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Jennifer C. Ricklin
David G. Voelz
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Vibration imagery of remote objects

Reinhard Ebert, Peter Lutzmann
Forschungsinstitut fuer Optronik und Mustererkennung (FGAN-FOM)
76275 Ettlingen, Gutleuthausstrasse 1, Germany
phone: +49 7243 992140, e-mail: ebert@fom.fgan.de

ABSTRACT

Laser vibrometry based on coherent detection technique allows to measure vibration characteristics of objects, based on its high Doppler resolution. Point targets were measured up to 40 km under medium turbluence conditions. Specifically vibration imaging offers an extensive potential for short-range civil applications [1] and for long-range target classification and identification [2]. For short range applications (up to few meters distance) laser vibrometry is used for investigating and testing of all kind of mechanical structures with respect to their vibration characteristics. Laser-Doppler based acoustic-to-seismic detection of buried mines shows a potential of this attractive technique at short range, mostly based on $\lambda = 632$ nm (HeNe laser). At longer ranges, the wavelengths of $\lambda = 10.6$ µm (CO2 laser) and $\lambda = 1.5$ µm (erbium fiber laser) are of interest, because of laser safety and better beam propagation through the atmosphere. Examples of the vibrometry technique with and without spatial resolution capability are shown here.

Keywords: vibrometry , vibration imagery, coherent laser radar

1. INTRODUCTION

For many years methods to classify and identify targets in the battlefield have been developed. There are passive methods, e.g. evaluation of the thermal image of a target, and active methods, e.g. analysis of the target radar echo. To prevent detection by a foe, passive or quasi passive procedures are preferred. Acoustic or seismographic methods are extremely sensitive to the propagation medium or additional battlefield effects and are therefore not very practical. Heterodyne laser radar is a method for measuring the vibration signature of the target offering the following advantages:

- comparatively covert (owing to small divergence and the short dwell time)
- high resolution (small wavelength)
- difficult to jam
- compatible with the current optical target detection sensors used on the battlefield

One possible benefit of shorter wavelength for vibration sensing comes from the modulation index which plays an important role in frequency modulation theory. Figure 1 shows the modulation index as a function of the wavelength, for a vibration amplitude of 5 µm.

The most common laser radar system – for long range applications - works on 10.6 µm wavelength, but because of rapid progress in compact solid state lasers (heterodyne-capable) in recent years, there has been increasing interest in laser-radar-systems at 1.5 or 2 µm. These offer the possibility of building smaller systems with lower cost components and are therefore more useful for tactical applications. Benefits of mid-infared over the far-infared wavelength are:

- higher Doppler resolution (due to the small wavelength)
- higher detector sensivity (incoherent mode)
- no or less need of detector cooling
- higher laser cross section of targets
- use of conventional optical materials

In particular drawbacks with coherent detection (vibration sensing) are:

- stronger impact of the atmospheric turbulence
- higher quantum limited noise

For short range applications like testing automibile components and the Doppler based acoustic-to-seismic detection of buried mines, the HeNe laser wavelength $\lambda = 632$ nm is used very effectively.

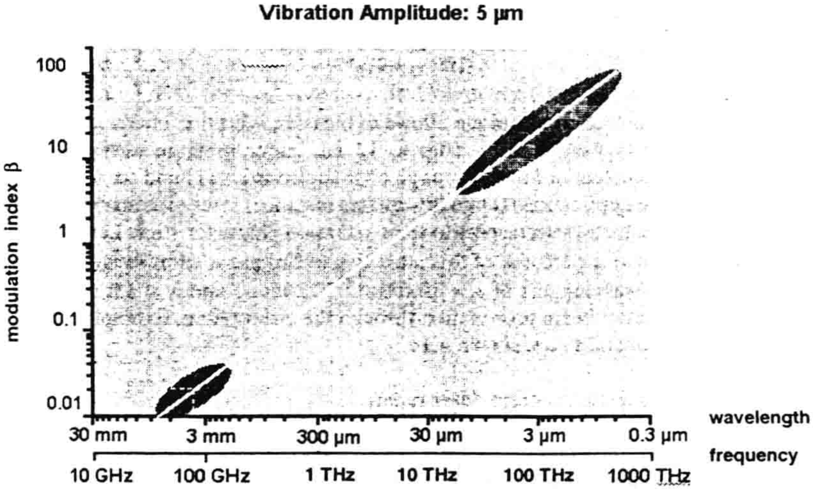


Fig. 1: Modulation index as a function of the wavelength.

2. LONG RANGE APPLICATION

2.1 Comparison of range performances of 10.6 µm and 1.5 µm laser radar systems

In order to discuss the range capability for the two wavelengths of λ=1.5 µm and λ=10.6 µm respectively, two generic laser radar systems are compared.

The carrier to noise (CNR) is given for a shot-noise limited coherent laser radar system (monostatic) for extended Lambertian target by /3/:

$$CNR = \frac{\eta \cdot \eta_{at} \cdot \eta_{pol} \cdot \frac{P_L \cdot \rho_T \cdot D^2 \cdot \lambda \cdot t_{opt}}{4 \cdot R^2} \cdot e^{-2\alpha \cdot R}}{h \cdot c \cdot B \cdot (1 + \omega_0{}^2 \cdot (\frac{3}{8} \cdot 2.91 \cdot (\frac{2\pi}{\lambda})^2 \cdot C_n^2 \cdot R)^{-6/5} + (\frac{\pi \omega_0{}^2}{\lambda R})^2)} \quad (1)$$

with

P_L:	source laser power	η_{at}:	antenna efficiency
ρ_T:	target reflectivity	η:	quantum efficiency of the photo detector
D:	transmitter / receiver diameter	ω_0:	$1/e^2$-beam radius at the transmitter
t_{opt}:	system optical efficiency	η_{pol}:	accounts for depolarisation due to the target

λ: laser wavelength
h: Planck's constant
R: range
ω_0: $1/e^2$-beam radius at the transmitter
C_n^2: structure constant of refractive index fluctuations
α: atmospheric extinction coefficient
c: speed of light
B: electrical bandwidth

The plots of Fig.2 are intended to show the different contributions (due to typical target reflectivities and atmospheric impacts) to the overall CNR, using equation 1. The system parameters applied to the calculation are also given in Fig.2.

The range performance is of the same order for both considered wavelengths. The loss due to the stronger impact of atmospheric turbulence with the 1.5 µm laser radar system is essentially compensated by the higher atmospheric extinction coefficient and the smaller target reflectivity with 10.6 µm.

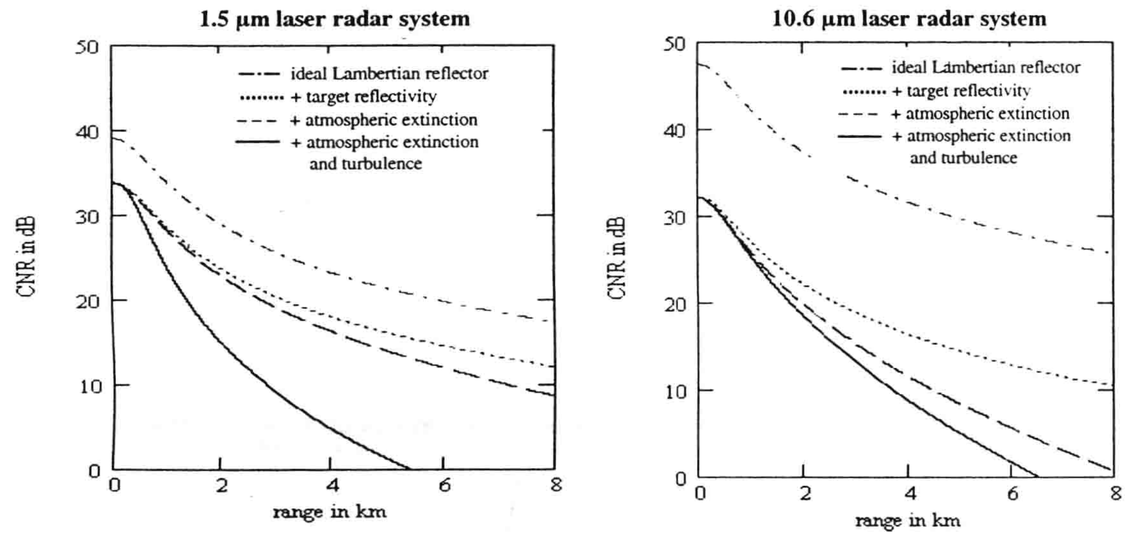


Fig. 2: Available carrier to noise ratio (solid line) assuming two generic systems with wavelengths of λ=1.5 µm and λ=10.6 µm.

The following parameters were assumed: transmitter and receiver diameter: 5 cm, quantum efficiency η: 0.8, antenna efficiency η_{at}: 0.7, efficiency (depolarisation effect) η_{pol}: 1, $1/e^2$ beam radius ω_0: 18 mm (1.5 µm) and 47 mm (10.6 µm), effective bandwidth B: 100 kHz, output power of the laser P_L: 1W, ρ_L : 0.30 (1.54 µm) and ρ_L 0.03 (10.6 µm), combined transmission loss of the receiver and transmitter t_{opt}: 0.5, collimated beam $(f=\infty)$, atmospheric extinction coefficient α: 0.14 km^{-1} (λ=10.6 µm) and 0.037 km^{-1} (λ=1.5 µm).

With common laser radar systems used over longer ranges, the laser beam is spread across most, if not all, parts of the target. This results in spatially unresolved target vibration signatures. Frequency distributions in the power spectra of such spatially unresolved vibration signatures are dependent on the area covered by the laser beam on target and on target aspect angle. Our aim was to investigate to what extent the target information content of the return signals would be increased by spatially resolving the vibration signature. Resolution may be achieved by using a scan device or a multi-element receiver. With such a 2-dimensional laser vibration sensing approach (vibration imagery) the target will be spatially resolved and one obtains a "data cube" consisting of a 2D map of vibration amplitudes across the target, one for each vibration frequency.

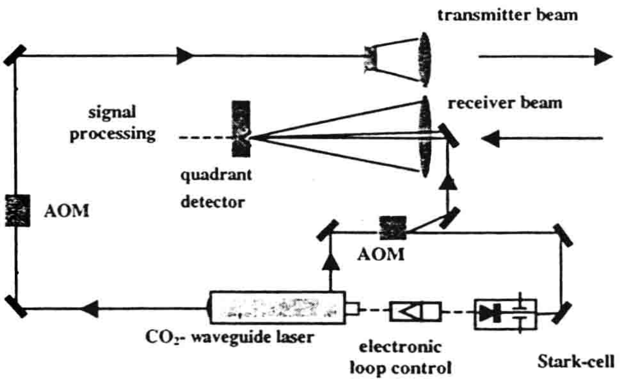
In summary, the main purpose of vibration imagery is to

- understand the principles governing vibration signature formation
- model spatially unresolved vibration signatures
- study the enhancement of classification potential of vibration
- signatures
- study the added capability of classifying concealed targets
- analyse the vibration behavior of large scale-structure
  (e. g. bridges and towers)

2.2 Experimental setup

The 10.6 µm–coherent laser radar (BASIS 2 of FGAN-FOM) used for the longest-range experiments has a bistatic configuration (Fig. 3). The laser source used is a CO2-waveguide laser with an output power of 8 W. The receiver aperture has a single meniscus lens, where the local oscillator (LO) beam was injected into the system. The LO was taken from the rear end of the laser in order to avoid the pickup of scattered, frequency-shifted radiation. Two acoustic-optic modulators (AOMs) with different modulator frequencies were used - one mounted in the transmitter path, the other one in the LO path - to limit spurious disturbances from stray reflections. The LO is reflected from a small mirror (fixed by three small rods in front of the entrance lens) and mixed with the receiver beam in the detector plane. The stabilisation of the laser amplitude was done by using a Stark cell. The intermediate frequency was set to 100 MHz. A cadmium mercury telluride (CMT) quadrant detector was used in order to analyse speckle effects. Each detector element "sees" only one quarter of the LO beam or the received laser power. The optical head was mounted on a motorized tripod, which could be rotated and tilted by PC-controlled stepper motors.

Some examples of laser vibrometry techniques with and without spatial resolution capability will be shown.



Performance data - CO_2 laser radar (vibration sensor) -	
Transmitter:	
Output power	8 W
Aperture diameter:	50 mm
Receiver:	
Aperture diameter	100 mm ∅
Field of View	0.4 mrad
HgCdTe quadrant detector (element size: 100 x 100 μm^2, space: 25 µm	225 x 225 μm^2
Intermediate frequency **one AOM (60 MHz) in the transmitter beam** **one AOM (40 MHz) in the LO beam**	100 MHz

Fig. 3: Schematic drawing of the optical part of the 10.6 µm–laserradar system and performance data of BASIS 2.

2.3 Point target vibration measurements

Figure 4 shows some examples of the power spectra after fm-demodulation of the received if-signal detected from a modulated retro-reflector (diameter: 5", modulation frequency range: 75 to 87 Hz) at different ranges by the 10.6 µm laser radar system described above. The data sets here shown are analysed on-line by an FFT-analyser. The occurrence of the other frequency components apart from the frequency of the modulated corner cube may be due to contributions of vibrations induced by the retro-reflector shielding. Such effects had been identified in prior experiments with comparable data.

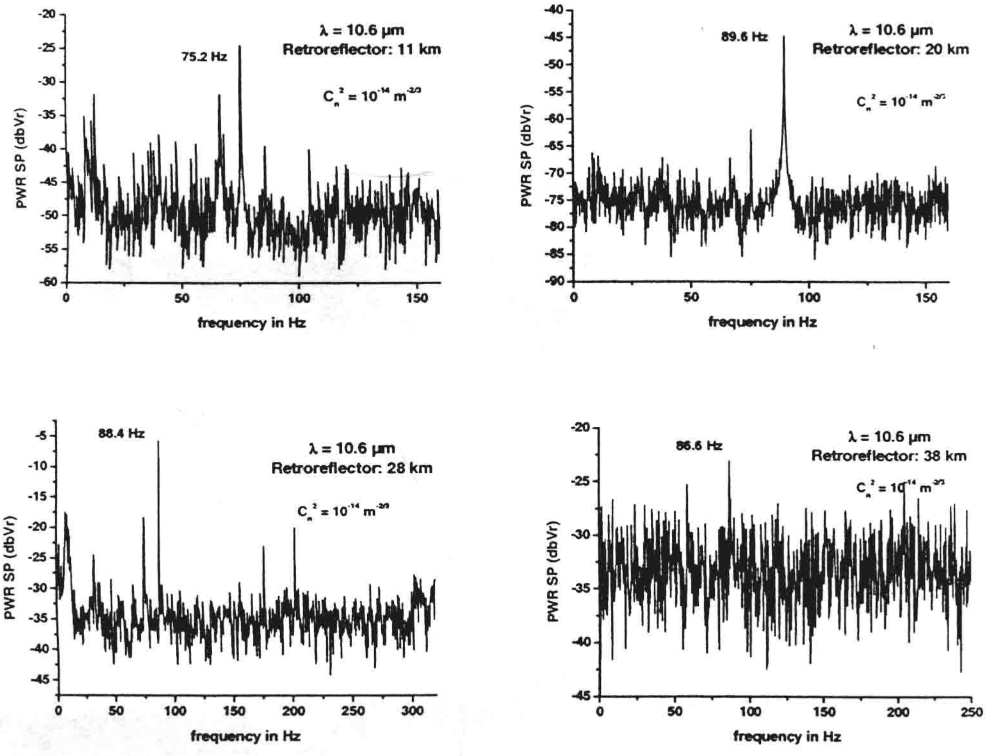


Fig. 4: Examples of the power spectra of the vibrating corner cubes rcorded by the 10.6 μm-system at different ranges (11, 20, 28 and 38 km).

2.4 Discrimination between target and decoy

The laser radar offers possibilities to extend the mission of thermal imagers with respect to certain reconnaissance tasks. The combination of a thermal imager with a simplified laser radar is a cost effective way to add range, velocity, and vibration information to the thermal image, in comparison to using a stand alone imaging laser radar system. Offering on-line the acoustic information of the frequency demodulated vibration information signatures to an observer via a headphone makes the thermal imager a much more powerful reconnaissance instrument, especially for decoy discrimination tasks.

The laser radar is also useful for distant targets that cannot be sufficiently spatially resolved for identification by a passive infrared system. The vibration and velocity signatures of different "hot spots" can help the observer to assess the threat and to discriminate real targets from decoys. An example of this application is given in Fig. 5. A thermal image was taken of a truck with idling engine, standing beside a heated metal box, both at a distance of 3.2 km. The beam of the CO2 coherent laser radar was pointed to the targets (white squares), which a thermal imager sees only as "hot spots". The vibration frequency spectra of the two hot spots are, however, quite different.

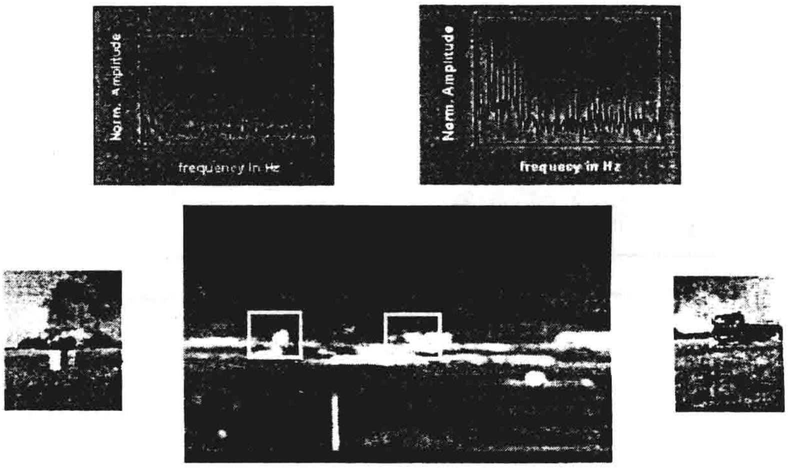


Fig. 5: Thermal image of heated metal box (left white square) and an idling truck (right white square) at a distance of 3.2 km, and visual close up pictures. The corresponding frequency spectra, measured with a CO2 laser radar, are shown above.

2.5 2D-vibration signatures

Since any surface vibration of the target produces a micro Doppler shift of the reflected laser beam, it is possible to place a vibrating target behind a partly obscuring screen (vegetation, smoke, camouflage net etc.) and still detect the target and (partly) reconstruct the geometrical shape of the target. Analogously to the well-known MTI (moving target indication) mode, this technique may thus be called VTI (vibration target indication).

Camouflage nets often have many large or small holes, which are known to enforce thermal convection and thus to assist the thermal camouflage behaviour. Laser beams can partly penetrate such nets and reach the target surface, but the fractional area of the openings is not very high. So the laser return contains a rather weak frequency modulated target return, plus a large but nearly unmodulated return from the net itself.

In a first step, we used standard frequency demodulation algorithms which turned out to be quite ineffective in dealing with a dominating backscatter at the IF frequency and the small Doppler-shifted signal (co-channel interference with small-amplitude target vibrations). However, more sophisticated algorithms can yield better detection of the contributing modulation from the vibrating target.

Figure 6, top and bottom, shows samples of raw data of a small civil truck, bare and camouflaged, respectively. Data were recorded using the CO2 laser radar at a resolution of 70 x 40 pixels.

A further 2D-vibration image (Fig. 7) shows a truck with a main vibration frequency of 32.5 Hz (idling) under strong turbulence condition ($C_n^2 \approx 10^{-13}\ m^{-2/3}$), recorded by the 10.6 μm laser vibration sensor. The number of pixels was 145x67 at a range of 300 m.

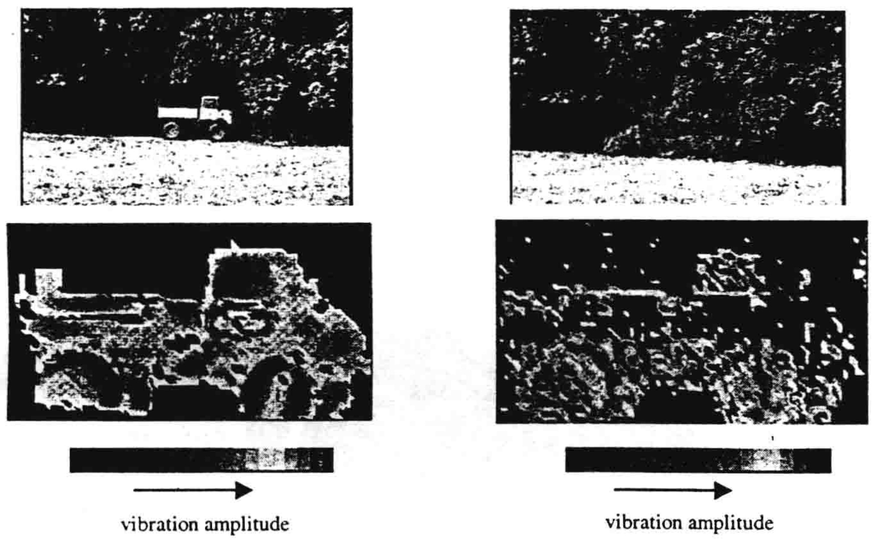


Fig. 6: Target (UNIMOG) with and without camouflage net along with the visual image.

Fig. 7: 2D-vibration image of a truck with a main vibration frequency of 32.5 Hz, recorded by the 10.6 μm laser vibration sensor under strong turbulence condition ($C_n^2 \approx 10^{-13}\ m^{-2/3}$): Engine idling, 145x67 pixels, range: 300m).

3. SHORT RANGE APPLICATION

3.1 Investigations and tests of automobile components

For short range applications (up to few meters distance) laser vibrometry is used for investigating and testing of all kind of mechanical structures with respect to their vibration characteristics. Selected automotive applications are:

- measurements of panel vibrations
- vibration testing of braking systems
- vibration testing on rotating systems
- scanning vibrometry for engine measurements