**Program Final Report**
**PFR-2720**

# Photoacoustic Sensing of Explosives (PHASE)

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# Photoacoustic Sensing of Explosives (PHASE)

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## LONG-TERM GOALS

There is a worldwide threat from concealed explosives that target unsuspecting civilians, military personnel, and political officials. Detecting trace explosives residue on exposed surfaces is key to finding the concealed threat device and network source that constructs such devices. To this end, rapid, safe, covert, standoff systems are urgently needed to detect explosive trace.

Long-term goals of the ONR – PHASE program conducted by MIT Lincoln Laboratory encompass developing a low SWaP system that can optimally detect low fill area trace level explosives residue on common surfaces from significant standoff that lead to 1) transport of concealed lethal explosives used in bomb making and 2) detection of concealed threat devices targeting unsuspecting civilians, military, and political personnel and high value structures, vehicles, and property. The envisioned system will provide useful target standoff and scan/search times for operational requirements that also meets safety requirements for people in the inspection area. The envisioned system will potentially be housed on a robotic platform, ground vehicle, be soldier carried, and/or mounted on a UAV.

## OBJECTIVES

Remote detection of trace explosives is a challenging problem that has been well studied, from both the signature and detection perspectives, and no systems have yet to be operationally deployed. The challenge stems from the nature of the explosives traces themselves, where nanogram-to-microgram quantities of small particulates are sparsely dispersed over a contaminated area, with localized contaminated areas often of the size of a fingerprint. Within a contaminated area, the portion of the surface covered by the explosive trace has been well characterized and is generally less than a few percent by area, meaning that for optical probes greater than a few millimeters in diameter, the majority (>99%) of the probe radiation will be incident on the underlying substrate. For many substrates, this creates a challenging background signal, which in most cases will overwhelm the much smaller signal arising from the portion of the probe beam incident on the actual explosive trace. Thus, the objective of remote trace detection is to detect these “low areal fill” surfaces in the presence of the overwhelming background signal from the underlying substrate. It is within this context that the various physical means of signal generation have been compared. Such methods include changes in reflection amplitude (imaging systems in the UV, visible, or IR), shifts in probe frequency (Raman or fluorescence spectroscopy), or resonant generation of thermal signals (photothermal spectroscopy). To date, only certain forms of fluorescence spectroscopy have enabled the detection of sparse (<1% filled) signatures, and those methods require multi-step molecular fragmentation and excitation processes, are limited in the range of chemicals they can detect, and/or require complex femtosecond lasers.

## EXECUTIVE SUMMARY

The program "Photoacoustic Sensing of Explosives (PHASE)" is currently under development by MIT Lincoln Laboratory under the direction of the Office of Naval research (ONR). The technique is designed to detect trace explosives from significant standoff, with the intent to provide early warning. Based on our ONR study to date:

1) PHASE shows a strong potential to rapidly detect and locate low fill, trace explosives residue on exposed surfaces from a standoff range of 1 - 50 meters. The current system has demonstrated 5-10 m standoff detection capabilities.
2) A single measurement to detect explosives residue at a single location point requires 10-60 µs of recording time that can provide a useful SNR for acquiring the explosives signature.
3) The PHASE system has demonstrated it can measure trace explosives concentrations as low as 100 ng/ $cm^2$.
4) The PHASE system performance has shown to date, that low fill trace explosives can be detected with a high probability of detection (Pd = 0.9) with a low false alarm rate (1.59 false alarms/$m^2$ and 1 false alarm in 794 cars passed) in measurement studies in laboratory conditions for trace levels down 10 µg/$cm^2$.
5) The current PHASE system has demonstrated it can detect low fill trace level explosives from a 5-10m standoff.
6) The proof-of-concept system developed by MIT Lincoln Laboratory has shown that there is a reasonable engineering path to construct a system that can sufficiently scan an area of 1 $m^2$ on the order of 1-10 seconds. The system could be used to scan a cued target area.
7) An operational system for field use will not require significant development of key components. These key components are currently available on the commercial market that can be used directly for the system.

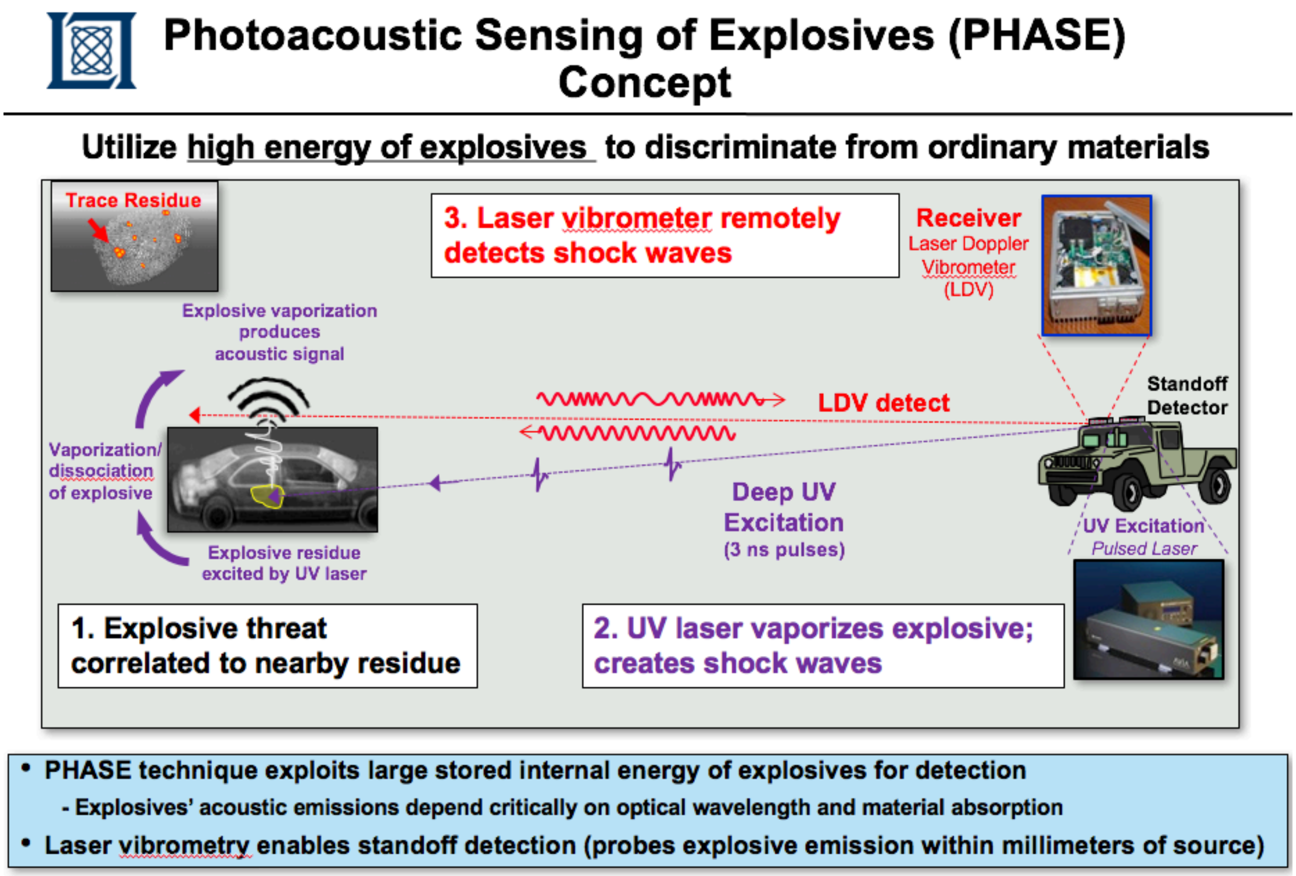
Based on results to date, we recommend that the PHASE system would be a good candidate to be developed further from its current form of a proof-of-concept platform to that of a higher TRL level, demonstration system that can be used for field and operational testing. However, prior to advancing to the next TRL development step, we will complete an outdoor, field test of PHASE from 5 meter standoff on test samples prepared by Mike Shepard's group (CIV NSWC IHEODTD). The field test will evaluate the ROC detection and false alarm performance of the PHASE system. This test will be completed in early FY19.

The PHASE technique and system is likely to significantly out-perform other currently investigated technologies with respect to, in combination - standoff range, data acquisition time, detection and false alarm capabilities, system cost, and time develop an operational system.

It is our request that ONR, help us at MIT Lincoln Laboratory seek a funding agent to further the development of PHASE to a higher TRL level for field testing in more operational settings than currently demonstrated for this technology.

## I. PHASE TECHNICAL APPROACH

PHASE is a non-resonant variation of photoacoustic spectroscopy reliant on UV induced photo-vaporization, which when used on explosive materials produces a unique ultrasonic signature. Short UV pulses vaporize explosives into the near atmosphere and generate acoustic signals, where a second sensing laser, remotely measures the emissions. PHASE exploits near-field ultrasonic acoustic waves from the explosives' release processes. These acoustic emissions, which exhibit signatures derived from the intrinsic explosive characteristics of explosives, also enable discrimination from benign materials. Because the ultrasonic signal is only produced by materials that undergo energetic phase changes upon UV illumination, most of the common substrate materials do not produce an interfering signal. It is for these reasons, that we believe the PHASE technique is promising for the remote detection of explosive traces in the presence of confusing clutter where other methods have not been successful.




In laboratory measurement studies, we have observed high detection probabilities with low false alarms of military and certain forms of homemade explosives down to 10 μg/cm$^2$ with detection capabilities down to 100 ng/cm$^2$ (late-generation fingerprint). In addition, we have been able to measure explosives' signatures from 30 meters and estimate 100m performance is possible using the current system configuration. Although our results have been encouraging, there is considerable work needed to determine if PHASE can detect many explosive types from nitro-bearing species (military-grade) and chlorate (HMEs) in more realistic conditions beyond our current laboratory studies. In addition, it is critical to evaluate the PHASE performance using eye and skin safe UV excitation levels.

## II. WORK COMPLETED – FY18

Under ONR sponsorship, MIT Lincoln Laboratory made the following advances: 1) evaluated picosecond time duration UV excitation pulse advantages over nanosecond time duration pulses (attempt to provide higher peak power while maintaining skin safety) 2) design, develop, and construct a 5-10m standoff co-located optical beam system to perform photoacoustic excitation and vibrational/acoustic signature measurement of explosives emissions in the PHASE detection process and 3) prepare for a critical field test to be conducted in calendar year 2018 or early 2019. Key results are shown in the figures below that are from the Lincoln Laboratory briefing presented this past June at ONR. Publications resulting from ONR funding are listed below.

*C. Wynn, R.W. Haupt, J. Doherty, R. Kunz, W. Bai, and G. Diebold, "The use of photoacoustic excitation and laser vibrometry to remotely detect trace explosives", Applied Optics, Vol. 55, No. 32 / November 2016.*

*W. Bai, G. Diedbold, C. Wynn, R.W. Haupt, and J. Doherty, "A numerical study of shock waves generated through laser ablation of explosives", Journal of Applied Physics, / 120, 194903 December 2016.*

## III. RESULTS

Key results are shown in the figures below that are from the Lincoln Laboratory briefing presented this past June at ONR.

**Overview -**

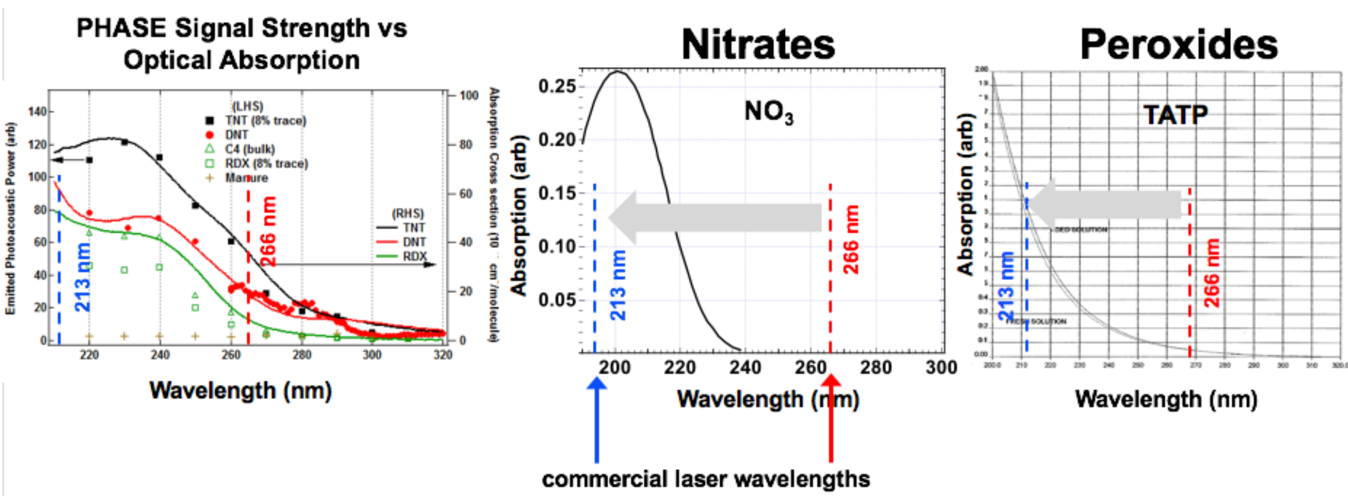



**Figure III(A). Optical absorption dependence and Expanded explosives types detection** – *In FY16 and FY17 studies we observed that many explosives types such as nitro-bearing species were reasonably detected using an excitation wavelength of 266nm while minimizing false alarms from most background and confusor materials. The addition of 213nm wavelength excitation enabled detection of additional explosives types such as peroxides including TATP and PETN.*

***Explosives detonation or deflagration risk factors****

Regarding detonation - we did see that we could detonate or at least deflagrate the peroxide based materials. Everything else however we saw only evidence of ablation. More detail is outlined in our two above mentioned peer-reviewed publications. Also note that the majority of military grade materials are quite stable. This is exactly why they are used, because they are relatively safe in those forms. They require a primary charge to set them off. We've seen that even for something like PETN, also used in det cord, that there was no evidence of detonation and/or deflagration. Thus, it is concluded form our studies that PHASE shows very minimal risk, if any, to cause detonation or deflagration of hazardous amounts of explosives materials

Example acoustic emission signatures are shown next for low fill explosives materials next.

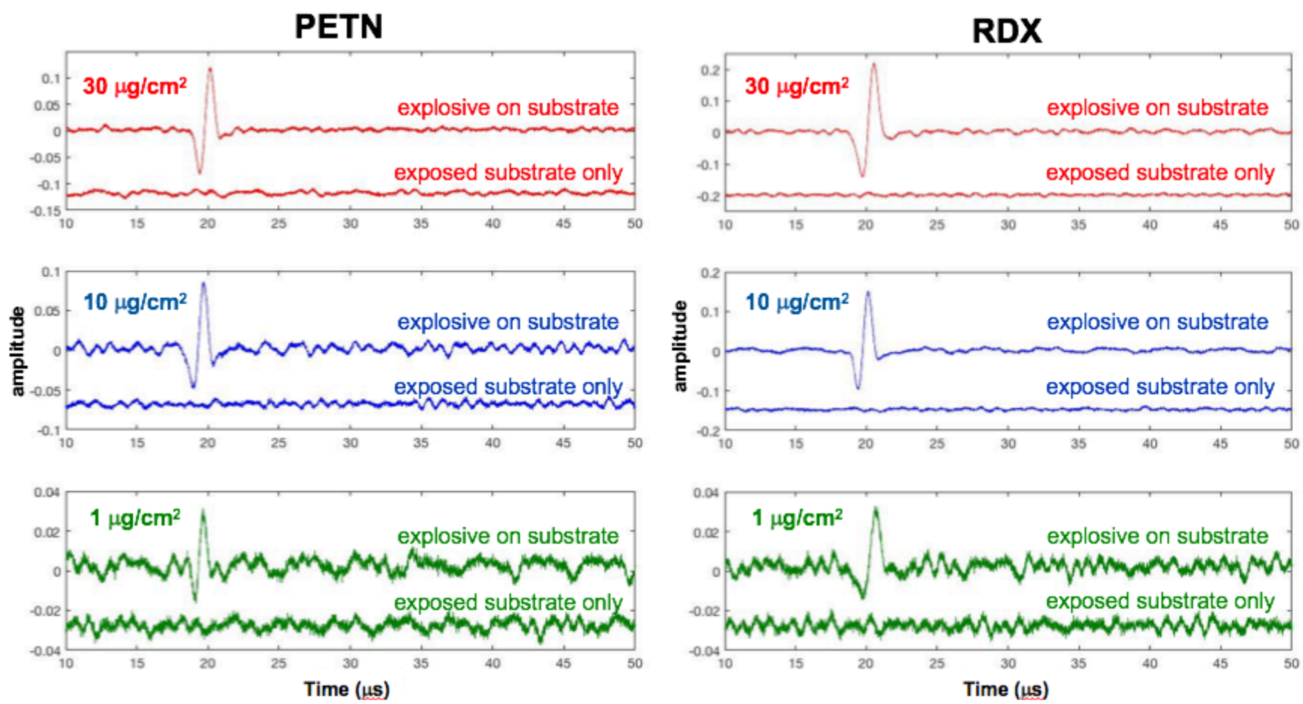



**Figure III(E). Signatures driven by 213nm absorption for low-fill explosives samples –** *The acoustic response measurements for the NRL low-fill samples are summarized in the figure. In the plots, the low-fill explosives time series response is compared with the response of the exposed substrate material (no explosives under the UV excitation beam). The explosives acoustic-ultrasonic emissions are clearly larger than those of just the substrate material shown below. The substrate does not exhibit an apparent time series signature in these measurements. The explosives acoustic response amplitude is observed to significantly increase by a factor of 4 with increasing concentration from 1to10 µg/cm$^2$ for the same excitation fluence level. However, the acoustic response amplitude increases slightly within 20% for the concentration level increase from 10 to 30 µg/cm$^2$.*

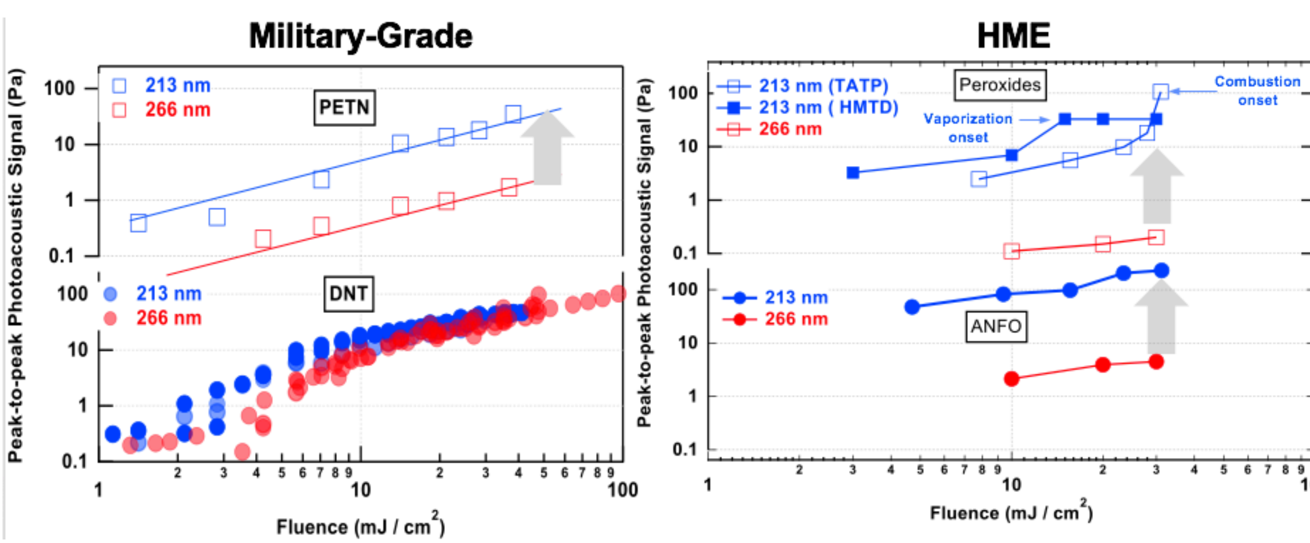
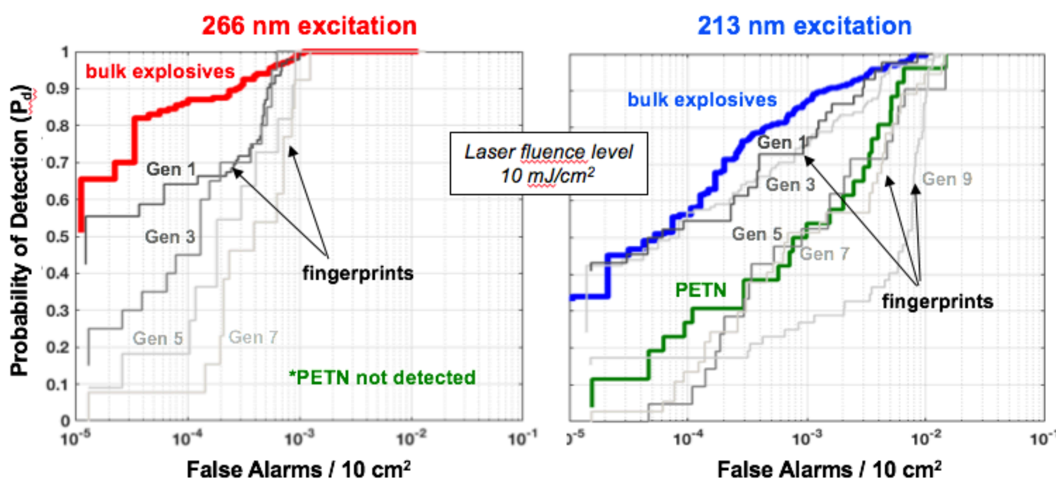
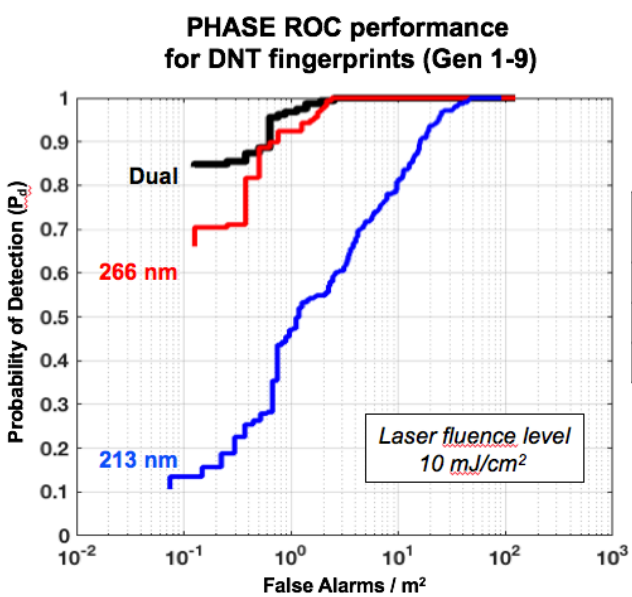


**Figure III(F). Effects of shorter UV excitation wavelengths on explosives –** *Laboratory measurements show the magnitude of the acoustic emission is directly proportional to the absorption of optical energy by the explosives material. The commercially viable solution of 266nm absorbs well for the nitro-bearing species military grade explosives which yield a significant acoustic emission. When using 213nm excitation, the acoustic signal amplitude increases significantly compared to 266nm excitation due to better optical absorption. Using the 213nm wavelength also enhances PHASE signals from HMEs. Specifically, peroxides are responsive and detected using this wavelength where, previously 266nm was ineffective. Higher fluence levels above 10 mJ/cm$^2$ are effective for TATP (30 mJ/cm$^2$) and HMTD (15 mJ/cm$^2$).*

- ROC performance estimated using classification algorithm based on times series signatures measured by laser Doppler vibrometer beam projection to within 4 mm of sample surface
- Metrics based on physical phenomena - Integrated signal power, Peak frequency power, Signal duration, Signal rarefaction Q, Mach number shift (MNS), Correlation confidence of MNS

** 30 different environmental background materials measured using PHASE system*




**Car Check Point Analysis**

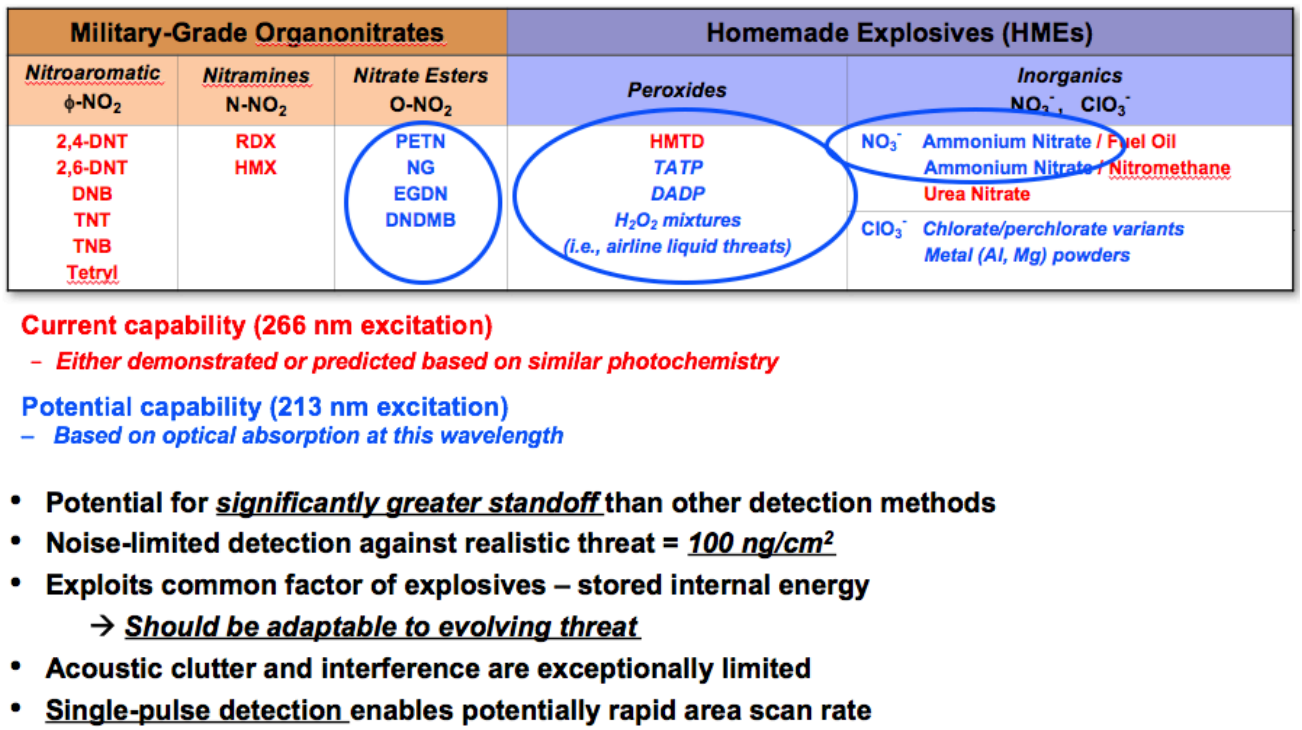
**Area (m²) with 1 False Alarm (FA) Observation**
**$P_d$ = 0.9**

| Excitation wavelength | Area (m²) per 1 FA | cars passed per 1 FA |
|---|---|---|
| Dual 266nm & 213nm | 1.59 | 794 |
| 266nm | 1.32 | 662 |
| 213nm | 0.06 | 31 |

** 30 different environmental background materials measured using PHASE system*

**Figure III(G). Explosives detection performance against common background** – *Laboratory measurements of explosives materials deposited on car panels show that trace-level and low fill explosives separate from clutter and are detected with reasonable confidence. 266nm wavelength excitation provided the best standalone performance, but missed key explosives since these types do not absorb 266nm very well. However, when adding a dual wavelength excitation of 213nm, then additional explosive types were detected while the algorithm was able to reject common background and confusor materials maintaining reliable ROC performance.*

**Summary -**



| Military-Grade Organonitrates | | | Homemade Explosives (HMEs) | |
|---|---|---|---|---|
| *Nitroaromatic* ϕ-$NO_2$ | *Nitramines* N-$NO_2$ | *Nitrate Esters* O-$NO_2$ | *Peroxides* | *Inorganics* $NO_3^-$, $ClO_3^-$ |
| 2,4-DNT<br>2,6-DNT<br>DNB<br>TNT<br>TNB<br>Tetryl | RDX<br>HMX | PETN<br>NG<br>EGDN<br>DNDMB | HMTD<br>*TATP*<br>*DADP*<br>*$H_2O_2$ mixtures*<br>*(i.e., airline liquid threats)* | $NO_3^-$ Ammonium Nitrate / Fuel Oil<br>Ammonium Nitrate / Nitromethane<br>Urea Nitrate<br>$ClO_3^-$ *Chlorate/perchlorate variants*<br>*Metal (Al, Mg) powders* |



**Figure III(H). Key Advantages of the PHASE technology** – *266nm UV provides unique signals for industrial-grade nitro-bearing species, HMTD, and some HMEs that contain nitrates, as the signal depends on their UV absorption. The explosives types were expanded using the addition of 213nm UV excitation demonstrated in laboratory measurements and are depicted in the blue text.*

**Task 1** - evaluate picosecond time duration UV excitation pulse advantages over nanosecond time duration pulses

The issue of whether the PHASE effect depends on fluence (energy/area) or on laser intensity (power/area) is of great interest for reasons of eye safety. In the deep UV where PHASE operates, the eye/skin limits for short pulses are fixed with fluence, which means that higher intensities could be used safely as long as the safe fluence levels are maintained. With this in mind, a picosecond class laser was procured and PHASE data was collected and compared to the prior nanosecond class laser based results. The results indicated very little difference (within experimental error which was largely driven by uncertainties in the laser spot sizes) between the two PHASE signals for a given fluence (chart 6), suggesting that the physics behind the PHASE signal is dependent on fluence and not intensity. Noting our prior work with Brown University [*W. Bai, G. Diedbold, C. Wynn, R.W. Haupt, and J. Doherty, "A numerical study of shock waves generated through laser ablation of explosives", Journal of Applied Physics, / 120, 194903 December 2016.*], we propose that the creation of the 'mass regime' is primary driver of the critical time scales.

A future PHASE system could be built with either a picosecond or nanosecond laser with no significant effect on performance. The nanosecond class lasers tend to produce more total energy thus they are the best candidate moving forward.

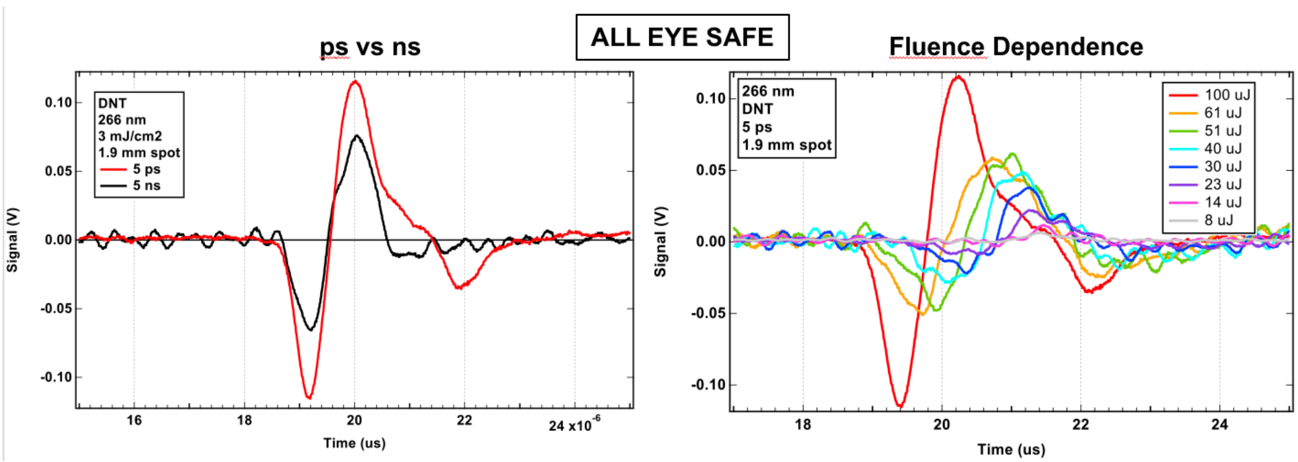



**Figure III(B). Explosives Acoustic Emissions Signal Magnitude for picosecond and nanosecond pulse width sources** – *A resultant signal peak-to-peak amplitude gain of a factor of 2 was observed for the picosecond pulse width in comparison to that of the nanosecond pulse width.*

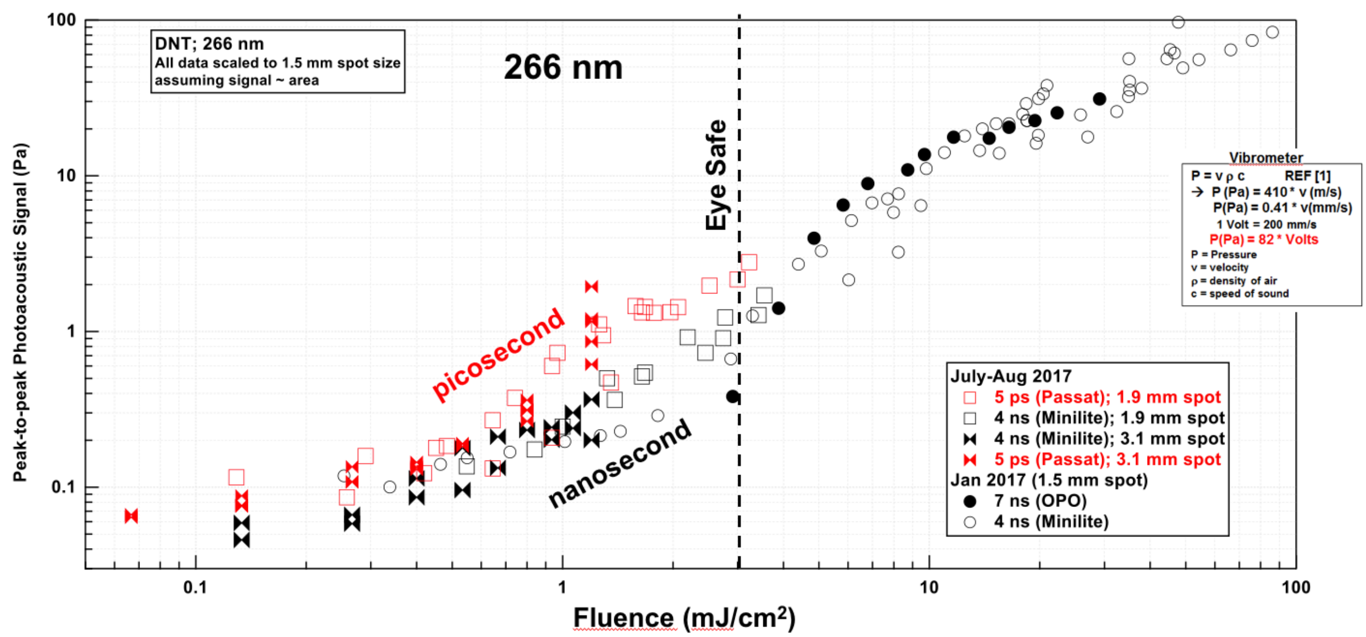



**Figure III(C). Explosives Acoustic Emissions Signal Magnitude for picosecond and nanosecond pulse width sources** – *A resultant signal peak-to-peak amplitude gain of a factor of 2 was observed for the picosecond pulse width in comparison to that of the nanosecond pulse width. Modest gains are achieved using the shorter pulse width which would provide a benefit in a fieldable system.*

**Task 2** – construction and testing of co-located Uv exciation and laser Doppler viobrometer measurement in 5-10m PHASE proof-of-concept system for field test configaration

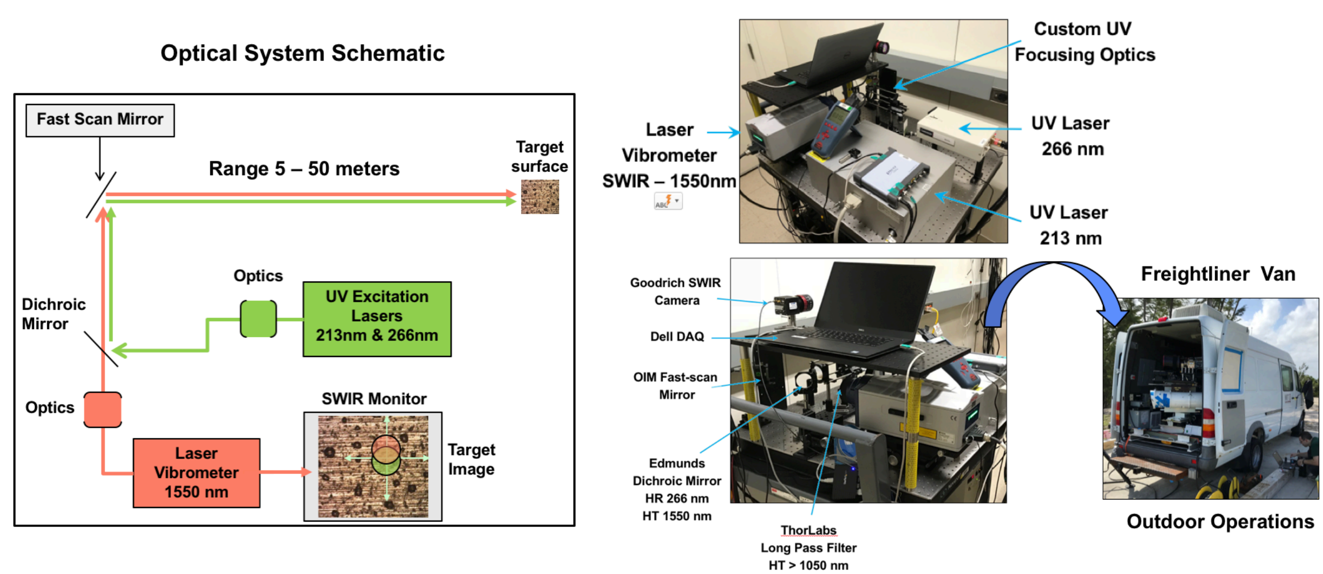



**Figure III(I). PHASE portable proof-of-concept system for 5-10m standoff explosive trace detection** – *MIT Lincoln Laboratory constructed a portable, bench-top system to detect trace level and bulk explosives detection* *from standoff. The system employs a 15 Hz rep rate 266nm or 213nm wavelength for photoacoustic excitation of the explosives trace. A 1550nm 10mW or 35mW custom Polytec laser Doppler vibrometer (LDV) is used to measure the acoustic emission. A fast scanning mirror steers the UV and LDV optical beams together in a co-located configuration. The LDV does not require any surface treatment such as reflexite tape or powder to enable the acoustic emission signal measurement. An IR imager with a large monitor (close to the operator) is used to help track the LDV and UV beams on the target. The large monitor image is also used to focus the LDV beam which provides the best SNR for performance. The portable system can then be transported and operated from the backend or side of the MIT LL van dedicated to the program. The van can be then be driven to field sites and is road worthy for testing anywhere in the U.S.*

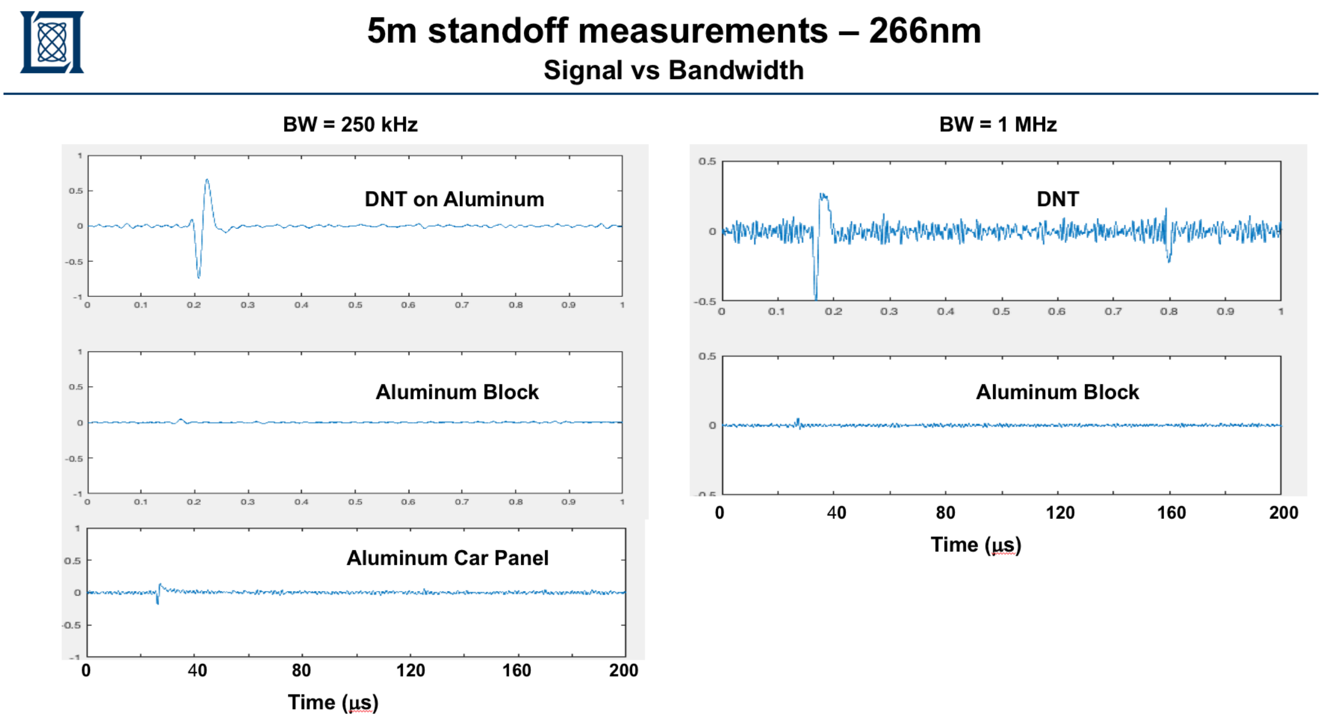



**Figure III(J). PHASE portable proof-of-concept system measurement for 5m standoff explosive trace detection – LDV bandwidth analysis** – *The LDV bandwidth is examined for 250kHz and 1 MHz. Low fill explosive acoustic signatures are clearly present with good to excellent SNR. Back ground substrate such as an aluminum car door panel in this example exhibit a minimal signal compare to that of an explosive (in this case a DNT particle – submillimeter diameter). The UV and optical beams are scanned with the fast steering mirror. 3 pulse responses are averaged for a total time span of 600 microseconds.*

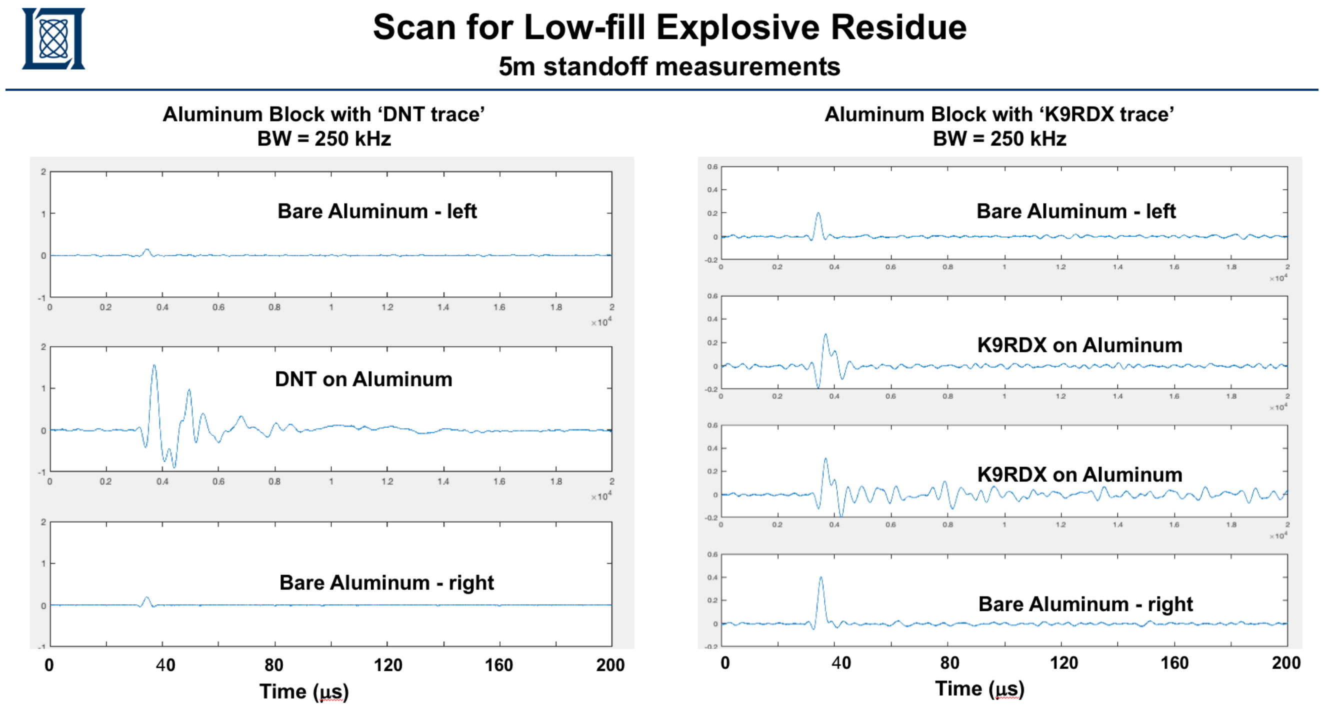



**Figure III(K). PHASE portable proof-of-concept system measurement for 5m standoff explosive trace detection – LDV bandwidth** – *250 kHz measurements. Low fill explosive acoustic signatures are clearly present with good to excellent SNR. Back ground substrate such as an aluminum car door panel in this example exhibit a minimal signal compare to that of an explosive (in this case a DNT and a K9RDX particle – submillimeter diameter). The UV and optical beams are scanned with the fast steering mirror. 3 pulse responses are averaged for a total time span of 600 microseconds. The explosives materials exhibit significantly different waveforms in comparison to the substrate signature when scanned. These signature differences are able to be determined from standard classifier algorithms.*

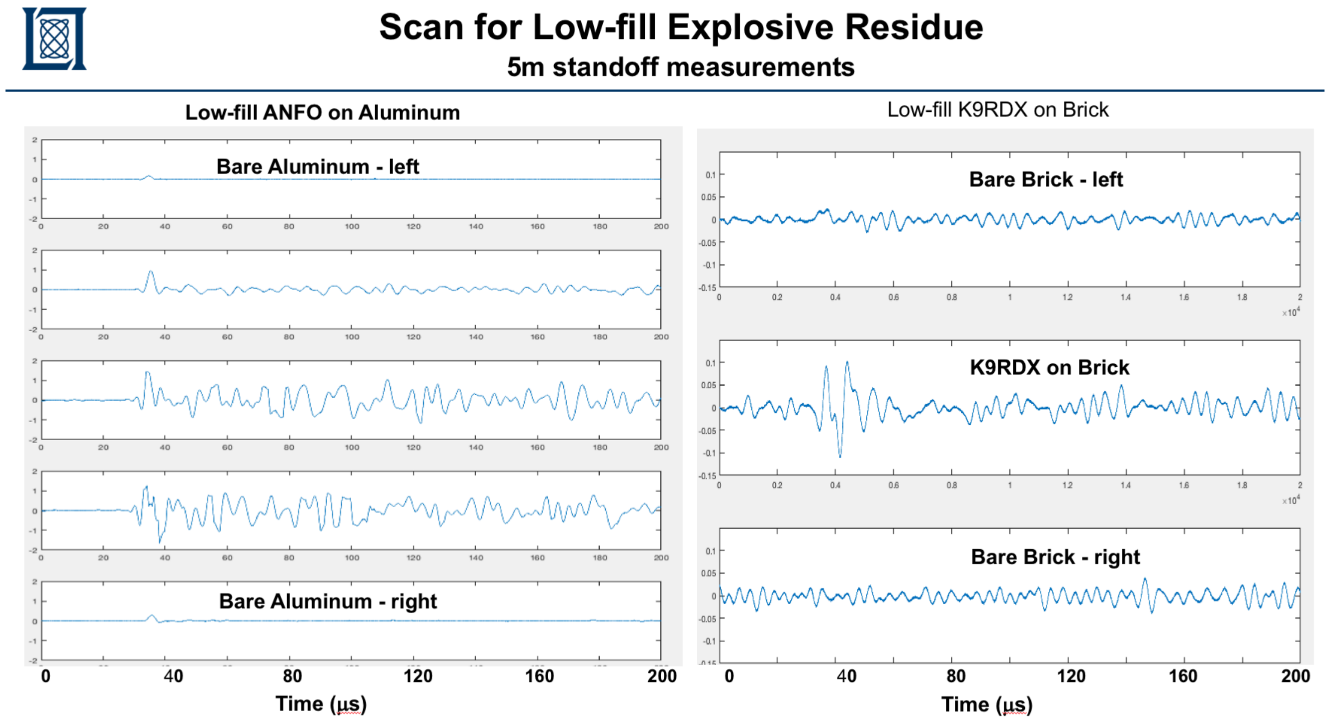



**Figure III(L). PHASE portable proof-of-concept system measurement for 5m standoff explosive trace detection – comparison of ANFO and K9RDX on different substrates**. *Low fill explosive acoustic signatures are clearly present with good to excellent SNR. Back ground substrate such as an aluminum car door panel in this example exhibit a minimal signal compare to that of an explosive (in this case a homemade explosive ANFO particle – submillimeter diameter). The UV and optical beams are scanned with the fast steering mirror. 3 pulse responses are averaged for a total time span of 600 microseconds. The explosives materials exhibit significantly different waveforms in comparison to the substrate signature when scanned. These signature differences are able to be determined from standard classifier algorithms.*

Based on these findings, it appears that the PHASE technology has the potential to detect trace level explosives from significant operational standoff ranges and time frames that are not currently available. Moreover, the technology has a potential path to provide an operational capability that has a form factor that can fit on a robotic platform, be soldier carried, or UAV-mounted. Performing PHASE standoff measurements on low fill trace explosive sample in filed conditions is the remaining task for the current funding that has been provided by ONR to date. Upon successful completion and outcome of the final task, it would likely be favorable to conduct further field testing and to transition to a higher TRL level to build a demonstration testing for desired operational conditions.

## IV. IMPACT/APPLICATIONS

Based on these findings, it appears that the PHASE technology has the potential to detect trace level explosives from significant operational standoff ranges and time frames that are not currently available. Moreover, the technology has a potential path to provide an operational capability that has a form factor that can fit on a robotic platform, be soldier carried, or UAV-mounted. However, there are a number of key risks that need to be addressed to determine if such a system can meet the requirements necessary for military use.

To date, successful covert standoff explosive detection systems have not been developed. If successful, PHASE approach may provide such a capability. This would significantly enhance existing methodologies for *in-situ* detection of Improvised Explosive Devices (IEDs) and concealed explosives devices. Applications include: 1) vehicle check point inspection, 2) robotic cued inspection, 3) mobile scanning for covert IED manufacturing facilities, 4) standoff suicide bomber detection, 5) baggage screening at airports, 6) package and container screening.

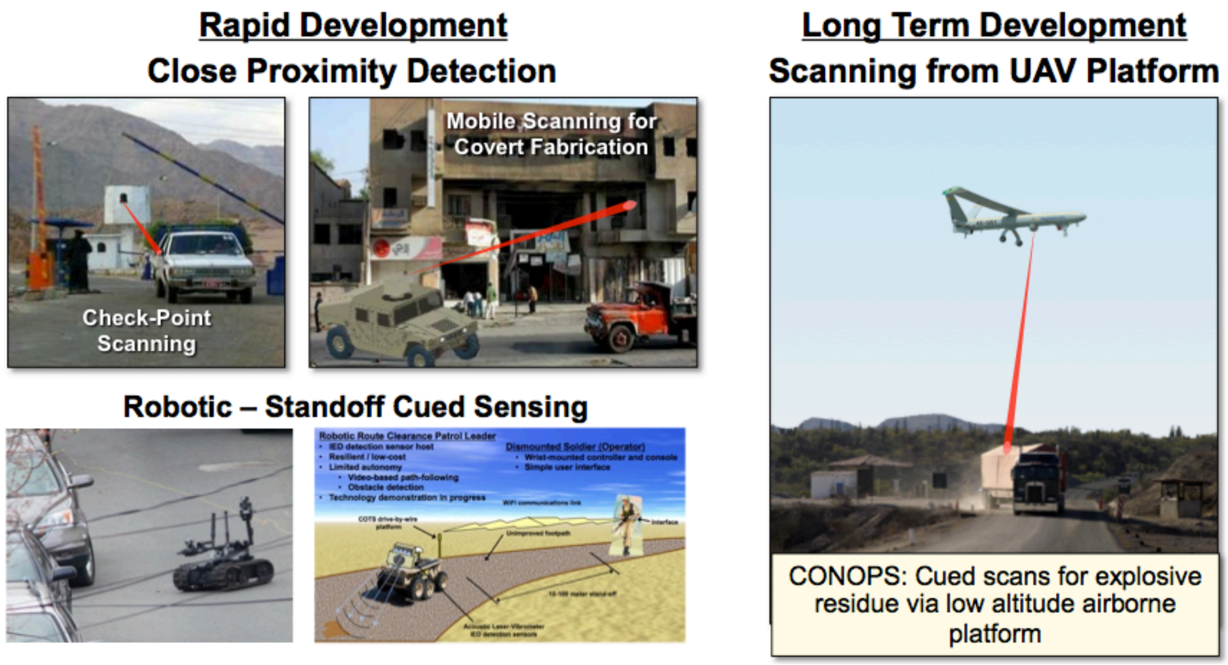



**Figure IVA. PHASE operational concepts** – *Rapid development likely for vehicle check point, robotic platforms, and soldier carried. Longer development times required for airborne platforms.*

**PHASE advantages over other techniques under consideration**

As briefed at ONR presentations during the June conference, the PHASE technology has several advantages over other approaches being considered for remote trace-level explosives detection:

1) Detection of low-fill trace-level 1 – 100 μg/cm$^2$ with particle sizes ~10μm or smaller from standoff

2) Requires small measurement times 10-20 microseconds using a single UV pulse to produce a signal with significant SNR that differs from the background environment,

3) Negligible acoustic clutter due to the high-frequency ultrasonic response used for detection

4) Required UV excitation fluence level could potentially be reduced to skin and eye safe levels

5) Laser Doppler vibrometer demonstrates a standoff skin and eye safe power level that can sufficiently measure trace-level explosives acoustic emissions, and

6) PHASE can be implemented using COTS components (UV source, laser vibrometer).

PHASE's advantages have the potential to provide a path for an operational system development that can be vehicle mounted, carried on a robot, or soldier carried. Such a system can potentially provide

1) measurement capabilities of trace-level explosives residue from 30-100m, standoff
2) useful coverage rates for cued scanning/sensing
3) skin and eye safe optical operation.

Other techniques under consideration such as Raman, SWIR, LWIR have the potential to meet some operational constraints, but may not fulfill a sufficient set of requirements. For example, Raman techniques have demonstrated the ability to measure trace level explosives (~100 $\mu g/cm^2$ ) from standoff. However, the dwell time for a single UV beam and measurement can require up to 60 seconds, which challenges the areal coverage rate. SWIR and LWIR techniques can operate at safe power levels, rapid measurement times, and from considerable range. However, these measurements would need to image the explosives particles themselves which challenges standoff significantly. Moreover, current SWIR and LWIR in their current configurations are unable to detect and measure trace level explosives from a significant distance.

## V. TRANSITIONS

Pending successful testing of prototype unit, larger scale production of PHASE sensor systems could be shifted to private industry. Assess relatively low unit cost would allow a system to be employed at the Marine Expeditionary Unit, EOD Mobile Unit level, and lower.

**Partnerships:** MIT Lincoln Laboratory personnel under direction of Rob Haupt (POC information: haupt@ll.mit.edu) would assemble prototype unit and integrate sensor systems.

**Government Testing:** Testing would require realistic mock-up of expected environment sensor would operate within. EOD Tech Division at NSWC India Head, EOD GRU 2 at JEB Little Creek-Fort Story, or USMC assets out of USMCB Quantico, VA would be viable candidates to provide support for testing. Facilities/Equipment: PHASE prototype would be fabricated at MIT Lincoln Labs facilities at Hanscom AFB. Discrimination algorithm development would be conducted at both MIT Lincoln Labs and US Naval Academy. MIT Lincoln Labs would utilize organic facilities, organization, and personnel to carry out fabrication of PHASE prototype.

## RELATED PROJECTS

1) C.M. Wynn, R. Kunz, M. Rothschild, "Photo-dissociation followed by Laser Induced Flourecence (PD-LIF)", funded by DARPA, Army Edgewood, 2006 – 2012.

2) R.W. Haupt, L. Jiang, R. Marino, "(LVID) - Laser Vibrometry from a Moving Ground Vehicle System to Detect IEDs and Landmines", funded by JIEDDO and the Army REF, 2010-2014.

3) R.W. Haupt and C.M. Wynn, "Non-contact Laser Ultrasound for Medical Imaging and Diagnostics", MIT Lincoln Laboratory Line Program – FY14-present

## PATENTS

C.M. Wynn, R.W. Haupt, S. Kaushik, and S.T. Palmacci, U.S. Patent 8,935,960, "Method and kit for stand-off detection of explosives," 2015.

**HONORS/AWARDS/PRIZES**

R.W. Haupt and C.M. Wynn, R&D 100 award winner (top 100 inventions of 2013), "PHASE – Photoacoustic Sensing of Explosives", 2013.

**PUBLICATIONS**

1) C. Wynn, R.W. Haupt, J. Doherty, R. Kunz, W. Bai, and G. Diebold, "The use of photoacoustic excitation and laser vibrometry to remotely detect trace explosives", *Applied Optics*, Vol. 55, No. 32 / Nov 2016.

2) W. Bai, G. Diedbold, C. Wynn, , R.W. Haupt, and J. Doherty, "A numerical study of shock waves generated through laser ablation of explosives", *Journal of Applied Physics*, / 120, 194903 Dec 2016.

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1) Haupt, R., C. Wynn, L. Jiang, and S. Palmacci, Photo-acoustic Detection of Explosives, New Technologies Initiative program at MIT Lincoln Laboratory, 2011.
2) Jiang, L., M. Albota, R. Haupt, J. Chen, and R. Marino, "Laser vibrometry from a moving ground vehicle", *Applied Optics*, 2011 May: 50(15) : 2263-73.
3) Wynn, C. and R. Haupt, Photo-acoustic Detection of Explosives, Advanced Concepts Committee program at MIT Lincoln Laboratory, 2010.
4) Haupt, R.W., M. Albota, L. Jiang, and R. Marino, 2010, " Laser-Vibrometry Detection and Imaging System (LVID)", Military Sensing Symposium MSS Active E-O Systems, Orlando, Florida.
5) Doherty, J.H., 2008, "Landmine detection with a standoff acoustic/laser technique", MIT Thesis, Cambridge, Massachusetts.