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Portable System for Standoff Detection of Trace Explosives on Surfaces

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14. ABSTRACT
This FY20/21 NRL NISE program (NRL WU #4X10) demonstrated standoff detection of trace explosives and surrogate analytes on surfaces relevant for Navy and Marine Corps needs. We have developed Infrared Backscatter Imaging Spectroscopy (IBIS) as a dedicated portable system to leverage recent advances in component technologies such as infrared (IR) quantum cascade lasers (QCL), IR focal plane arrays, and machine learning algorithms. We have also successfully developed algorithms to detect and identify threat chemicals by their infrared spectral signatures.

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Portable System for Standoff Detection of Trace Explosives on Surfaces

Executive Summary: We have developed Infrared Backscatter Imaging Spectroscopy (IBIS) as a dedicated portable system to leverage recent advances in component technologies such as infrared (IR) quantum cascade lasers (QCL), IR focal plane arrays, and machine learning algorithms. IBIS is unique among active IR approaches in that it utilizes continuous wave (rather than pulsed) illumination for high duty cycle investigation, rapid wavelength sweeping for speckle mitigation, and differential image processing to remove the static background and allow detection from a single pixel. This FY20/21 NRL NISE program (NRL WU #4X10) demonstrated standoff detection of trace explosives and surrogate analytes on surfaces relevant for Navy and Marine Corps needs. During this 18 month program, we demonstrated much faster wavelength scanning speeds (from ~several seconds to 0.16 seconds) for ~ 2 inch X 2 inch spot. This allowed rapid detection and identification in high probability areas of physical contact (e.g. a door handle), longer standoff distance (from 1 meter to 5 meters), improved laser spot pointing for reduced false alarms, reduced SWAP (size, weight and power), and detection of a broader range of target analytes on more substrate materials. We have also successfully developed algorithms to detect and identify threat chemicals by their infrared spectral signatures. The results of this work and demonstration will help NRL to transition this technology to meet Navy, Marine Corps and DOD needs.

Figure 1. The NRL IBIS cart.

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Innovation/Navy Need: The need for technology that can detect explosives at standoff distances has been well documented by JUONS, JIDO Capability Needs[i], USMC Strategic Plan S&T Objectives (STO)[ii] and ONR S&T Objectives[iii]. The asymmetric threat from explosives and IEDs is an ongoing problem for DOD in general and in addition, this threat carries over into domestic and transportation security. NRL 6365 has developed a cart-based portable system platform for the standoff detection of trace explosives on surfaces. This system is based on Infrared Backscatter Imaging Spectroscopy (IBIS), a technology developed under previous NRL Base 6.2 and externally funded programs. In our laboratory, we have demonstrated detection of relevant trace (low nanogram) levels of explosives including RDX and PETN on various surfaces including glass, metal, plastics, and painted car panels. The work summarized in this report targeted an order of magnitude improvement in laser wavelength scanning speed with a concomitant improvement in surface scanning speeds, combined with improved algorithm techniques to detect and identify trace levels of explosives found on solid surfaces in fingerprints or as material spills.

Technical Approach: Infrared Backscatter Imaging Spectroscopy (IBIS) has been developed within NRL 6365 since the start of an FY15 6.2 Base program (WU#6848). Over the last 15+ years of working in this field, we have considered many technologies for the standoff detection of trace explosives. We have developed IBIS as the most mature and likely candidate to meet the necessary objectives of sensitivity, speed, eye or skin safety, specificity, and system size. Our latest IBIS platform leverages recent advances in component technologies such as infrared (IR) quantum cascade lasers (QCL), IR focal plane arrays, and machine learning algorithms. Our work with IBIS is unique among active IR approaches in that it utilizes continuous wave (rather than pulsed) illumination for high duty cycle investigation, rapid wavelength sweeping for speckle mitigation, and differential image processing to remove the static background and allow detection from a single pixel. In comparison, Raman spectroscopy being developed by other researchers, suffers from issues with low photon scattering efficiency and undesirable fluorescence signals. The resulting Raman need for more laser photons at the target leads to concerns about eye safety, photo-degradation of the target, and long detection times. Most other proposed optical approaches suffer with similar issues and with technology maturity, or in achieving all of the system objectives, leaving active IR as the plausible choice, and IBIS as its preferred implementation.

The IBIS approach used in this work is based on active infrared imaging (Figure 2), where we tune the emission wavelength of a commercial QCL as it illuminates the target while we collect image frames at each wavelength. The resulting data forms a hyperspectral image cube (Figure 3) from which the spectrum of a region of interest on the target (down to a single pixel) is generated by extracting the intensity from each frame. The spectrum is compared to a library of known threats for detection and identification of explosives. We have used our cart-based system to demonstrate:

- ✓ Sensitivity to ng quantities of explosives (RDX, PETN, etc.)
- ✓ Specificity between explosives (RDX, PETN, TNT, DNT, etc.) and non-explosives
- ✓ Discrimination from substrates (car paint, glass, cardboard, vinyl, nylon, cell phone case, etc.)
- ✓ Standoff distances up to ~5 meters in laboratory conditions
- ✓ Spectral signatures even in the presence of large amounts of sand on the target surface
- ✓ Eye-safe illumination using a compact infrared (stealthy) QCL
- ✓ Laser wavelength scan time of 160 ms to cover 6.0 to 11.0 microns
- ✓ Laser interrogation spot size 2 inch X 2 inch

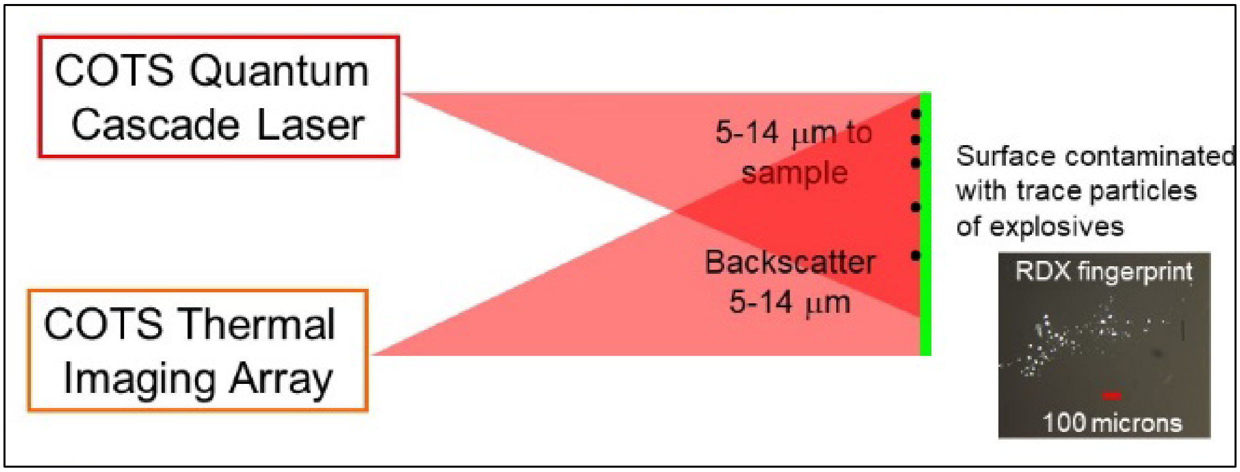

Figure 2: IBIS Schematic. A commercial off-the-shelf (COTS) IR quantum cascade laser illuminates a contaminated surface while an IR camera collects image frames of the scene. The inset shows a microscope image of a fingerprint containing RDX explosives particles. In IBIS, the IR laser tunes across the spectrum through signature absorption features for explosives, drugs and other chemicals of interest. The technology can by eye-safe, stealthy, and sensitive to trace quantities. Detection can be performed at several meters of standoff distance.

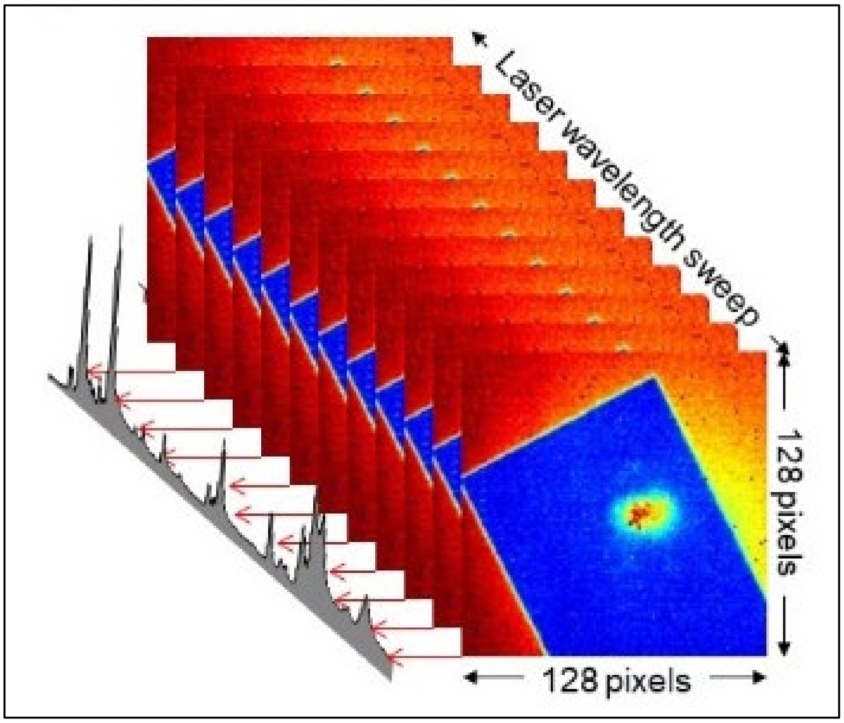

Figure 3: The IBIS hypercube. An image frame is collected at each wavelength. Images are collected at 1600 frames per second. Spectra are extracted from pixels or regions of interest. Each frame represents an image of the target at a single known wavelength. Slicing through the frames for a given pixel yields the spectrum of the material in that area of the image. The spectrum can be matched to a library of signatures to detect and identify chemicals of interest.

Technical Background: The technology and results of IBIS have been published in a series of publications in the open literature and are available by searching the authors' names or upon request. For the organization of this Memorandum Report, we first briefly summarize a subset of our previous results for technical background reference, and then in subsequent sections we emphasize advancements made under the NISE program. IBIS Spectra (Fig. 4) are extracted from regions of interest (typically 19 contiguous pixels) within the IBIS hypercubes. These spectra are compared against a library of known infrared threat chemical signatures. We have implemented a detection algorithm based on a convolutional neural network (CNN). The network is trained to recognize spectral signature patterns, before being asked to return an identification classification on the measured IBIS data. Figure 5 shows an example where the CNN correctly identified caffeine (a simulant for drugs of abuse) in the pixels where it was present (white areas in Fig. 5b). Although training the network requires a large library database, the identification of an "unknown" takes just a few milliseconds.

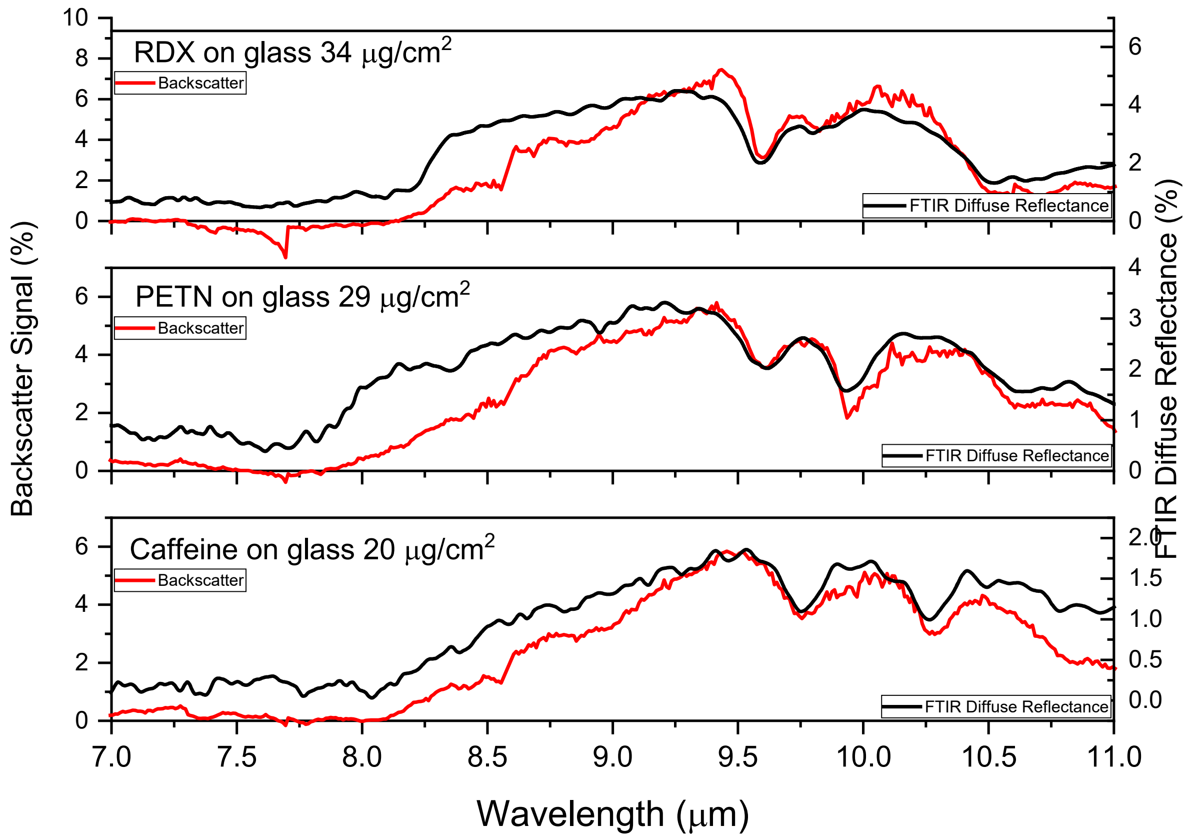

Figure 4. The spectral IBIS (red) and FTIR (black) results from three different materials deposited onto glass. The IBIS spectra closely match the reference chemical signatures.

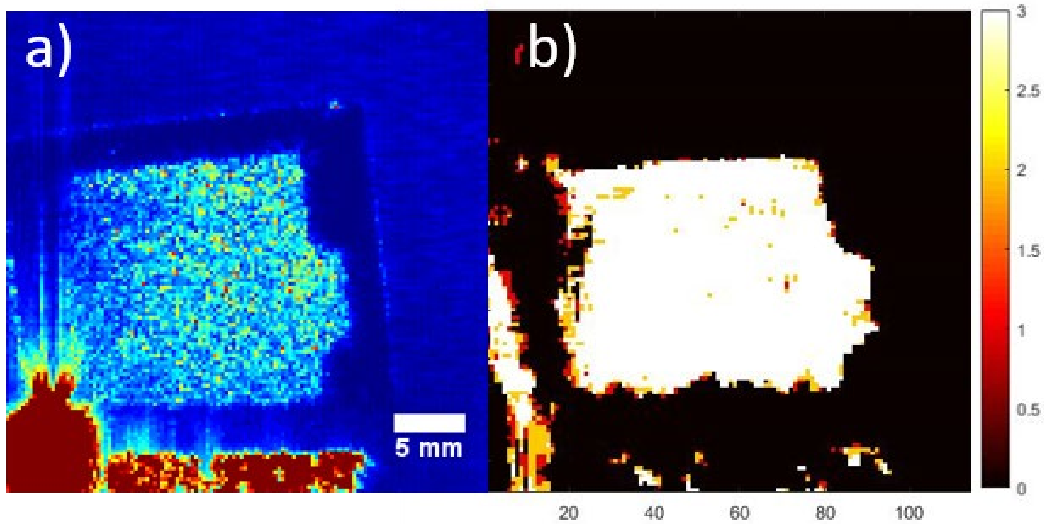

Figure 5. a) A selected frame, for a particular wavelength of IR light, from the IBIS hypercube collected from a glass slide loaded with caffeine at 20 $\mu m/cm^2$. b) The results from the CNN analysis of the hypercube. When the CNN algorithm finds the spectrum from the respective pixel matches caffeine as the first choice, the pixel is white, second choice orange, and third choice is red. If caffeine was not in the first 3 guesses of the CNN, the pixel was assigned to be black.

Technical Maturity: IBIS was originally developed under the NRL FY15 6.2 Base Program (WU#6848) entitled "Wide Area Infrared Standoff Detection of Explosives". That program culminated in 2018 and was documented in the Base Program Final Closeout report. That report refers to several published papers documenting detection of the explosives TNT, RDX, DNT, PETN, KClO3, (and other relevant analytes) on typical substrates such as glass, nylon, polyethylene, and chrome-plated plastic. We have documented standoff detection down to the nanogram sensitivity level, which is sufficient to detect true trace (fingerprint) quantities. From 2019 to 2021, NRL 6365 secured external support from DTRA JIDO to further advance this technology (WU# 9413). Under this NRL NISE and JIDO programs, we implemented hardware upgrades that allowed us to improve the way that we synchronize the collection of camera frames and calibrate the wavelength associated with each frame. We have also undertaken new algorithm methods for generating detection and identification classifiers. These algorithms are based on machine learning convolutional neural networks (CNN) that recognize patterns in library databases to match unknown spectra for detection and identification of explosives threats.

Accomplishments during this NRL NISE program:

1. LONGER STANDOFF

Performing any spectroscopy at longer stand-off distances increases the challenges such as reduced light returning to be measured, wider field of view, lower spatial resolution, and beam wander. At 5 m standoff, the IBIS field of view is about 150 mm X 150 mm as opposed to about 50 mm X 50mm at 1-meter standoff. When performing measurements at 1 m, IBIS is able to spread the beam to cover the entire field of view and collect the backscattered signal from the entire field of view at one time. This is not possible to do at 5 m because there is not enough backscatter signal returning to the camera, so the beam is collimated to provide a spot size of about 30 mm diameter at the target 5 m away. This retains the intensity on target so that the only signal loss is proportional to the reduced optical collection cone at the longer standoff.

The QCL system used in IBIS measurements exhibited significant beam wander during initial experiments at 5 meter standoff, and this resulted in areas of high irreproducibility and error in the data, especially at chip handover spectral bands. Figure 6 shows the results from an IBIS measurement at 5 m stand-off for a test coupon of caffeine. Despite these longer stand-off challenges, the extracted IBIS spectrum in red shows excellent agreement with the FTIR diffuse reflectance spectrum in black. In Figure 6, we placed a blue block over the spectral region that exhibited significant noise due to beam wander and want to inform the reader that since the collection of this data, the IBIS system has received an upgrade to mitigate this beam wander issue. That accomplishment will be discussed in the next section.

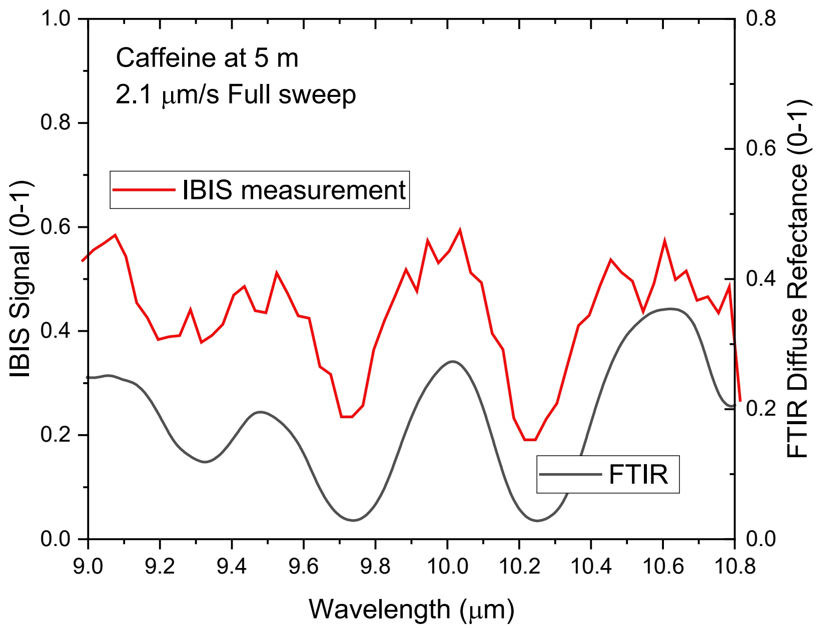

Figure 6. The IBIS signal plot Illustrates the results of an IBIS measurement of caffeine at 5 m stand-off (red) versus the FTIR diffuse reflectance (black).

2. IMPROVED LASER BEAM POINTING

Laser beam pointing is critical to keep the beam on the same target within the field of view of the IBIS camera. This is especially challenging at longer standoff where a slight change in beam angle corresponds to a further spatial deviation at the target. The laser spot position must also be stable for all wavelengths and repeatable from sweep to sweep. Due to issues with laser beam wander primarily caused by laser mode hops (wavelength), the multi-chip QCL was upgraded at the vendor to include an active beam pointing system that is calibrated to steer the beam to the same position at any arbitrary wavelength. Although this upgrade was performed very late in the NISE program, we were able to demonstrate dramatically improved beam spot stability. This translated directly into improved IBIS signatures and detection confidence.

Figure 7 illustrates the issue of beam wander of the QCL used for IBIS. IBIS camera images are 128 X 128 pixels. Blue pixels represent low signals, while red pixels indicate high signals. Panel A) shows an example image of the laser beam spot position during an IBIS measurement. Panel B) shows an example image of the laser beam spot after wandering to a new position. Excessive beam wander requires that the target sample be homogeneous on the scale of the wander, or else the IBIS spectra of any given region of interest will not match the library spectra of known threats such as explosives. Panel C) plots the beam centroid position after the beam wander upgrade. The wander is measured to be just a few pixels across the entire spectral range and is significantly reduced from the ~50 pixel wander observed prior to the upgrade. This enables the spectral extraction of small regions of interest, and allows the detection of inhomogeneous targets such as explosives traces.

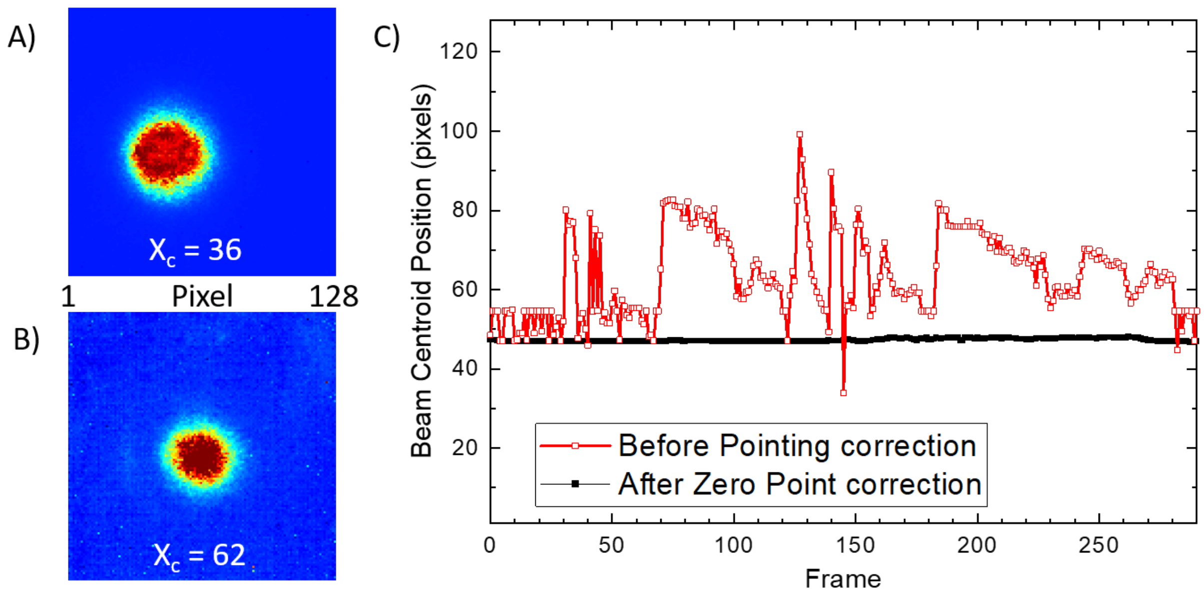

Figure 7. Beam wander of the quantum cascade laser used for IBIS. IBIS camera images are 128 X 128 pixels. Blue pixels represent low signals, while red pixels indicate high signals. A) Example image of the laser beam spot position during an IBIS measurement. B) Example image of the laser beam spot after wandering to a new position. C) After the beam wander upgrade, the wander is measured to be just a few pixels across the entire spectral range. Prior to the upgrade, the beam wandered as far as 50 pixels from the desired location.

3. FASTER SCAN SPEEDS

A main objective of the NISE project was to push the IBIS system toward the goal of standoff chemical detection in "real-time". This is achieved by increasing the infrared illumination wavelength sweep rate as well as increasing the standoff distance. One recent upgrade to the IBIS system is the implementation of a Daylight Solutions MIRcat-QT to improve the speed at which the QCL system is able to sweep through the entire 6 µm to 11 µm illumination range. At its fastest scan speed of 50 µm/s, the entire spectral range is scanned in 160 milliseconds. Decreasing the time spent sweeping through illumination wavelengths is an important step toward practical real-time standoff or non-contact chemical detection.

The results shown here are from an optically dense sample of acetaminophen powder. This material is used as a surrogate for explosives and drugs of abuse since it can be safely handled in bulk. The sample was prepared by pressing several milligrams of acetaminophen powder into a small (~1 cm diameter) depression in a 1 inch by 1 inch piece of aluminum. The sample was oriented vertically and held at distances of both 1 m and 5 m from the system.

In Figure 8, the backscatter spectrum of acetaminophen collected at several different wavelength tuning speeds is compared to the diffuse reflectance FTIR spectrum. The figure shows the results from tuning over the whole 6 µm to 11 µm spectrum. Since the entire illumination wavelength range is 5 µm, the entire range sweep at 2.1 µm/s is completed in 2.5 seconds, 4.2 µm/s finishes in 1.3 seconds, and at 50 µm/s the entire wavelength range is swept in only 0.16 seconds. As seen in the figure, the quality of spectrum is not significantly degraded by increasing the sweep speed. Both of the slower sweep speeds, the red 2.1 µm/s trace and the blue 4.2 µm/s trace, compare well to the diffuse reflectance FTIR spectrum across the entire wavelength range. The green, 50 µm/s trace matches the other two traces, especially above 9.0 µm. Below 9.0 µm there is a more noticeable, yet still minor, deviation between the fastest and the slower scans. However, it is important to note that the largest acetaminophen signatures, such as the pronounced signal dips near 8.9 µm, 8.5 µm, 7.5 µm, and 7.25 µm, are also still prominent in the fastest scan.

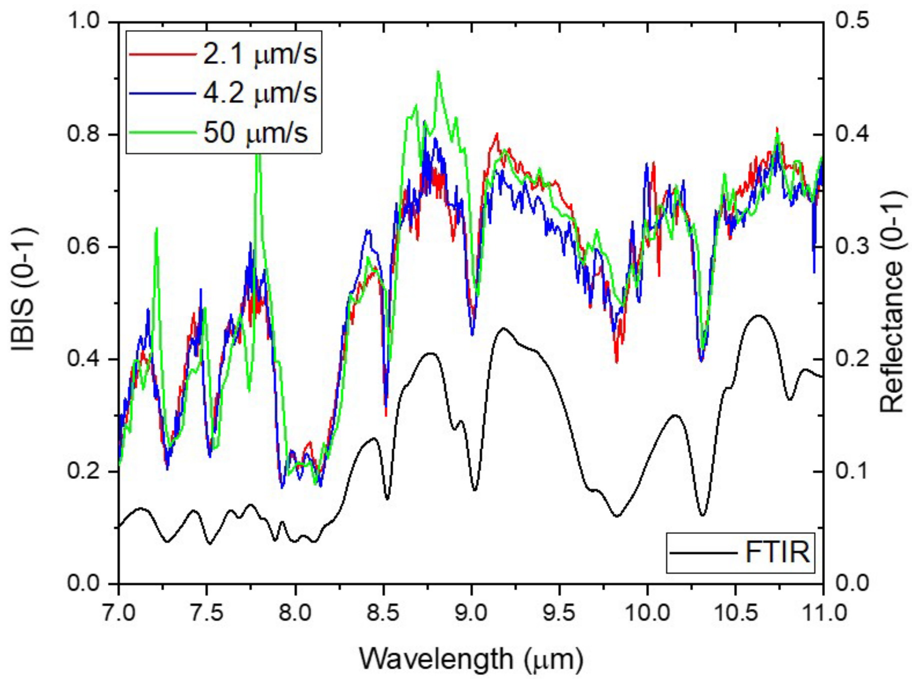

Figure 8. Comparison of different wavelength scanning speeds. The sample is acetaminophen and the standoff distance is 1 meter. The slowest scan speed covers the entire wavelength range in 2.5 seconds, while the fastest is able to cover the entire range in only 0.16 seconds. Even at the fastest speed, the IBIS cart spectrum matches well to the diffuse reflectance FTIR spectrum.

4. ADDITIONAL ANALYTE AND SUBSTRATE MATERIALS

To make IBIS practical for Naval and wider DOD applications, it must be trained to detect a list of relevant materials, including in the presence of arbitrary benign substrate materials. Prior to the NISE project, we focused on a few high priority explosives (e.g. RDX and PETN) and a few surrogate analyte materials (e.g. acetaminophen, caffeine) that could be safely handled in bulk. We also utilized a few representative substrates (glass, bare metal, painted metal, plastic) that exemplify some major classes that would be expected during some applications. During the NISE project, we have substantially expanded both the analyte library and the substrate range. Table 1 below lists the explosives, drugs of abuse, other analytes, and substrates that were added to the IBIS library during the NISE project.

New Explosives or explosives related chemicals	New Drugs	Other New Analytes	New Substrates	Relevant Substrates
$KClO_3$	Heroin	Warfarin	Acrylic (poly(methyl methacrylate)	Black painted metal
HMTD	Cocaine	Lactose	Cardboard	Car panels (Red, Black)
$KClO_4$		Ibuprofen	ABS plastic (acrylonitrile butadiene styrene)	Cell phone cases
Tetryl			Vinyl (Polyvinylchloride)	Nylon fabric
TNT			Delrin (Polyoxymethylene)	Packing Tape
KNO_3				
NH_4NO_3				

Table 1. The explosives, drugs of abuse, other analytes, and substrates that were added to the IBIS library during the NISE project.

5. COMPACT BREADBOARD

One goal of the NISE program was to reduce the size, weight, and power (SWAP) of the IBIS system (Figure 1). While we focused on other aspects of the IBIS system, we did manage to make progress on reducing SWAP toward the end of the NISE project. The images below in Figure 9 show an updated prototype IBIS platform with a reduced SWAP, when compared to the previous IBIS Cart. Panel A) shows a top view of the prototype optical breadboard, which has reduced optical complexity while adding a two-axis beam-steering galvo mirror. The breadboard has a 40% smaller area than the previous IBIS Cart. In panel B), The IBIS optical breadboard is shown mounted on a pan/tilt stage on a new, shorter, and lighter cart. The pan/tilt stage allows the cart to interrogate targets anywhere within a wide cone of angles, without moving the entire cart, as required for the previous cart. Panel C) show a front view of the new, shorter cart. The previous IBIS cart is in the background.

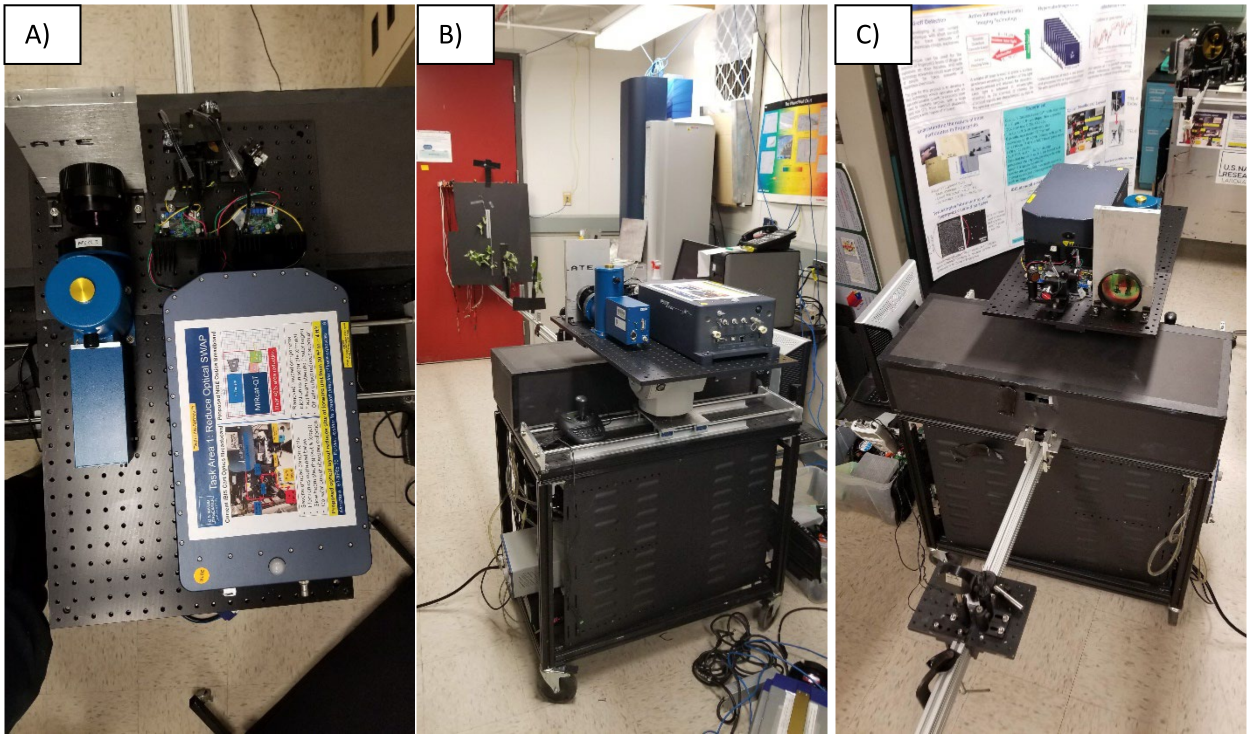

Figure 9. The prototype IBIS platform with reduced SWAP. A) The prototype optical breadboard has reduced optical complexity while adding a two-axis beam-steering galvo. The breadboard has a 40% smaller area than the previous IBIS Cart. B) The IBIS optical breadboard is mounted on a pan/tilt stage on a new, shorter, and lighter cart. C) A front view of the new, shorter cart. The previous IBIS cart is in the background.

6. ALGORITHM

Another goal of the NISE project was to further develop an algorithm that could classify the IBIS spectral data to detect threat materials such as explosives. For this effort, we focused on convolutional neural networks (CNN), which utilize patterns in the spectra to rapidly (~milliseconds) classify threats. Employing synthetic data as a library to match with empirical data is an important milestone in the implementation of the CNN for a system based on IBIS, but is not sufficient to transition the technology. In order to transition IBIS into a field technology it must be able to collect and classify experimentally measured targets. Pre-training a CNN is especially expedient for the analysis of hyperspectral images where a large number of spectra (as many as 16,384) are generated simultaneously. Using a pre-trained CNN, the classification of an unknown spectrum can take just a few milliseconds of processing time. As an example, we measured a heterogeneous sample containing RDX particles confined to a 1 mm region near the center of a 50 mm square glass slide, shown in Figure 10b. Each pixel in the IBIS hypercube undergoes is run through the CNN (which was previously trained on synthetic data to detect 44 different analytes) for classification.

The CNN assigns every pixel a label from the list of 44 trained analytes. Figure 10 shows the IBIS classification signal from the hypercube collected from the 1 mm spot target of RDX on glass. The left panel, Figure 10a, is an image generated from the pixels classified as one of the four explosives in the list, with those pixels colored orange. Any pixel that was not labeled as an explosive is colored black. The right panel, Figure 10b, is the frame from the IBIS hypercube measured at λ= 9.25 μm (a high point in the reflectance spectrum of RDX), which illustrates where to expect to find the signal from the explosives close to the center of the image. Comparing the two panels in Figure 10 shows good "chemical target mapping" performance from the CNN trained on a synthetic data set when applied to an experimentally collected IBIS hypercube.

According to our optical microscopy analysis for particle counting and mass loading calculation, the 1 mm contaminated spot contains about 0.650 μg of RDX total. The left panel of Figure 10 has about 30 pixels that were classified as containing explosive, indicating that on average each of those pixels would represent about 21 ng of material. Based on this analysis, at one meter standoff distance, IBIS is successfully detecting and mapping explosives particles on a substrate at trace mass loading levels.

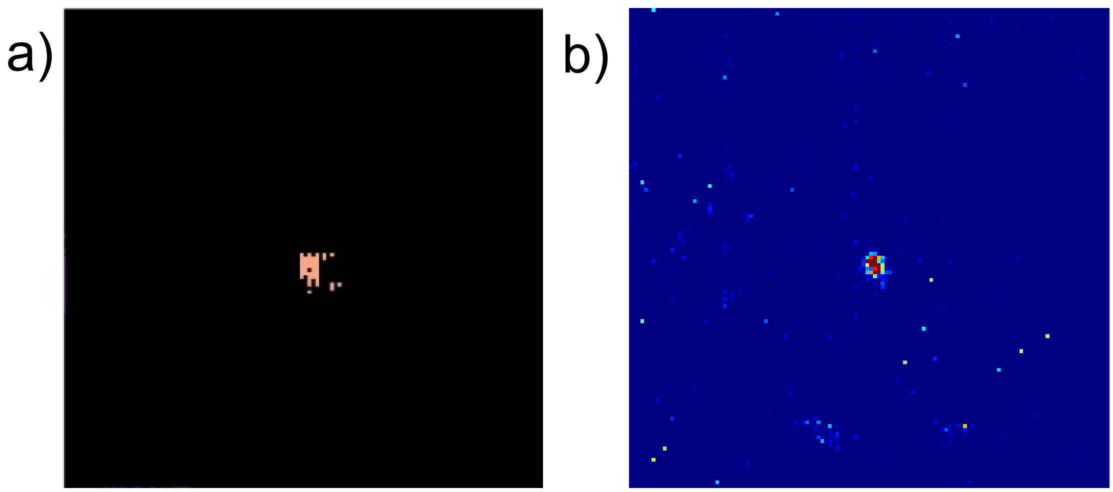

Figure 10. a) Left panel is a "chemical target map" image generated by CNN classification of spectra from an IBIS hyperspectral image cube. Pixels where the CNN found explosives were colored orange, pixels where explosives were not found were colored black. b) The right panel is a frame from the IBIS hyperspectral image cube corresponding to a wavelength where RDX has high reflectivity (9.25 μm).

Technology Transition: The ultimate objective of the IBIS development project is to transition the IBIS technology beyond NRL and ultimately toward applications to meet Navy, Marine Corps, DoD and DHS needs. The NISE project helped push IBIS toward technology transition in several ways and to multiple external sponsor organizations. The Joint Improvise Defeat Organization (JIDO), within the Defense Threat Reduction Agency (DTRA) is currently funding NRL to further develop the IBIS technology and demonstrate its capabilities to detect explosives. In addition, we are working to transition active infrared standoff detection technology to industry through third party sponsors such as the Intelligence Advanced Research Projects Agency (IARPA) SILMARILS program, the DHS SED-V program, and the ongoing DHS Vehicle Screening program. To transition the technology with a commercial partner, specifically for DOD applications, we have recently submitted a White Paper to DASA with an industry partner.

Summary/Conclusions: The 2020/2021 IBIS NISE program successfully achieved its numerous objectives to advance the Infrared Backscatter Imaging Spectroscopy technology to detect explosives at standoff distances in support of Navy and Marine Corps needs. As part of this project, the effective standoff distance was increased from 1 meter to 5 meters, and the sample measurement time was reduced from several seconds to 0.16 seconds. In addition, the beam wander was reduced to substantially improve the signal to noise ratio. The IBIS technology was demonstrated to detect a range of additional chemical targets, and in the presence of several new relevant substrate materials. A compact breadboard was designed to reduce the size of the optical platform by 40% while adding a beam steering and scene pan/tilt capability. In addition, a convolutional neural network (CNN) algorithm was developed to detect explosives on a pixel-by-pixel basis from the collected IBIS hypercubes. Finally, technology transfers were achieved through external sponsorship from DTRA, IARPA, and DHS.

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