this system can be emphasized both the divergence of the LASER beam and the diameter (altered or not).

By way of example, we present a methodological principle below. Thus, on the assembly shown in figure 18, the photo paper is supported in the focus of the collimator with a focal length of 2m. The photographic paper must be of Polaroid black and white type or equivalent, which has previously been veiled and developed. A LASER impulse is triggered by actuating the LASER emitter button. Remove the photo paper holder, measure the size of the "burned" spot (Fig. 19.) by the LASER impulse with a Brinell magnifier or microscope.

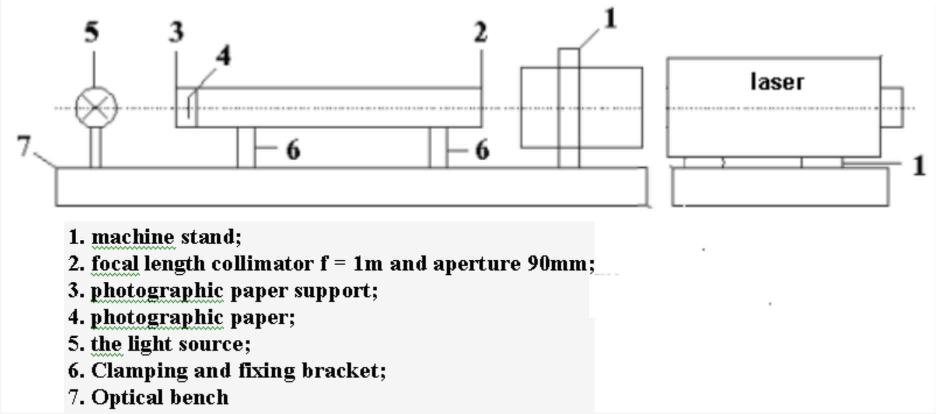

Fig. 18. Example of the LASER beam diameter and divergence scheme.

Fig. 19. Front view of the orifices made at the interaction of the LASER beam with the photographic plate (Note the contact points in which the LASER beam impressed the photographic plate).

6. Conclusions

Examination of the analysis leads to the following observations:

- as the probability of false alarm (P_{fa}), at the same signal-to-noise ratio is higher,
- the higher the probability of detection (P_d);
- there is the possibility of benchmarking the performance of LWS in more or less
- severe ambient conditions; sensitivity of LWS depends on NEP: the higher the NEP, the higher the LWS efficiency;
- the influence of turbulence on detection probability decreases with NEP increase;
- the variance of SNR is proportional to the NEP power ratio;
- influence of turbulence decreases as atmospheric attenuation increases;
- influence of turbulence on detection probability decreases with SNR increase;
- the severity of the mechanical stress is much higher than in the case of turbulence variations;
- the results allow optimization of LWS systems design.

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