

# Laser-induced Acoustic Detection of Shallow-buried Objects

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## Abstract

A Laser-induced acoustic technique has been demonstrated for the potential application of underground object detection. The high acoustic impedance mismatch between granular soil and buried mine (usually landmines are made from plastic, rubber and metal) gives good contrast for detection. We obtained 3-D images of underground objects by scanning a pulsed laser across the surface of the ground and keeping the acoustic detector at relatively fixed position with respect to the laser spots. A signal processing method is introduced by using de-convolution filter. When a laser pulse impinges on the surface of ground, a laser-induced acoustic pulse will be excited after a sudden increase of surface temperature followed a sudden volume expansion. We used a laser vibrometer as acoustic receiver and found that the acoustic pulse width depends on laser pulse width. Using 100ns CO<sub>2</sub> laser, we obtained 4~5 $\mu$ s acoustic sound pulses.

Key words: Demining, laser induced acoustic detection, landmine detection, photoacoustic

## 1. Introduction

The standard inductive detector works very well with metallic mines. Unfortunately, more and more landmines are being made from plastic, rubber, or other kinds of non-metallic materials. The new challenge for de-mining research is detection of non-metallic landmines and decreasing the false alarm rates of low-metal-content landmines.

Several new techniques show their future potential for de-mining, including Ground Penetrating Radar (GPR), Microwave Enhanced Infrared Thermography (MEIT) and Laser-induced Acoustic Detection. Although GPR shows good results for imaging buried mines or other underground objects, there is a blind region for shallow buried mines that is caused by strong reflections at the ground surface. MEIT and Laser-induced Acoustic Detection can compensate to solve this problem. MEIT shows the differences of dielectric and thermal properties while the laser-induced acoustic detection exposes differences of the acoustic impedance between buried objects and granular soil. Because of the underground clutter, surface roughness and vegetation, detection of underground objects is very complicated. Thus, there is no "silver bullet" approach for this problem. We believe that the landmine detection strategy should be an integrated approach of several techniques.

Laser-induced acoustic detection is a new de-mining technique based on the photo-acoustic effect. When a light pulse impinges on the surface of a medium, the quick expansion of the medium caused by the sudden temperature increase produces a shock wave in the bulk of this medium. This phenomenon has been observed in the 19<sup>th</sup> Century and analyzed in the early 1960s. The basic idea of laser-acoustic mine detection is to ping across the surface by laser pulses and detect the sound echoes. Just like tapping a wall or floor to find studs or holes, the sound echoes will help us locate and image buried landmines. The time-delay of acoustic echo contains the depth information of underground objects. Thus, a 2-D scan on the surface gives a 3-D image of underground objects.

Using laser induced acoustic waves in mine detection has several advantages. First of all, compared with other traditional methods, there is no contact with the ground during the excitation of the acoustic wave. This minimizes the safety concerns in mine detection. Secondly, the acoustic pulse width is very short, so we can obtain good depth

resolution. In addition, the flexibility of the scanning laser beam makes it easy to scan across the ground and get a 3D underground image.

In our previous work, we used a LSI PRF-150 pulsed CO<sub>2</sub> laser to generate acoustic pulses. The wavelength of the laser is 10.6 $\mu$ m and its pulse width is about 100ns, with the energy per pulse being 150mJ. Mine simulants were buried into a 30cm by 60cm sandbox. Several acoustic receivers were in use, including two audio microphones, and two PZT transducers with 30kHz center frequency and narrow bandwidth. The acoustic signal can be detected both in air and in the bulk of the sand. The signal is then digitized by a HP-54615b Oscilloscope and finally saved to file on a computer.

From the acoustic echoes, we can obtain the outlines of underground objects. This shape information gives us a possibility to distinguish the clutter, such as rocks, from real mines.

## 2. Experiment

### 2.1 Underground imaging

In order to obtain underground images, we need to scan across the surface of ground. There are two different ways to collect acoustic echo signals. One is by burying the detector under the surface of ground, shown in Figure 1. When the laser spot scans across the surface, the distance from acoustic source to receiver is changing from point to point. Thus, the acoustic echo from mine will have different time delays at different positions. These differences will distort the shape of underground objects and increase the difficulties for signal processing.

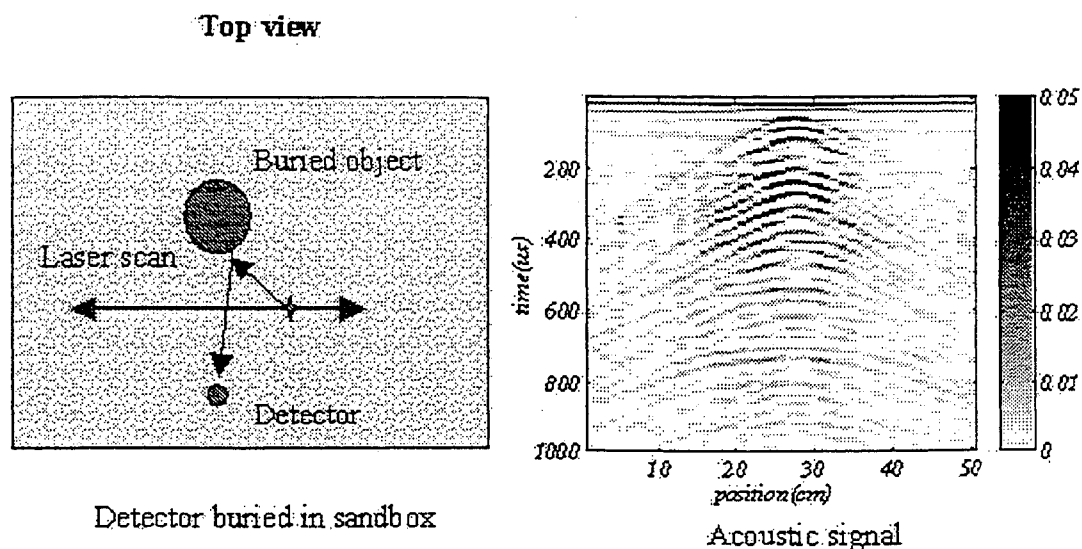


Figure 1. Signal for buried detector in sandbox.

The other way is to put the acoustic detector over the surface of ground, and make the relative position of laser spot and detector fixed, as shown in Figure 2. The echo signals have equal time delay if the reflecting surface is flat. This method is more useful than the first one. It is a safer method because there is no ground contact. Digging a hole and burying a detector are not acceptable in landmine detection. Another important point is the delay time related to depth. The distance between the laser spot and the detector is fixed during the scan so that the image we obtain will be a vertical slice of the underground world without distortion. It also will be much easier for signal processing.

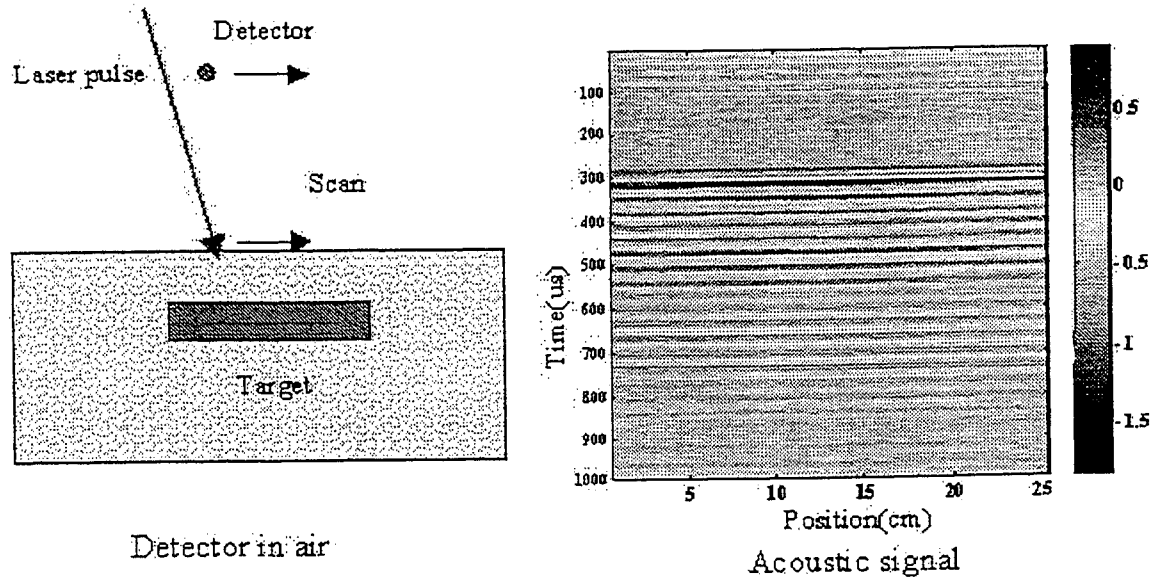


Figure 2. Detector is put over the surface.

From Figure 2, we can see the strong acoustic signals from the surface of the sand. Because of the difficulty in coupling the acoustic wave from sand to air, the sound echo signal reflected from targets is very weak. The echo signal is submerged in the ringing of the detector. A simple way to remove the influence of detector ringing and background noise is subtraction. Unfortunately, the surface of the ground is usually not perfectly flat, the amplitude of the photo-acoustic signal is not constant. So, the subtraction method only works in very critical conditions.

In order to find a better image of underground objects, let's consider that the acoustic detector and preamplifier have an overall unknown impulse response  $h_d$ . The detected signal  $y(t, x)$  should be a convolution of acoustic signal  $s(t, x)$  and this unknown impulse response.

$$y(t, x) = x(t, x) \otimes h_d(t) + n(t) \quad (1)$$

where  $n(t)$  is noise. In frequency domain, equation (1) has the form:

$$Y(\omega, x) = S(\omega, x) \cdot H(\omega) + N(\omega) \quad (2)$$

We assume that the system function is independent of the laser spot position, thus  $H(\omega) = H(\omega, x_0)$ . Consider that the acoustic signal is excited by a pulsed laser with a pulse-width of 100ns, we believe the acoustic pulse should also be a narrow pulse. Based on these two assumptions, without mine, the acoustic signal should be a single narrow pulse without other reflections (We substitute an impulse for the narrow pulse). Thus, in frequency domain,  $S(\omega, x_0) \approx 1$ . If we neglect noise, an estimation of the system function could be  $H(\omega) \approx Y(\omega, x_0)$ .

From the above analysis, we can estimate the acoustic signal  $\hat{S}(\omega, x)$  shown as:

$$\hat{S}(\omega, x) = Y(\omega, x) \cdot F(\omega) = Y(\omega, x) \cdot \frac{Y^*(\omega, x_0)}{|Y(\omega, x_0)|^2 + \varepsilon} \quad (3)$$

where  $F(\omega)$  is the filter function needed to recover the acoustic signal,  $\epsilon$  is a very small number which shows the noise level and helps to avoid the singularity in the frequency domain when  $Y(\omega, x_0) = 0$ . The purpose of equation (3) is to eliminate the influence of detector and preamplifier (especially the ringing of detector and noise), so we call it a de-convolution filter.

After we process the received signal using de-convolution filter, we can get the image of underground objects. Figure 3 shows an experiment we performed.

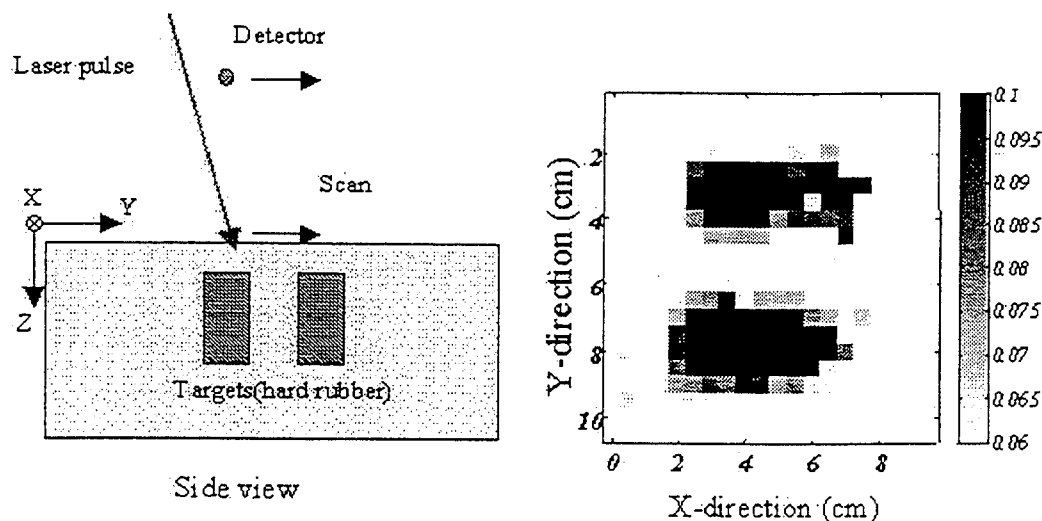


Figure 3. Experimental setup and the image of buried targets after de-convolution process.

In this experiment, two identical pieces of hard rubber have been buried 0.5cm deep in a sandbox. The distance between these two pieces is about 2cm. We used LSI PRF-150 CO<sub>2</sub> laser (150mJ/pulse, 100ns pulse-width, 10.6 $\mu$ s) to create acoustic signals. The detector was a transducer (30kHz center frequency, narrow bandwidth). A 21 by 21 point 2-D scan across 10cm by 10cm area was made on the surface of sand. We processed the signal using the de-convolution filter. Because the time delay corresponds to depth, we obtained a 3-D image of the underground objects. Shown as Figure 3, a particular time-slice clearly shows that two underground objects are separated about 2cm.

## 2.2 Acoustic pulses

Although there is no doubt that the laser-induced acoustic detection can provide 3-D shape information of underground objects, a lot of questions remain about the mechanism of photo-acoustic effect: How large is the temperature change at the surface? What is the shape of the acoustic pulse? What are the speed of sound, attenuation coefficient and so on. These are important for future research of acoustic mine detection.

We performed an experiment to explore the characteristics of laser-induced acoustic waves in an attempt to understand the influence of laser source in this procedure, such as laser energy density, laser pulse width and the wavelength of laser pulses. Another main purpose is to measure the acoustic pulse shape, then decide what kind of detector should be used. In this experiment, we used three different lasers as the sources of laser-induced acoustic waves, and two acoustic receivers to detect the acoustic pulses. The lasers are PRF-150 CO<sub>2</sub> laser (150mJ/pulse, 100ns pulse width, 10.6 $\mu$ m), Shoebox CO<sub>2</sub> laser (18mJ/pulse, 100ns pulse width, 10.6 $\mu$ m) and BMI Tripled

Nd:YAG laser (5mJ/pulse, 6ns pulse width, 355nm). The first two CO<sub>2</sub> lasers are produced by Laser Science Inc. with the wave length of 10.6  $\mu$ m. The Nd:YAG laser is produced by BMI division of Thomson Components and Tube Corp. The wavelength is 355nm. Figure 4 shows the pictures of a LSI shoe box laser and a BMI laser vibrometer. The detectors we used are B&K hydrophone type 8103 (frequency range: 0.1Hz to 180kHz) and BMI laser Vibrometer (double Nd:YAG, 70Mhz Bragg cell, 4 Mhz bandwidth).

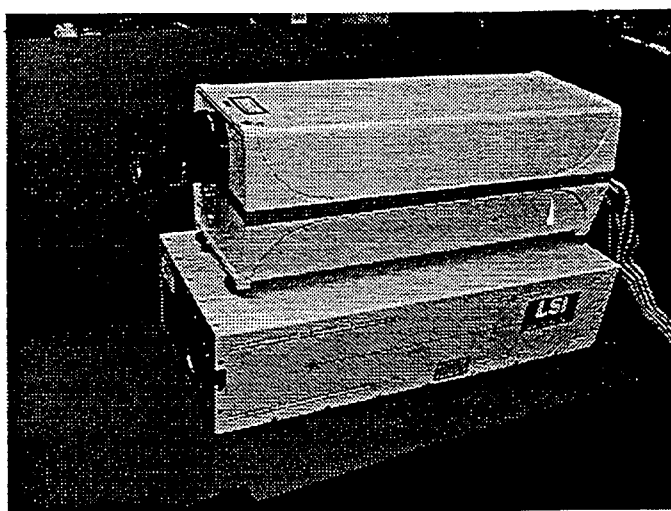


Figure 4. LSI shoebox CO<sub>2</sub> laser (bottom) and BMI laser vibrometer

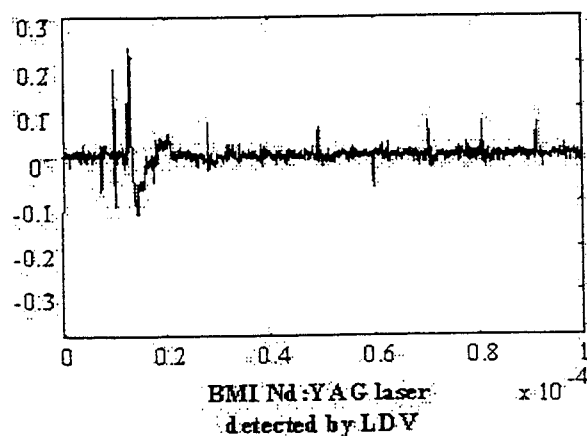
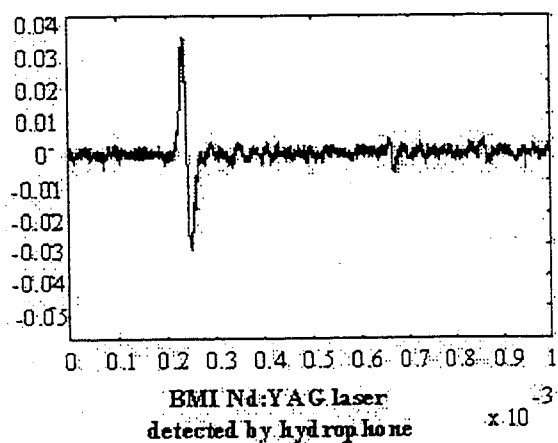
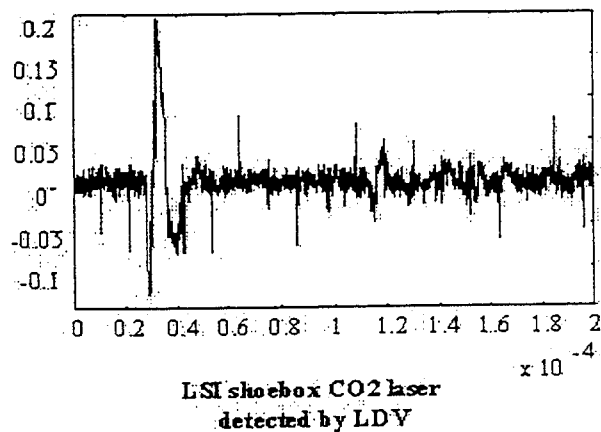
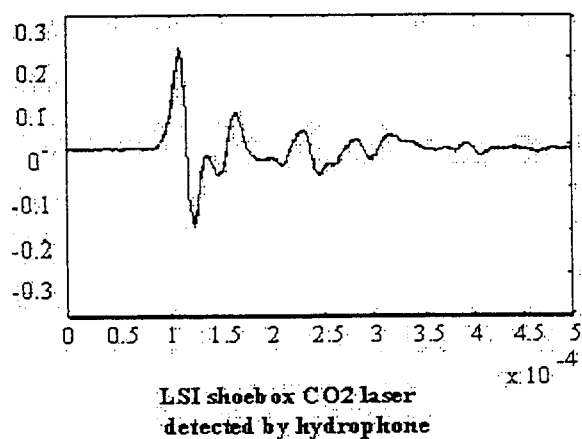


Figure 5. The acoustic pulse shape detected by hydrophone and laser Doppler vibrometer (LDV)

Apparently, the amplitude of the acoustic signal depends on the energy density of laser pulse. Both the shoebox CO<sub>2</sub> laser and Nd:YAG lasers need to be focused to generate acoustic wave. Qualitatively, tighter focusing yields a higher energy density, thus producing stronger signals. PRF-150 CO<sub>2</sub> laser has higher output energy per pulse than the other two lasers. It can excite acoustic wave without focusing. Some of the acoustic signals are shown in Figure 5. The acoustic signal is excited by the quick temperature rise and volume expansion. The amplitude of acoustic signal mostly depends on the laser energy density and the absorption of the laser light. Because the absorption is very strong at all the light frequencies, the generation of acoustic energy is efficient and the wavelength of laser won't make significant differences. Another interesting phenomenon is that the shorter pulse of laser excites shorter pulse width of the acoustic wave. 100ns CO<sub>2</sub> laser pulse induces 4~5 $\mu$ s acoustic pulse, 6ns tripled Nd:YAG laser pulse excites acoustic pulse with the pulse width less than 1  $\mu$ s. Because the bandwidth of laser vibrometer is as high as 4Mhz, we believe the signal we measured using laser vibrometer shows the real shape of acoustic pulse. The signal measured by B&K hydrophone is limited by the bandwidth of the detector itself.

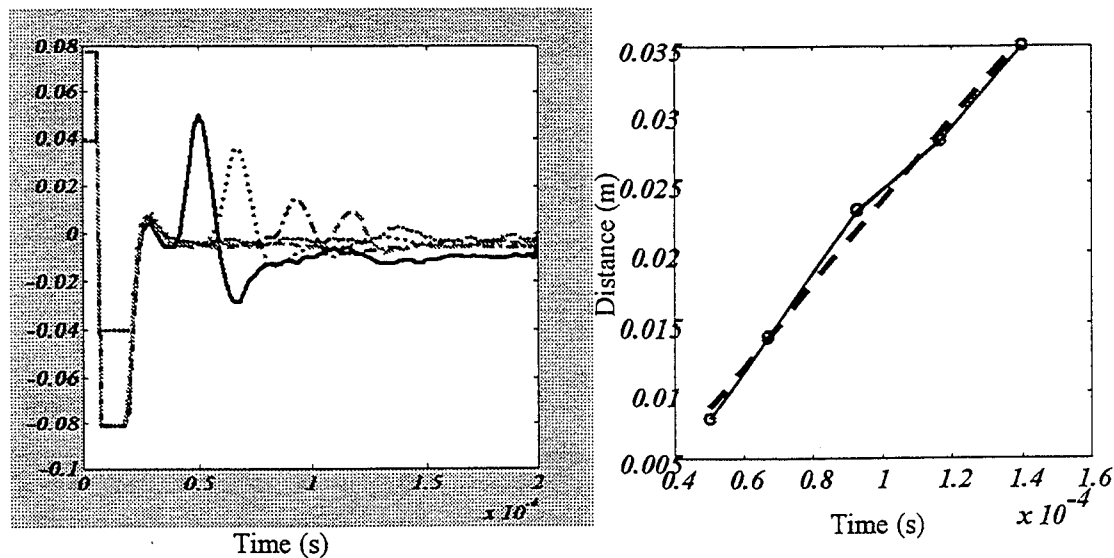


Figure 6. Propagation of acoustic wave in sand. The speed of sound in sand is about 280m/s, attenuation factor is about 85m<sup>-1</sup>.

In order to measure the velocity of sound in sand, we used PRF-150 CO<sub>2</sub> laser to excite acoustic wave in sandbox. We used B&K hydrophone type 8103 as detector. It was buried at different depth in the sandbox. We assumed that the system delay between the triggering of laser pulse and the generating of acoustic pulse is constant. Thus, by measuring the amplitude of acoustic signal and the propagation time at different depth, we can obtain information about attenuation factor and velocity of acoustic waves in sand. In this experiment, we buried the detector at different depths from 0.8cm to 4.5cm, shown as Figure 6. We found that the speed of sound in sand is about 280m/s. The attenuation factor is about 90m<sup>-1</sup>. The attenuation of acoustic wave in sand is very fast. This is the reason that laser-induced acoustic detection works only for shallow buried mines.

### 3. Conclusion

As shown in this paper, by applying a de-convolution filter, we can obtain the shapes of shallow buried objects from the data of laser-induced acoustic detection. This technique not only numerically decreases the false alarm rates of

low-metal-content landmines by providing shape information, but also gives a feasible solution for the detection of non-metallic mines.

Laser-induced acoustic signals can be detected by both conventional transducer and laser vibrometer. The latter one has a much higher frequency response, thus it can provide more frequency information about the acoustic pulse. A laser vibrometer probably is the best sensing device in mine detection. The whole detection procedure will be laser excited and laser detected, there is no surface contact in the detection. It is also not difficult to integrate these two optical systems such that the scanning of ground is made easier.

The amplitude of laser-induced acoustic pulse mostly depends on the energy density of laser pulse. We can focus the laser beam to generate much stronger acoustic pulses. The pulse width of acoustic signal somehow depends on the laser pulse width. 100ns CO<sub>2</sub> laser pulse excites 4~5us sound pulse, 6ns Nd:YAG laser pulse excites ~1us sound pulse.

Sand is not a good medium for acoustic wave. The attenuation factor is about 90m<sup>-1</sup>. Thus, the laser-induced acoustic detection can not work well for deeply buried objects.

PRF-150 CO<sub>2</sub> laser is strong enough to generate acoustic pulse in sand without focusing. It will cause easily audible sound if focused. Some interesting phenomena occur after focusing, such as explosion on the focus point and the generation of visible light. This will be the future work of laser-induced acoustic detection.

#### 4. Acknowledgement

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#### 5. References

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