Tracking Honey Bees Using LIDAR (Light Detection and Ranging) Technology

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Sandia National Laboratories

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Abstract

The Defense Advanced Research Projects Agency (DARPA) has recognized that biological and chemical toxins are a real and growing threat to troops, civilians, and the ecosystem. The Explosives Components Facility at Sandia National Laboratories (SNL) has been working with the University of Montana, the Southwest Research Institute, and other agencies to evaluate the feasibility of directing honeybees to specific targets, and for environmental sampling of biological and chemical "agents of harm". Recent work has focused on finding and locating buried landmines and unexploded ordnance (UXO). Tests have demonstrated that honeybees can be trained to efficiently and accurately locate explosive signatures in the environment. However, it is difficult to visually track the bees and determine precisely where the targets are located. Video equipment is not practical due to its limited resolution and range. In addition, it is often unsafe to install such equipment in a field. A technology is needed to provide investigators with the standoff capability to track bees and accurately map the location of the suspected targets. This report documents Light Detection and Ranging (LIDAR) tests that were performed by SNL. These tests have shown that a LIDAR system can be used to track honeybees. The LIDAR system can provide both the range and coordinates of the target so that the location of buried munitions can be accurately mapped for subsequent removal.

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Introduction

Previous work has demonstrated [1] that using honeybees as sample collectors to transport contaminants to the hive for detection is a viable field analytical methodology for mapping the location of environmental contaminants, especially in areas where physical access is limited. A single colony of honeybees forages over large areas ($\approx 2 \times 10^6 \, m^2$), makes tens of thousands of foraging trips per day, and returns to a fixed location where sampling can be conveniently conducted. Honeybees are in direct contact with most environmental media (air, water, soil and vegetation) and, in the process, encounter contaminants in gaseous, liquid and particulate form. Multiple hives can be used to map the distribution and concentration of the target compounds.[2]

The Defense Advanced Research Projects Agency (DARPA) has recognized that biological and chemical toxins are a real and growing threat to troops, civilians, and the ecosystem. Sandia's Explosive Component Facility (ECF) has been involved in numerous projects aimed at detecting land mines, unexploded ordnance (UXO), and chemical warfare agents by characterizing and modeling their degradation in the environment. The ECF has been supporting the Controlled Biological and Biomimetric Systems (CBBS) program of DARPA, Defense Sciences Office, in evaluating the feasibility of using honeybees for environmental sampling of biological and chemical "agents of harm".

The DARPA work has focused on the detection of buried landmines and UXO. The honeybees are trained to associate the odor of TNT and DNT, which are typical energetic materials associated with buried mines and UXO with a food source. Honeybees rapidly search a large area to locate these odors. Tests to evaluate the performance of bees using prepared targets have relied on video cameras. However, a technology that would provide deminers with a standoff observation system is needed before the bees can be used to search a live minefield. Video cameras and other visual methods such as manual telescopic observation do not provide the range or accuracy needed to definitively locate the buried munitions.

LIDAR (Light Detection and Ranging) was investigated to assess the feasibility of using this technology for tracking bees. LIDAR is a remote sensing technique that uses laser light in much the same way that sonar uses sound, or radar uses radio waves. Laser light pulses are transmitted over the area where bees are trained to fly to a specific target. Some of the laser light that strikes the bees is scattered back to a detector collocated with the laser. The time between the outgoing laser pulse and the return signal is used to measure the distance from the bees to the LIDAR. By using a narrow laser beam and scanning this beam over time, one can produce a map of the location of the bees (and other objects that scatter light). The LIDAR system can provide both the range and coordinates of the target so that the location of buried munitions can be accurately mapped.

Instrumentation

A typical LIDAR system consists of a pulsed laser transmitter and a receiver telescope and detector system(s) as shown in Figure 1. In operation, a short pulse of laser light (typically ~10 ns long) is transmitted through the air. As this laser pulse propagates, it encounters air molecules, aerosols, dust particles, and other objects that scatter light. Some of the laser light is scattered back towards the LIDAR system and is collected by a telescope and subsequently detected and analyzed by instrumentation attached to this receiver telescope. (A thorough discussion of laser remote sensing systems may be found in reference 3.)

The information provided by a given LIDAR system depends on the laser used and on the type of detectors and instrumentation on its receiver. The simplest LIDAR detects elastically scattered light (i.e. light of the same wavelength as the laser) using a photomultiplier tube (PMT) and is able to produce a record of the intensity of the scattering signal versus time, much like the signal produced by a radar or sonar system. If the laser beam encounters a hard object, a cloud of dust or aerosols, or a swarm of bees, a larger-than-normal scattering signal is produced. The distance from the scattering objects to the LIDAR can be calculated by measuring the time-of-flight of the laser pulse and using the relation $R = \dfrac{c\Delta t}{2}$, where R is the range to the scattering object, Δt is the round-trip time of flight, and c is the speed of light. The main limitation of the simple backscatter LIDAR is that it gives little or no information about *what* scattered the light back to the receiver. The implication of this fact for our experiment is that it may be difficult or impossible to distinguish light scattered by bushes or trees by light scattered by a swarm of bees.
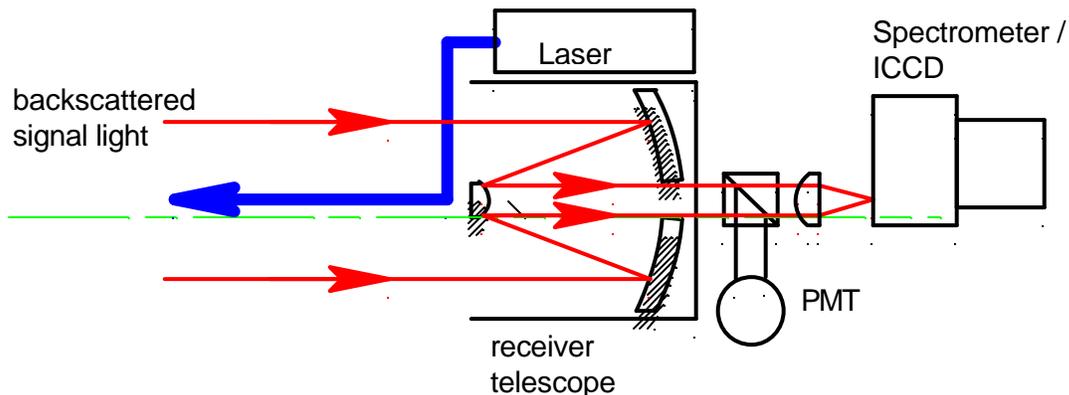

Figure 1: Schematic of LIDAR system.

Some LIDAR systems use spectral information from the backscattered light in order to help identify the source of the scattering. One such system uses laser

induced fluorescence (LIF) to distinguish one scattering material from another. In these systems, the laser wavelength is usually chosen to be in the ultraviolet where many materials absorb light and subsequently re-emit light at wavelengths longer than the excitation light. The backscattered fluorescent light is analyzed with a spectrometer and detector. The principal advantage of an LIF LIDAR system is that it can provide information to identify the origin of the scattering and this can be used to distinguish a signal of interest from backgrounds.

The honeybee tracking proof-of-concept experiments were conducted using an existing LIDAR system at the Area III sled track facility at Sandia National Laboratories in Albuquerque, NM. Although not optimized for tracking bees, this LIDAR system was already set up and conducting field test measurements at the sled track facility and we were able to collect proof-of-concept data to show that LIDAR systems can be used to track honeybees. Later in this report, we will discuss the design of a LIDAR system optimized for tracking honeybees.

The LIDAR system used for these experiments was designed primarily for ultraviolet laser induced fluorescence (UV LIF) measurements. It is equipped with a pulsed 355-nm laser and a 30-cm-diameter collection telescope in a coaxial configuration (as shown in Figure 1). Backscattered and fluorescent light collected by the telescope is detected by two main detector subsystems. The instrument collects a small fraction of the light (about 2%) and sends it to a photomultiplier tube (PMT) that records the elastic backscatter signal as a function of time (or range). The majority of the collected light is sent to a grating-based spectrometer with an intensified charged coupled device (ICCD) detector in its back focal plane to record time-gated fluorescence spectra.

The elastic backscatter signal recorded by the PMT originates from light scattered by aerosols, dust, and hard objects such as bushes, trees, and buildings. This is the signal we monitored for tracking honey bees. The PMT signal is digitized with a 100 MHz digitizer (10 ns sample spacing) to yield a 1.5-m spatial resolution. (The range resolution is given by $\Delta R = \dfrac{c\,\Delta t}{2}$ where c is the speed of light and Δt is the time interval of the measurement). The laser pulse length is also about 10 ns long, consistent with the 1.5-m resolution of the digitizer.

The fluorescence signal is a time- and wavelength-resolved signal that originates from laser-induced fluorescence by aerosols and other objects in the beam. By recording the wavelength-resolved fluorescence, it is possible to discriminate between various materials. Since the ICCD is time gated, the fluorescence signal can be localized in either space or time. This minimizes the amount of background fluorescence compared to the fluorescence signal from the ranges or targets of interest. In these experiments a fluorescence gate was used with a width of between 50 ns and 300 ns, corresponding to a range interval of 7.5 m (50-ns-wide gate) to 45 m (300-ns-wide gate). In each case, the gate is centered near the location between the bee hive and the target dish.

The laser used in this LIDAR is a flashlamp-pumped Q-switched Nd:YAG laser that operates at a pulse repetition rate of 30 Hz (Figure 1). It emits short pulses of 355-nm light with a pulse length of ~ 10 ns. The pulse energy can be varied between 1 mJ/pulse to 40 mJ/pulse. The laser beam has a divergence of ~500 µRad (full angle) yielding an illumination spot of about 0.7 m diameter at the experiment location. The field of view of the collection telescope is ~850 µRad. If there is some shot-to-shot pointing jitter in the laser beam, the backscattered light will still be collected.

Experimental Setup

For these proof-of-principle measurements, no attempt was made to scan the LIDAR to find bees. Instead, the LIDAR system, beehive, and target feeder dish were set-up in a near-linear arrangement, and the laser beam was aimed so that it propagated over the feeder dish (without hitting it) and near the entrance of the hive (also without hitting it). Figure 2 shows this near-linear arrangement schematically. Both elastic backscatter and laser induced fluorescence signals were recorded as a function of time in an effort to observe the bees as they traveled between the hive and the target dish. Observers near the hive and target dish noted the relative density of bees at various times and this information was correlated with the LIDAR data. The advantage of this setup was its simplicity: we did not have to differentiate between signals caused by the bees and signals from other scattering objects in the field of view. The disadvantage of this arrangement is that we could only observe bees over an extremely limited field of view: in this experiment, a cylinder approximately 0.5 m in diameter.

The hive was located 1360 m from the LIDAR and the target dish was located 1326 m from the LIDAR. For all the measurements, the target dish was approximately 24" above the ground. Some early measurements were made with the hive close to the ground, and other measurements made with the entrance to the hive about 24" above the ground. It was important to verify that the backscatter signal originated from bees and was not backscatter from the bee box or target dish. Figures 3 and 4 are photos showing the orientation of the beehive, feeder and LIDAR system. The target feeders are located on top a (blue) 55-gallon polyethylene barrel. For the experiments described in this report, the hive entrance was located at the same vertical distance as the feeder, but offset a slight amount so that the laser beam would not strike the beehive itself. As mentioned previously, the laser beam propagated directly over the target feeders (without striking the feeders).
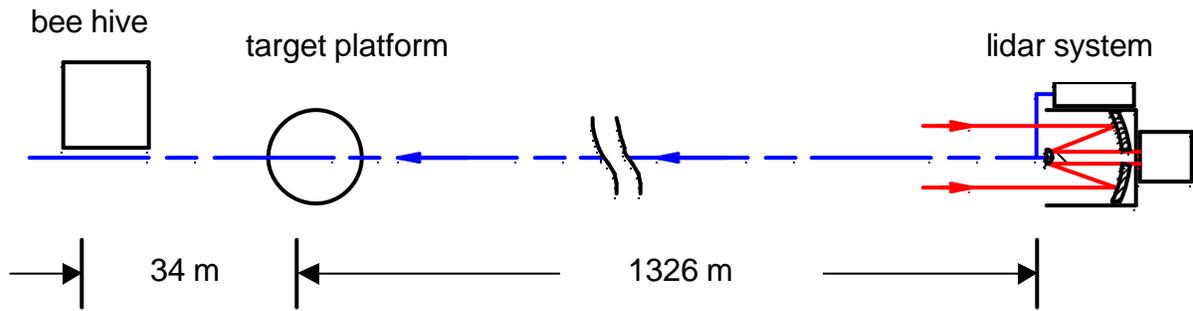
Figure 2: Diagram of experimental setup showing the near linear alignment of the LIDAR system, target platform, and bee hive.
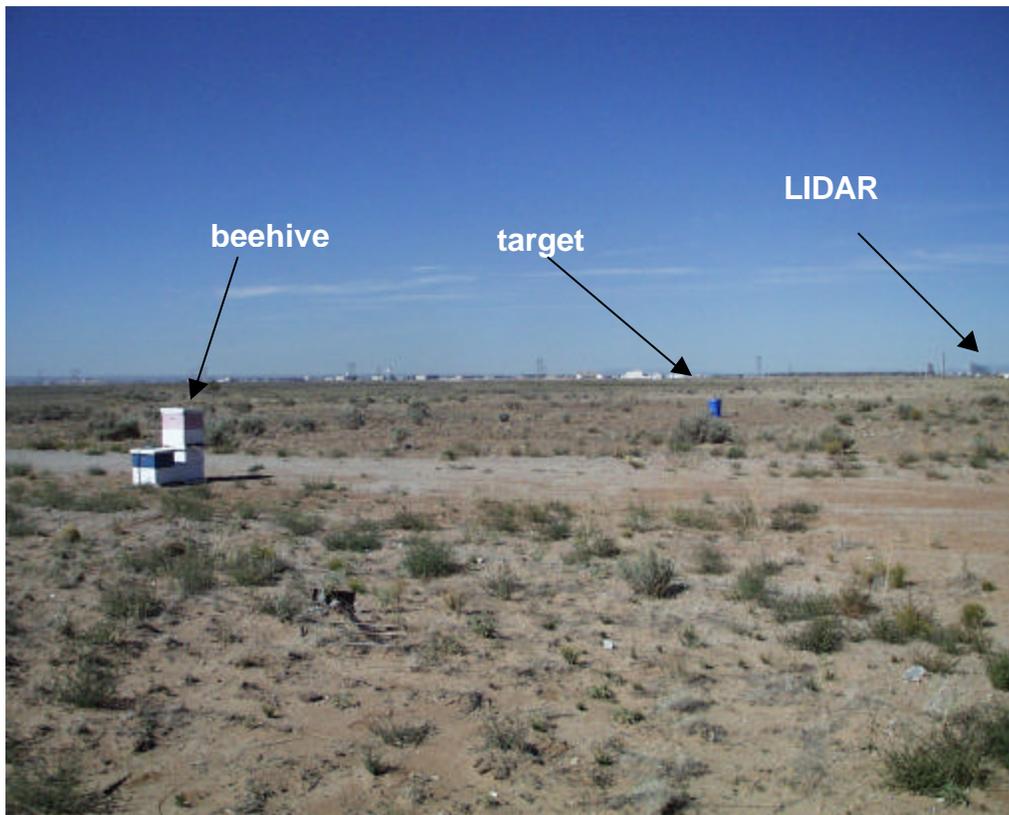

Figure 3: Photo showing height of targets and spacing between hive and target feeder.

Figure 4: **Photo that illustrates the near-linear relationship between the hive, target, and the LIDAR system, and also illustrates shows the distance between the LIDAR and the targets.**

In any LIDAR system, the backscatter return from bushes, trees, structures, or the ground itself can produce cluttered signals that may interfere with the interpretation of the signal from the material of interest. For these experiments the target was placed in an area relatively free from bushes, trees, or other scattering objects. This simplified the background. Also, the terrain between the LIDAR system and the hive was very level, and the LIDAR system was located on an elevated platform with the laser beam originating about 8 feet above the ground to avoid interference from the scrubby bushes characteristic of the New Mexico desert area.

Experimental Results

Figure 5 shows a typical elastic backscatter signal recorded during this experiment. Figure 5a shows the elastic backscatter signal from about 500 m to 2200 m from the LIDAR. For ~100 m, the signal is saturated due to the high gain setting of the PMT and the strong backscatter signal. Since this saturation occurs far from our range of interest, it does not affect the signals acquired near the target or hive. Figure 5a also shows the typical signal falloff due to increasing range, signals coming from near the target and hive locations, and signals coming from the ground and bushes several hundred meters behind the target and hive. The characteristic $1/R^2$ signal roll-off is also seen in Figure 5A. Sharp signals were observed due to scattering from bees, first from near the target, and next from near the hive. Signals from bushes and other ground clutter behind the experiment were also present. Figure 5b shows the elastic backscatter signal zoomed in near

the bee experiment and shows more clearly the well-defined spikes due to bees near the target dish and bees near the hive. Also shown is a quadratic fit to the baseline of the backscatter signal. Figure 5c shows the baseline-corrected backscatter signal that is used for further analysis of the data. The backscatter data must be baseline corrected to account for variations in the transmitted laser energy, shot-to-shot beam pointing variations, and temporal variations in the average aerosol concentration in the atmosphere, all of which affect the baseline. Once the data is baseline corrected, changes in the backscatter signal can be readily identified, indicating the presence of bees or other scattering objects in the field of view.
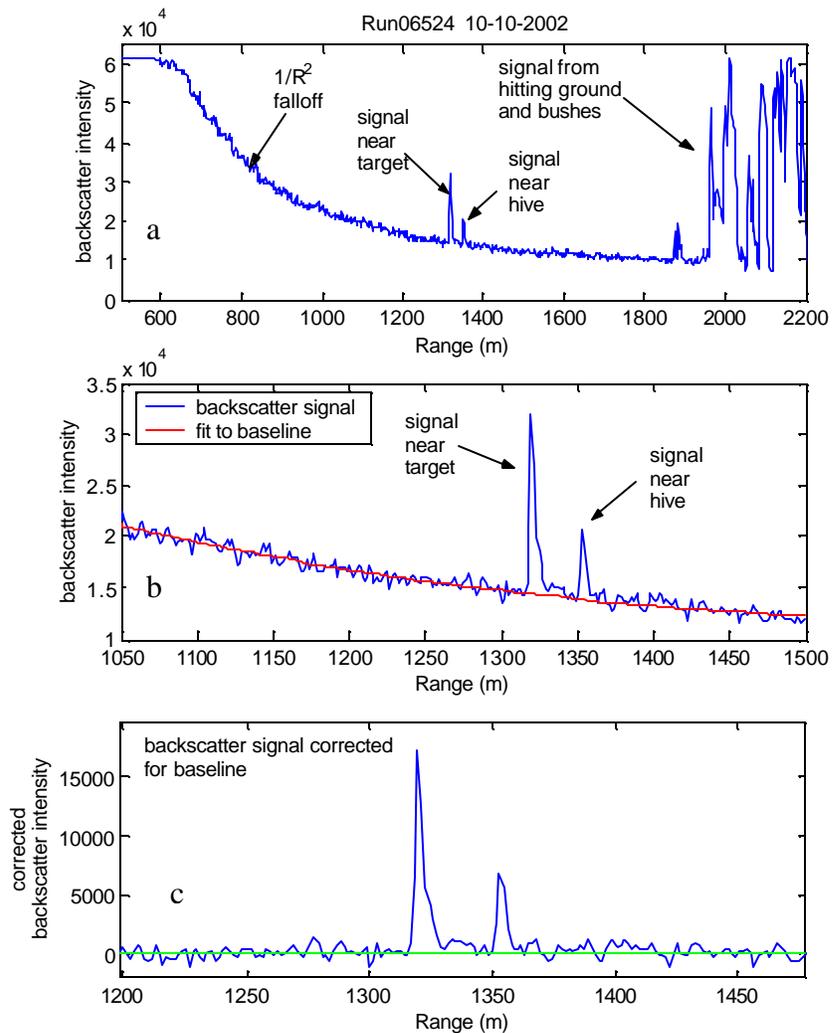

Figure 5: LIDAR backscatter signals.

All of the backscatter signals shown in this report are 15-pulse (0.5-second) accumulations of the signal. This signal accumulation was done both to improve signal-to-noise ratio and to keep the data files to reasonable sizes.

The alignment of the LIDAR laser beam with respect to the target feeder and bee hive was carefully arranged to avoid backscatter signal clutter from the bushes and other ground clutter that are abundant on our test range. Also, to ensure that we were observing backscatter from bees and not from the target dish or the bee hive, the laser beam was manually positioned using a piece of green fluorescent paper to visualize the beam. The 355-nm laser beam causes the green paper to fluoresce, and its fluorescence is bright enough to be observed even in daylight conditions. Using the green paper, the laser beam was aimed just to the east of the hive entrance (which was facing east), making sure that no part of the laser beam actually hit the hive or the target dish.

Data acquired during this experiment are shown in Figure 6. Figure 6a shows the mean backscatter signal from 1250 m to 1450 m. The first peak is from bees near the target dish and second peak is signal from near the hive. In order to provide an unambiguous signal from the bees, a frame of bees was removed from the hive and was shaken near the feeder location. The bees initially swarmed near the target feeder and then dispersed. Figure 6b shows the backscatter signal from the target dish area ($\pm$ 1.5 m) as a function of time. A large increase in the backscatter signal (above background) was observed from t = 0 to t = 50 seconds coming from the bees swarming near the target area. Observers near the target area corroborated the fact that after the bees were shaken from the frame, they swarmed around the target area and eventually dispersed, consistent with the signal shown here and its time history. Figure 6c shows the backscatter signal near the hive ($\pm$ 1.5 m) as a function of time. This signal is difficult to correlate with the presence of bees, and may be primarily due to the extreme edge of the laser beam hitting the hive itself.
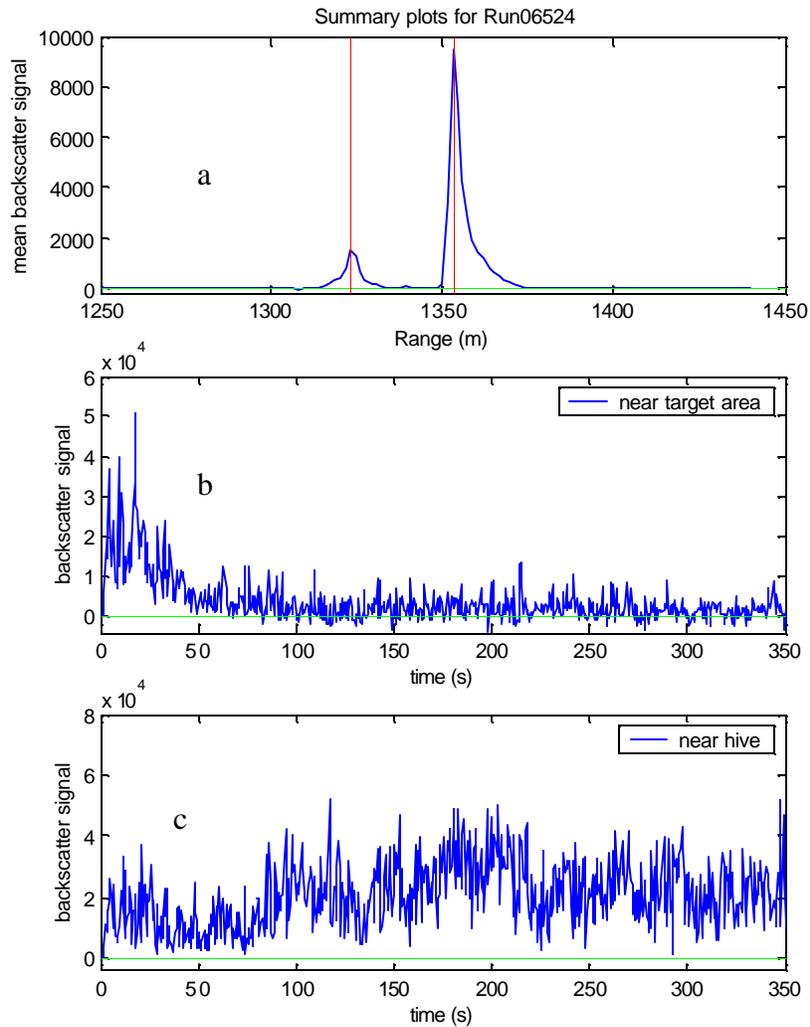
Figure 6: Summary of data from Run 06524.

Another frame of bees was shaken near the target dish area and the data for this experiment is shown in Figure 7. As in the previous experiment, the bees initially swarmed around the target area and eventually dispersed, consistent with the signal shown in Figure 7b. As in the previous data run, the backscatter signal from near the hive, shown in Figure 7c, is ambiguous at best – it is probably the result of scattering from the hive itself, despite efforts to avoid this. Although there may be some signal due to bees near the hive, the signal from the hive itself is too large, and the variation in this signal due to laser beam jitter makes separation of the bee signal from the background impossible.

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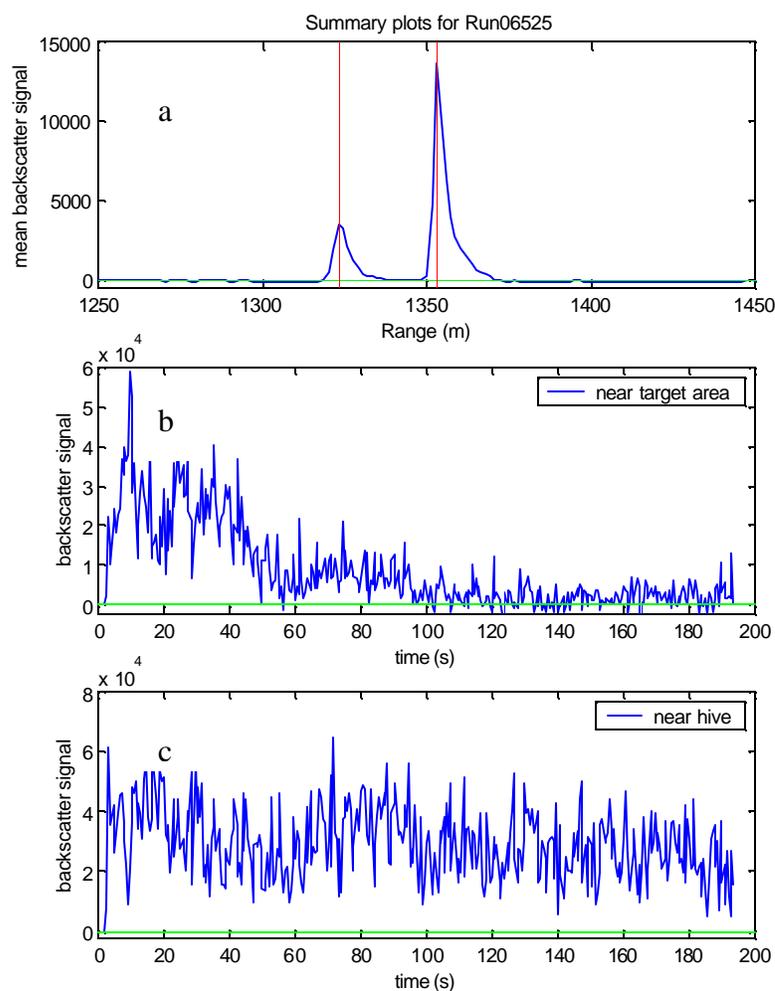
Figure 7 Summary of data from Run 06525.

In order to provide a baseline for the previous data sets, we recorded a data set in which few, if any, bees flew into the laser beam. Figure 8 summarizes this background data in the same format as the previous data. Figure 8b shows very little signal near the target area, and essentially sets the lower limit or noise floor of the previous data sets. Figure 8c shows that the signal near the hive is relatively large, even in the absence of bees. Along with other data and observations throughout the experiment, we believe that the signal near the hive is due largely to the fringes of the laser beam hitting the edge of the hive. Beam motion due to laser beam pointing jitter along with atmospheric beam steering is likely the major source of variation of this background signal.
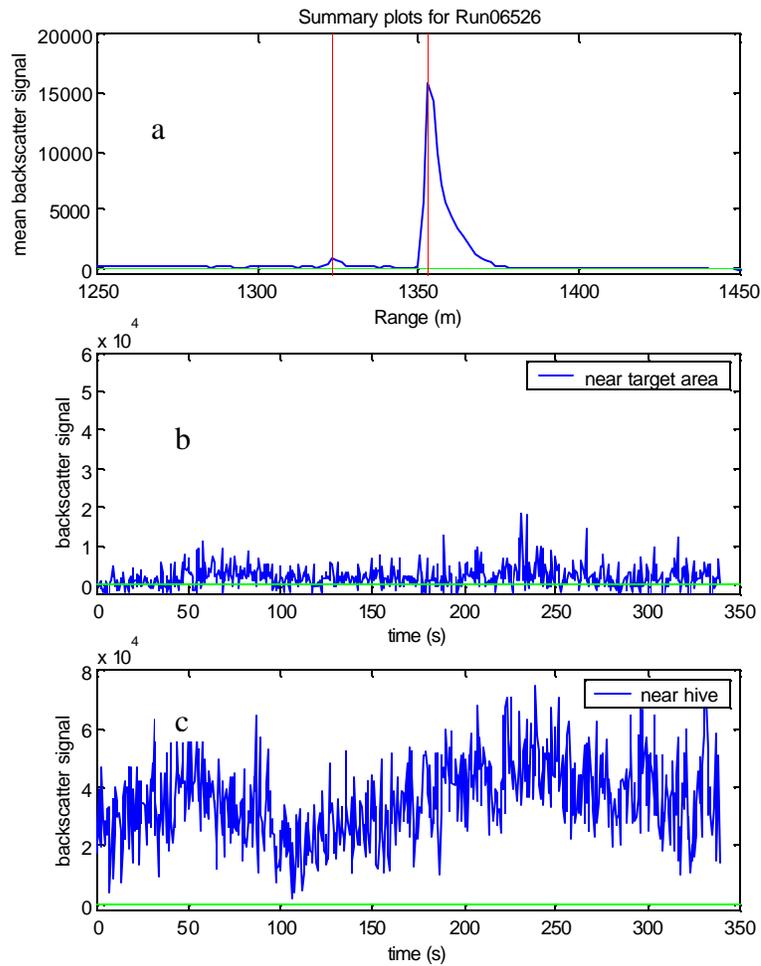
Figure 8 Summary of data from Run 06526.

From the data shown in Figures 6, 7, and 8, it is clear that we were able to observe backscatter signals from a swarm of bees near the target feeder. When the backscatter signal is plotted as a function of time, as in Figures 6B and 7B, a large increase in signal was observed at the same time that the bees swarmed near the feeder.

It is difficult to unambiguously detect bees near the hive with our current LIDAR system. This is due to the fact that the edges of the laser beam struck the side of the bee hive, causing a larger backscatter signal than any bees that may have been in the laser beam. Future experiments may be able to improve this by using a smaller diameter laser beam or by tagging the bees with a fluorescent dye and observing fluorescent emission instead of elastically scattered light.

Using the current LIDAR and experimental setup, we were not able to observe bees in transit between the target area and the hive. Bees were observed when they swarmed in appreciable numbers, primarily near the target feeder area. The main reason for this is that the LIDAR beam was pointed in a fixed direction, and the bees, in general, did not choose to fly from the feeder to the hive along this line-of-sight. As the field observers noted, the bees tended to fly close to the ground when in transit, not at the ~24" level of the LIDAR beam. Also, since the laser beam diameter was about 18" (near the experiment), the bees would have to fly somewhere inside an 18" diameter region from the feeder to the hive in order to be detected by the LIDAR. Future experiments could avoid this limitation by scanning the laser beam to look for bees, albeit with the added complexity of having to differentiate between signals coming from bees and signals coming from bushes and other fixed scattering objects.

Although we collected spectrally dispersed LIF data throughout this experiment, the spectra were close to background level. Either the bees do not fluoresce naturally with 355-nm excitation or there were too few bees in our laser beam to yield an appreciable signal. In future experiments, it may be useful to tag the bees with a fluorescent dye so that their LIF signal is relatively strong and spectrally unambiguous. This would allow reliable discrimination of the bees from background, even if the laser beam strikes objects such as trees, bushes, or the bee hive structure itself.

Conclusions

These proof-of-concept tests have demonstrated that:

- An elastic backscatter LIDAR system can be used to detect swarms of honeybees at a distance of > 1300 meters from the receiver. A LIDAR system optimized for collecting backscatter signal from bees could have even better sensitivity than demonstrated in these experiments.

- Backscatter signals from bushes, trees, and ground clutter can interfere with the detection of bees and the discrimination of bees from other scattering objects in the field. In the current experiments, careful positioning of the LIDAR beam was critical to obtain unambiguous elastic backscatter signals from the bees. In any realistic implementation of LIDAR technology for tracking bees, background clutter will be unavoidable since bees tend to fly near the ground and forage on plants near the ground. Some additional means of differentiating the backscatter from the bees and the backscatter from background clutter will be needed in future experiments.

Based on the results of these experiments, we are encouraged that LIDAR systems may be useful in tracking bees, and offer the following suggestions for future follow-on experiments:

1. An experiment should be designed to study whether tagging bees with a fluorescent dye could increase the sensitivity of the technique and aid in discriminating between bees and background clutter. The dye should be chosen to fluoresce in the orange part of the spectrum to avoid interference with chlorophyll fluorescence. The backscatter PMT could be fitted with a bandpass filter to eliminate elastically scattered light and pass fluorescence from the dye. Thus, the backscatter signal vs. time (range) would be only sensitive to bees (or objects dusted with the fluorescent dye).

2. A LIDAR system optimized for tracking bees could be designed that would provide better results than those obtained with the non-optimal system used for this demonstration. In addition, an optimized system might be designed to be more compact and more easily field deployable. In an optimized LIDAR the design might use:
   - a small (~4" diameter) receiver telescope
   - a miniature solid-state laser source (diode-pumped system)
   - a scanning system
   - two PMT channels: one for elastic backscatter and one for laser induced fluorescence
   - software to automatically differentiate bees from the cluttered background

3. Since bees tend to fly (and swarm) near the ground, for a practical system, it may be necessary to elevate the LIDAR and look down on the area to be monitored. In this case, a miniature scanning LIDAR system detecting laser induced fluorescence (from a dye tag) could be deployed on a tower or from a cherry picker. In this scenario, tagging the bees with a fluorescent dye would be essential to allow discrimination of the bees from the background. A 2-D scanning system would be needed in order to raster scan the LIDAR beam over the region of interest.

4. In the near term, it may be possible to conduct further experiments using a new, more portable scanning LIDAR now under development at Sandia. This is a smaller LIDAR with an enhanced elastic backscatter channel.

References

1. National Research Council, Animals as Sentinels of Environmental Health Hazards. National Academy Press. **1991.**

2. Bromenshenk, J.J.; Smith, G.C.; Seccomb, R.A.; King, B.E.; Alnasser, G.H.; Henderson, C.B.; Wrobel, C.L.; New and Improved Methods for Monitoring Air Quality and Terrestrial Environment. Annual Report. **1997.** US Army Center for Environmental Health Research, Ft Detrick, MD. Usa Contract DMA 17-95-C-5072.

3. Measures, R. M., Laser Remote Sensing: Fundamentals and Applications, Kreiger Publishing Co., Malabar, FL, 1992. ISBN:0-89464-619-2

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