# Optical detection of honeybees by use of wing-beat modulation of scattered laser light for locating explosives and land mines

Kevin S. Repasky, Joseph A. Shaw, Ryan Scheppele, Christopher Melton,
John L. Carsten, and Lee H. Spangler

An instrument is demonstrated that can be used for optical detection of honeybees in a cluttered environment. The instrument uses a continuous-wave diode laser with a center wavelength of 808 nm and an output power of 28 mW as the laser transmitter source. Light scattered from moving honeybee wings will produce an intensity-modulated signal at a characteristic wing-beat frequency (170–270 Hz) that can be used to detect the honeybees against a cluttered background. The optical detection of honeybees has application in the biological detection of land mines and explosives, as was recently demonstrated. © 2006 Optical Society of America

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## 1. Introduction

Antipersonnel land mines kill approximately 15,000–20,000 people each year in roughly 90 countries.[1] Current detection methods for land mines include sweeping hand-held metal detectors over suspected minefields.[1] However, this method results in high false-alarm rates because of its inability to differentiate between land mines and other metallic objects and to detect plastic and plasticlike materials also used in land mines.

Active research in land mine detection includes electromagnetic induction, infrared and hyperspectral imaging, electrical impedance tomography, ground-penetrating radar, electrochemical methods, and biological methods.[1] The most common type of biological detection uses a trained dog and a handler. The dog is trained to detect the odor associated with the explosive contained in the land mine and then to alert the handler. To accomplish this, the team must work in the minefield, placing both the dog and handler at risk. A recently demonstrated biological detection technique[2–5] uses honeybees to locate buried land mines and explosives through the honeybees' sense of smell and their natural foraging behavior. Honeybee conditioning is accomplished by the addition of trace amounts of the major chemical components of the explosive into a feeder. The honeybees are thus conditioned to associate the chemical smell with food, and, when the honeybees are released over a minefield, they will pause over the land mines as they forage for food. A series of experiments in 2001 and 2002 demonstrated that trained honeybees were able to detect vapor levels higher than 50 parts per trillion (parts in $10^{12}$) (pptr) of 2,4 dinitrotoulene (2,4-DNT) mixed in sand.[4]

The demonstrated ability of honeybees to detect explosives has led to a need for methods to remotely detect the presence and dwell time of honeybees in flight. In 2002, a team from Sandia National Laboratory demonstrated the ability to detect honeybees at a distance of 1 km by using a direct-detection lidar instrument.[6] The lidar instrument was aimed directly over a beehive where there was a high density of bees. However, this system was not tested with low honeybee density away from the beehive. In 2003, an experiment was performed with scanning direct-detection lidar and honeybees at a land mine test

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K. S. Repasky (repasky@ece.montana.edu), J. A. Shaw, R. Scheppele, and C. Melton are with the Electrical and Computer Engineering Department, Cobleigh 610, Montana State University, Bozeman, Montana 59717. J. L. Carsten is with the Department of Physics, EPS 264, Montana State University, Bozeman, Montana 59717. L. H. Spangler is with the Department of Chemistry, Gaines Hall 108, Montana State University, Bozeman, Montana 59717.

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facility at Fort Leonard Wood, Missouri.[7] This experiment demonstrated the feasibility of using honeybees to find the explosives and a lidar instrument to find the bees. However, the direct-detection lidar was unable to determine whether the backscattered signal resulted from a honeybee or vegetation.

In the direct-detection bee lidar experiments, it was observed that the lidar detected many more bees in copolarized light than in cross-polarized light.[7] Subsequent laboratory measurements demonstrated that laser light scattered from bee wings has a much lower depolarization ratio (2%–8%) than that for bee bodies (15%–30%). These two facts together suggest that a significant lidar backscatter signal from honeybees may arise from wing reflections. Therefore, one possible way to discriminate the return signal of a honeybee from that of vegetation and a cluttered background is to use the frequency-modulated signal resulting from light scattered from moving honeybee wings.[8–10] Insect detection and identification by use of modulated light have been investigated and reported in the literature. Reed *et al.*[8] used a stroboscope to study the wing-beat frequency as a way to identify insect species, and Unwin and Ellington[9] published a paper describing the photodetector and electronic circuit used to detect the wing-beat frequency of various insects.

In this paper we present a diode laser instrument capable of honeybee detection in a cluttered environment. A continuous-wave (cw) diode laser provides an output beam that illuminates a target. An illuminated honeybee's wings will scatter light back to the instrument with intensity modulation resulting from the wing motion. This modulated signal will be between 170 and 270 Hz, the characteristic wing-beat frequency of honeybees. This modulated signal can easily be discriminated from larger background signals that are not modulated.

This paper is organized as follows. A description of the instrument is given in Section 2. In Section 3, laboratory measurements are presented. Field measurements are shown in Section 4. In Section 5, a discussion of the results is presented. Finally, in Section 6 some brief concluding remarks are made.

## 2. Experimental Setup

A schematic of the optical layout of the diode laser system used to detect honeybees is shown in Fig. 1. A cw single-mode Fabry–Perot laser diode is used as the laser source for the instrument. The laser diode can provide up to 100 mW of optical power in cw operation at 808 nm with a horizontal polarization with an aspect ratio of approximately 3 to 1. A commercial current and temperature controller is used to operate the laser diode. The output light from the laser diode is collimated by an aspheric lens with a focal length of 4.5 mm and a numerical aperture of 0.55. An achromatic anamorphic prism pair is used to shape the output of the laser diode and collimating lens into a more circular beam. The light is next incident upon a 37 mm diameter diverging lens with a focal length of −50 mm. After the diverging lens, the horizontally polarized light passes through a polarizing beam-splitting cube and a quarter-wave plate, producing circularly polarized light that is collimated by a 150 mm diameter lens with a focal length of 450 mm that collimates the light producing the output of the instrument. The optical power of the instrument was set at 28 mW, well below the 100 mW maximum optical power of the diode laser. Output light scattered back to the receiver from objects in the field of view passes through a 150 mm diameter lens and through the quarter-wave plate to create vertically polarized light. The backscattered vertically polarized light is directed by the polarizing beam-splitting cube through a narrowband filter onto a photomultiplier tube (PMT). The narrowband filter has a 10 mm passband centered at 810 nm. The PMT is biased with a commercial high-voltage supply with a voltage of −600 V. The voltage output of the PMT is proportional to the optical power incident upon the PMT comprising backscattered laser light and background light.

The PMT voltage passes through an amplifier with a gain of 400, after which it is filtered by a four-pole Butterworth low-pass filter with a 3 dB cutoff frequency near 500 Hz to produce a band-limited signal. This filter was needed to eliminate aliasing effects during the subsequent signal processing.[11] After the amplifier and low-pass filter, the voltage signal could be studied with an oscilloscope, a rf spectrum analyzer, or an analog-to-digital (A/D) board and a computer.

An A/D board was used to sample the output voltage signal of the PMT with a sampling rate of 5000 samples/s. These samples were collected over a period ranging from several seconds to several minutes to create a digital time series of the detected light. A Fourier transform of the sampled signal was performed with MATLAB software to create a power spectrum as a function of time.

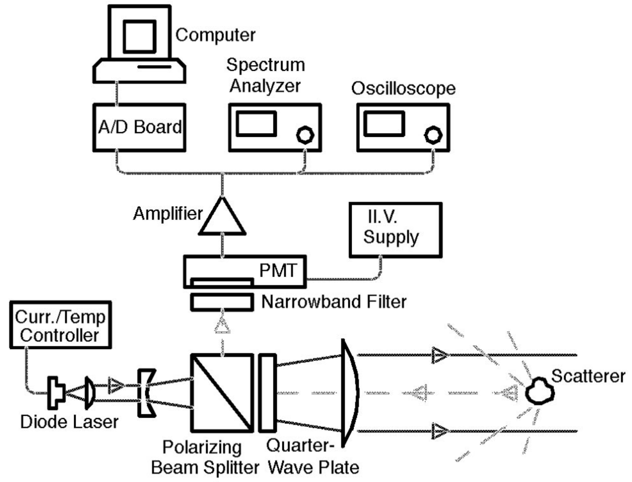

Fig. 1. Experimental setup used for remote detection of honeybees by means of wing-beat modulation of the return signal of a cw laser.

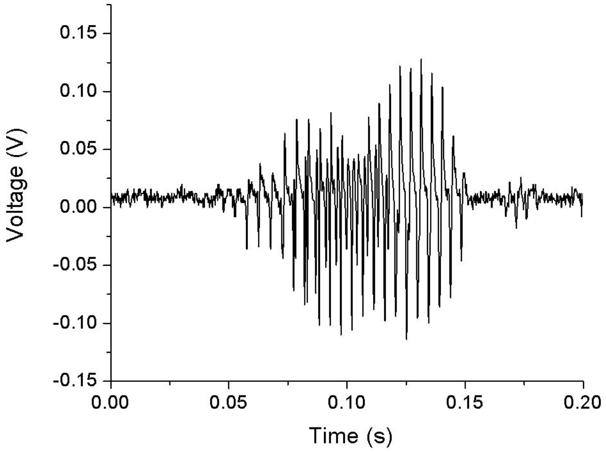

Fig. 2. Plot of voltage as a function of time of the return signal. The light scattered back to the detector from the moving bee wing causes a modulated return signal with a frequency specific to the honeybee. The modulated return signal can be used to pick out a honeybee as it flies through the laser beam against a cluttered background.

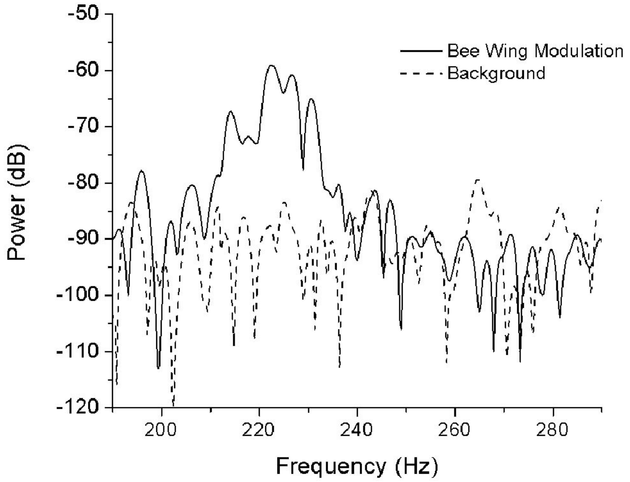

Fig. 3. Plot of the return signal as a function of frequency. The solid curve represents a modulated return signal from a honeybee's moving wing while the dashed curve represents the background return signal.

## 3. Laboratory Experiments

The instrument shown in Fig. 1, which is contained on a 60 cm × 60 cm optical breadboard, was initially tested in a laboratory setting. A small glass jar was placed approximately 4 m away from the instrument. The jar provided backscattered light that was easily seen by the dc-coupled oscilloscope. The coupling of the oscilloscope was changed from dc coupling to ac coupling, and a live honeybee was placed in the jar. A plot of the ac-coupled voltage as a function of time is shown in Fig. 2. The honeybee began flapping its wings from between 50 and 150 ms and stopped. The light scattered from the bee's moving wings produced a modulated signal at the PMT that is easily seen in Fig. 2 even though a greater amount of light is scattered by the jar.

A plot of the PMT signal power as a function of frequency is shown in Fig. 3, again measured with a honeybee placed in a jar approximately 4 m away from the instrument. The solid curve represents the return signal modulated by bee wing flapping, whereas the dashed curve represents the return signal when the bee stopped flapping its wings. The signal from the wing-beat-modulated scattered light produces a modulated signal near 200 Hz. The frequency spectra of the modulated return signal varies as the environmental conditions and the honeybee's activity levels change. However, measurements we performed showed the modulated return signal from the bee wings to be in the range of 170–270 Hz.

## 4. Field Measurements

The instrument was operated in the field in the summer of 2004, and measurements were made of honeybees flying into and out of a bee hive. The instrument was placed 20 m away from a beehive, as shown in Fig. 4. A portable generator was used to provide the electrical power for the instrument. A white wooden beehive and background vegetation, clearly visible in Fig. 4, would make direct-detection measurements impossible. During the field tests, the output of the PMT was sent to a preamplifier and a band-limiting filter. A computer was used to record the PMT signal as a function of time. After data were collected, a MATLAB program was used to compute a discrete-time Fourier transform of the signal. A plot of the power spectrum as a function of time is shown in Fig. 5. Time is plotted along the $x$ axis and frequency along the $y$ axis, and the relative power at a particular frequency at a particular time is represented by the gray scale. These typical data show honeybees flying through the laser beam in the 4–9 s time window. The honeybee detection signal shows up at 170 Hz, along with the second harmonic near 340 Hz and the third harmonic near 510 Hz. Data shown in Fig. 5 were taken with the laser aimed at the white

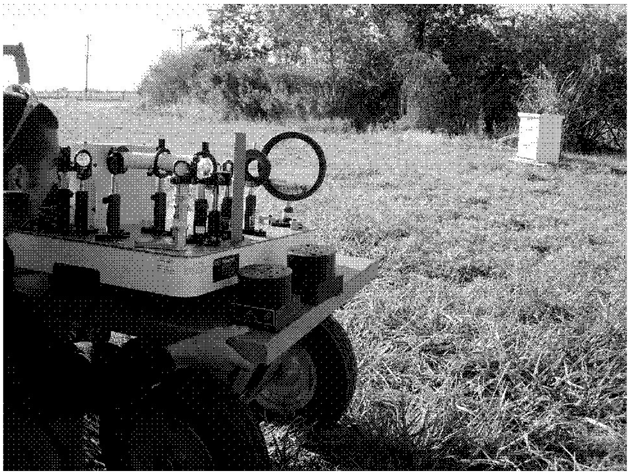

Fig. 4. Field measurements made with the instrument shown in Fig. 1. The white beehive surrounded by vegetation is visible in this photograph.

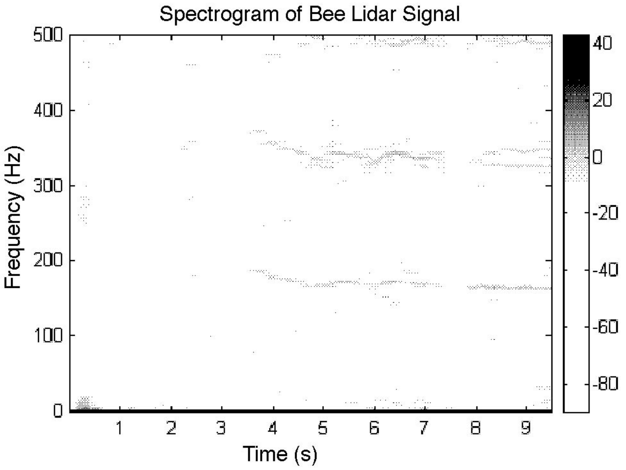

Fig. 5. Field detection of honeybees by the instrument shown in Fig. 1. Time is plotted along the $x$ axis, and frequency is plotted along the $y$ axis. A plot of the power in each frequency bin is represented by the gray scale. Honeybees flew into the laser beam during the 4–9 s time window of the plot. The honeybee detection shows up at a frequency near 170 Hz. The second harmonic of the wing modulation shows up near 340 Hz.

beehive, providing a high level of backscattered light. This light, however, is not modulated and provides a signal at the dc level. In this way, the return signal from the honeybees can be differentiated from the return signal from the background. Similar results were obtained when the laser beam was aimed at the background vegetation.

## 5. Discussion

The importance of using the modulated light reflected from moving honeybee wings is that a honeybee can be detected against a cluttered background. Initial tests of explosive detection by use of bees to detect the land mines and a scanning direct-detection lidar to detect the bees were carried out at Fort Leonard Wood, Missouri, in the summer of 2003.[7] This experiment successfully showed that bees can be trained to find the chemical vapor plume associated with buried explosives and lidar can be used to find the bees. However, the direct-detection lidar could not distinguish between light scattered from bees and light scattered from other sources such as vegetation. The instrument described in this paper presents a solution for detecting bees against a cluttered background.

The envisioned deployment of the instrument described in Fig. 1 is a checkpoint case for which ranging information is not important. As cars and trucks are stopped at a checkpoint, the instrument can be used to determine whether explosives are hidden in any of the vehicles from a safe stand-off distance. In this case, the infrared, lower-power, eye-safe operation of the instrument is a benefit. Other deployment cases include scanning modest areas for area reduction in humanitarian demining.

Land mine detection can benefit from the honeybee-specific signal of the modulated return signal but requires ranging information. The maximum frequency component of the modulated signals we look at, as in Fig. 5, is 500 Hz. If this frequency is the band-limited frequency, then the Nyquist frequency is 1 kHz.[11] Thus, if a pulsed laser was used in this instrument with a pulse repetition frequency of greater than 1 kHz, the modulated return signal that is due to the honeybee wing flapping can be uniquely determined. Ranging information is obtained by the time of flight of the return signal, as in standard lidar applications.

## 6. Conclusions

Land mine and explosive detection is a vexing humanitarian issue. One demonstrated solution to this problem is the use of conditioned honeybees[2–5] and lidar.[6,7] However, direct-detection lidar cannot determine whether the scattered signal results from honeybees or vegetation. The instrument presented in this paper uses the modulated return signal scattered from moving honeybee wings to produce a frequency-dependent signal that can be detected easily, even against a cluttered background that produces large dc return signals.

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