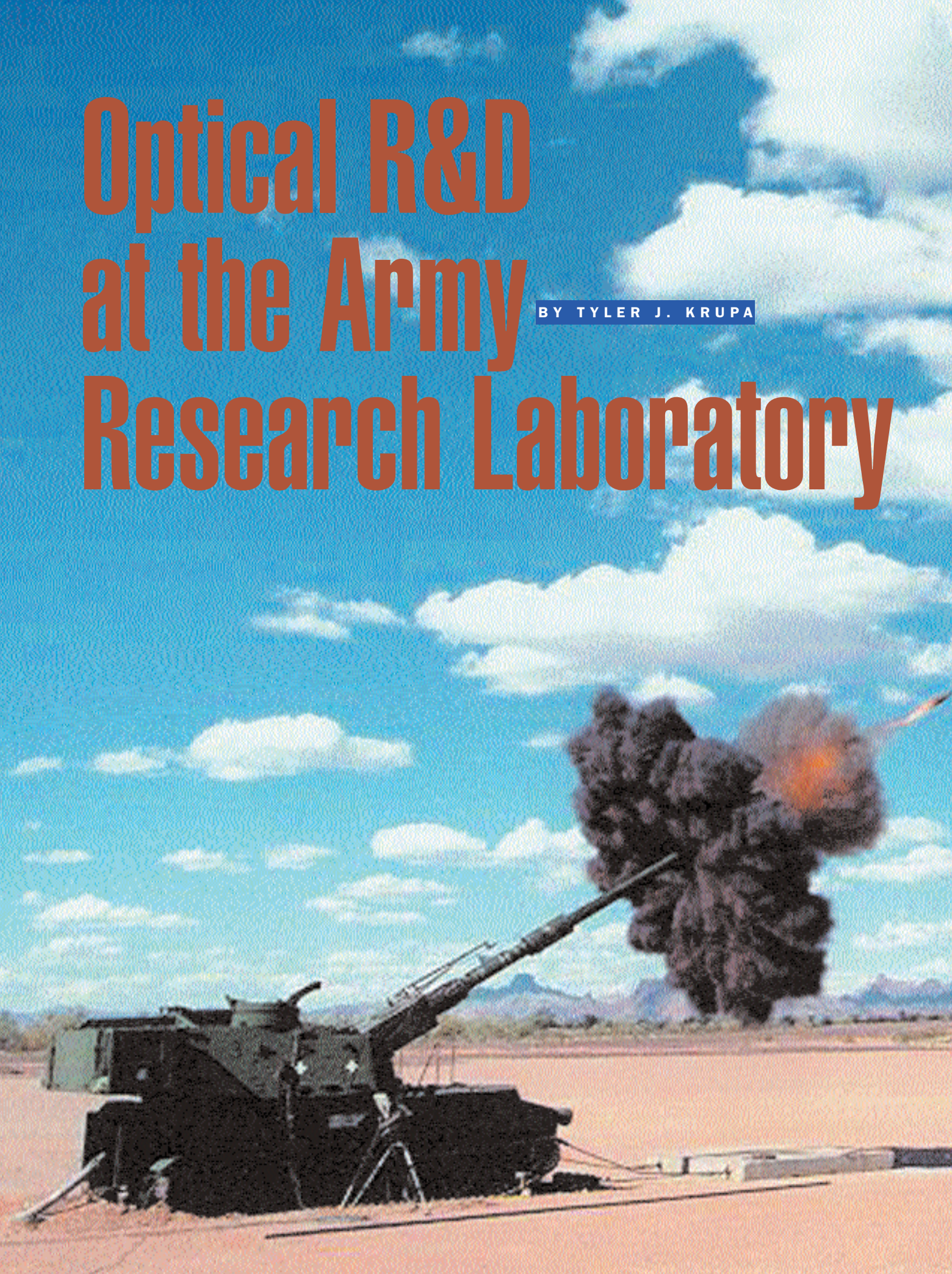
Optical R&D at the Army Research Laboratory

BY TYLER J. KRUPA



As clearly evidenced during the 1991Gulf War, optical technologies are playing a significant role in modern-day US Army operations. Night vision devices, missile guidance systems, and target detection are just a few of the optical applications that have proven capable of increasing military efficiency and decreasing the number of casualties. Since such a large part of the Army's success now depends on sophisticated systems and weaponry, active research and development (R&D) in cutting-edge optical technology has become a priority.

The Army Research Laboratory (ARL), with sites at Aberdeen Proving Ground (APG) and Adelphi, MD, pursues research and technology development to enhance the effectiveness of America's armed forces and protect the safety of war fighters. Research efforts span the gap between *basic research*, to improve our understanding of scientific phenomena, and *technology generation*, to support system developments. A number of important projects involving optical technology are underway at the ARL. To demonstrate the key role of optics in Army applications, this article highlights three specific research areas that have been identified by the military as being particularly promising.

Optical sensors for measurement of toxic and hazardous compounds

For a variety of reasons, the Army must possess advanced capabilities to evaluate the presence of toxic and hazardous compounds during peacetime and periods of military conflict. ARL's applied spectroscopy group at Aberdeen Proving Ground is engaged in a number of chemical sensing projects. Group members Drs. Andrzej W. Miziolek, Kevin L. McNesby, Robert G. Daniel, R. Reed Skaggs, and postdoctoral research associate Dr. Richard T. Wainner are developing advanced sensors for detection of toxic gases during fire suppression tests of halon alternative compounds (see Figure 1). They are also using applied spectroscopy for plasma and environmental research.

Applied spectroscopy, for example, is now being used by the Army to identify new fire suppressants

Figure 1. M-1 Abrams tank under test assault conditions for fire suppression research and development.

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Figure 2. Dr. Kevin McNesby and the tunable diode laser absorption spectroscopy (TDLAS) set-up. McNesby is adjusting the lock-in amplifier for phase-sensitive detection of a near infrared laser operating at ~1.3 microns, which corresponds to the HF 0-2 overtone transition.

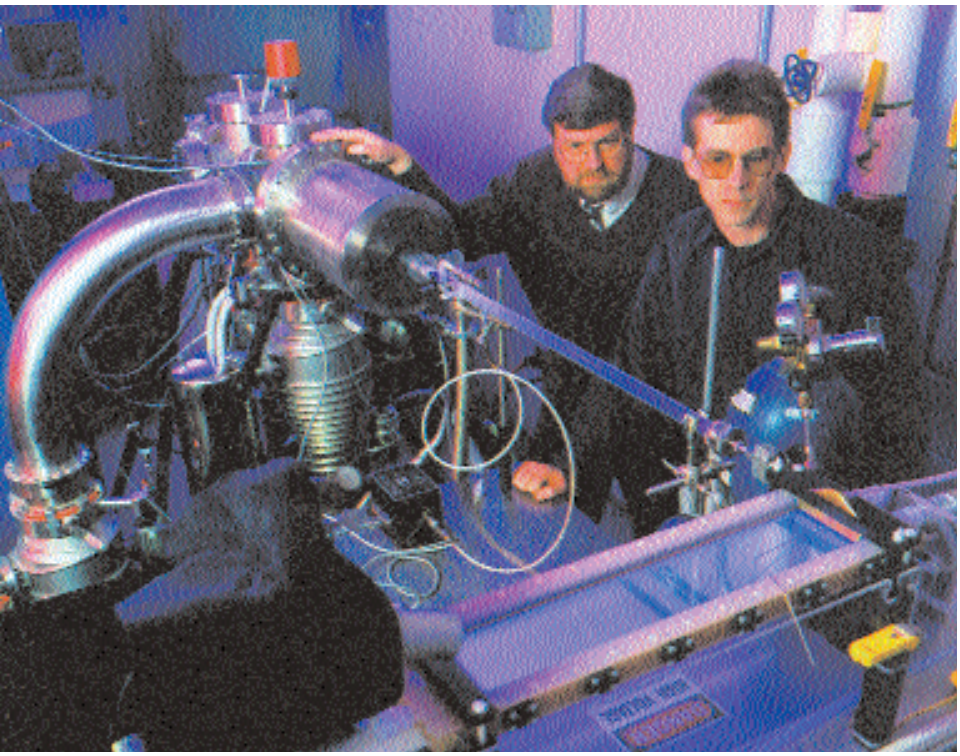

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Figure 3. Drs. Robert Daniel and Andrzej Miziolek observing a silent discharge plasma, the output of which is being sampled by a triple quadruple mass spectrometer.

for use on military ground fighting vehicles. The Army needs to find new fire suppressants that will work quickly, produce a minimum of toxic gases, be compatible with storage materials, and meet environmental safety standards. The need has become more compelling as a result of new concerns about the destruction of the stratospheric ozone layer by the fire-fighting agent halon 1301 (CF_3Br). To assist in the testing and evaluation of halon replacement agents, the ARL group has performed research using two optical sensing techniques: laser-induced breakdown spectroscopy (LIBS) and near-infrared tunable diode laser absorption spectroscopy (NIR-TDLAS).

Hydrofluorocarbons represent one of the most promising groups of candidate halon replacement compounds. Unfortunately, they are not as efficient as halon 1301 and tend to produce toxic hydrogen fluoride (HF) molecules as they suppress flames. For applications inside the crew compartment of Army fighting vehicles such as the M1 Abrams tank (see photo), there is concern about excessive production of the toxic and corrosive HF, which could affect soldiers and equipment. The ARL group, in collaboration with William Bolt of the Aberdeen Test Center and Steve McCormick of the US Army Tank-Automotive & Armaments Command (TACOM), have developed a TDLAS-based HF chemical sensor for use in full-scale fire suppression testing of various halon alternatives.[1-2] This sensor was first assembled and tested in the laboratory (see Figure 2); it was later transitioned to field use in a particularly hostile measurement environment consisting of intense transient flame. This chemical sensor allows for real-time measurement of HF concentrations down to the parts-per-million level.

Emission and laser spectroscopy are used along with mass spectrometry to understand the chemical reactions that occur during non-thermal plasma (NTP) processing of air streams which simulate exhaust gases generated during jet engine testing (see Figure 3). The ARL group is collaborating with the Los Alamos National Laboratory (LANL), the National Institute of Standards and Technology (NIST), and McMaster University (Ontario, Canada) on a project to use NTPs to clean up such exhaust, which contains large amounts of nitrogen oxides and hydrocarbons. Spectroscopic diagnostics of various stable and reactive species inside the plasma—in conjunction with computational fluid dynamics (CFD) simulation of the plasma reactor being carried out by Dr. Michael Nusca of the ARL—is shedding new light on the chemical processes that occur inside these plasmas.[3] A better understanding of such mechanisms allows for scale-up and optimization of plasma reactors for practical field applications.

The ARL spectroscopy group is also collaborating

with ADA Technologies (Littleton, CO) on an Army Research Office-sponsored project to develop field-portable laser-induced breakdown spectroscopy (LIBS) sensors. In LIBS, a technique based on solid-state lasers, a pulsed laser is focused on a sample to form a plasma (see Figure 4). The plasma produces atomic, ionic, and molecular fragment emissions characteristic of the elemental composition of the irradiated sample (Figure 5). Lenses or fiber optics are then used to collect the emission of atomic and molecular constituents excited within the plasma. Typical LIBS plasma temperatures are in the 20,000 to 25,000 K range for gases at atmospheric pressure.[4] The LIBS detector captures the plasma emission spectrum in the 200- to 800-nm range, which is analyzed to identify and quantify the sample components. Most elements emit light in the 200- to 900-nm region.

The ARL team has demonstrated that LIBS, like NIR-TDLAS, is a sensitive technique for the detection of halon alternatives.[5-6] Single-shot spectra have been recorded with nanosecond time precision for application in large-scale fire suppression tests. This work has been supported by the Department of Defense's Next Generation Fire Suppression Technology Program (NGP). Other military applications of LIBS include the detection of energetic materials and the detection of chemical and biological warfare agents.

Environmental applications for LIBS are also evolving. Recently Dr. Russell Harmon of the Army Research Office performed field studies using the ADA-developed portable LIBS sensor to detect lead (Pb) in paint and soils at Ft. Carson, CO, and in air particulates in Panama City, Panama.

A second group at ARL/APG is developing luminescent sensors for the detection of chemical and biological agents in water. Dr. Ray Yin of the Polymers Research Branch, along with postdoctoral research associates Drs. Amanda Jenkins and Matthew Bratcher, have constructed novel polymer based materials for chemical and biological agent detection.[7] The chemical sensing materials are designed to selectively detect phosphonate-containing species in water, such as pesticides and nerve agents. The chemical sensing materials, based on molecular imprinting and sensitized lanthanide luminescence, function by selectively binding the phosphonate group to a functionality-imprinted

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Figure 4. Dr. Richard Wainner creates an LIBS spark, shown in the computer monitor.

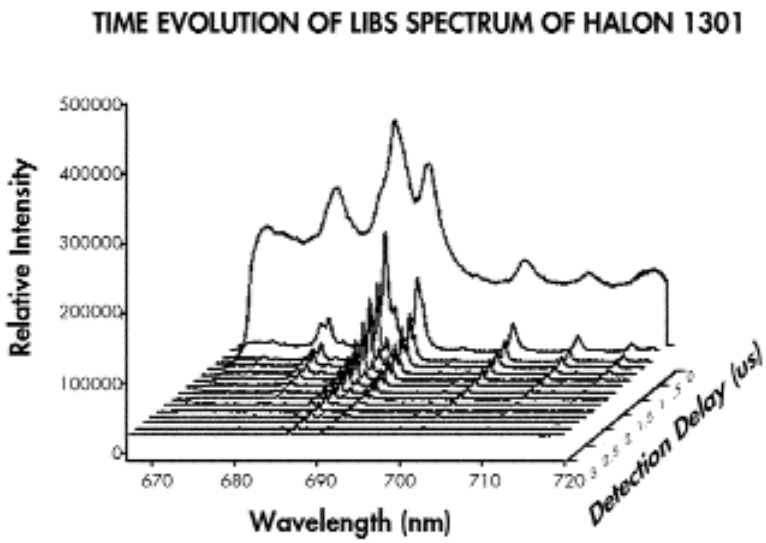


Figure 5. Time-resolved LIBS spectra for 1% halon 1301 in an air flow. The spectral features originate from atomic fluorine plasma emission.

Figure 6. Field-portable LIBS instrument overview.

co-polymer possessing a coordinatively bound luminescent lanthanide ion. The resulting co-polymer is coated on a multi-mode optical fiber, and the ligand field shifted luminescence is excited using a 470 nm light-emitting diode (LED). A miniature spectrometer is used to monitor the changes in lanthanide luminescence that result when the analyte is coordinated to the co-polymer. The limits of detection for this type of sensor are in the low parts per trillion in solution, with linear ranges from low parts per trillion to parts per million. The same instrumental scheme has also been used to construct biological agent sensors. In this case, however, a polymer film containing a fluorescent dye specific for biological detection replaces the imprinted polymer. Preliminary results indicate that the biological sensors will be sensitive in the parts per billion region or lower.

Laser ignition

Scientists at the Army Armament Research, Development, and Engineering Center (ARDEC) and the ARL have successfully developed the Laser Ignition System (LIS), a laser firing method poised to revolutionize the way the military fires large caliber cannons. The LIS requires no primer or igniter materials to fire weapon systems. Currently, all large caliber Army cannons use a primer and igniter material to ignite the propellant charge. A soldier needs to load the projectile into the cannon, insert a primer into the gun breech, and then fire the gun while standing at the rear of the weapon by pulling a lanyard that initiates the firing process. The LIS eliminates the need for a soldier to stand behind the weapon since the laser used is computer controlled, which makes it safer to fire.

"Laser ignition is the first major change in the way guns have been fired in the past 100 years," says Dr. Brad Forch, chief of the Ignition and Combustion Branch of the Weapons and Materials Research Directorate.

A key aspect in development of the LIS was finding an inexpensive but reliable window in the breech of the gun through which the laser could be fired. The problem was finding windows that could stand up to firing, which puts up to 50,000 pounds of pressure per square inch on the inside of the barrel. Forch and his team, which includes Drs. Richard Beyer, Stephen Howard, and Mike McQuaid, helped solved this problem by developing a sapphire window that could withstand numerous shots without breaking. The ARL developed window costs about $100 to produce, as compared to $3,000 for earlier windows. Once Forch's team had developed the window, work on the LIS progressed rapidly.

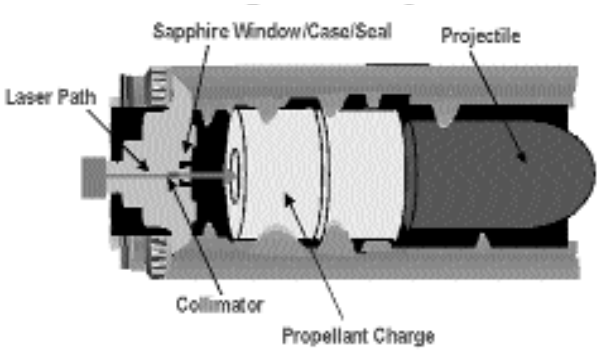
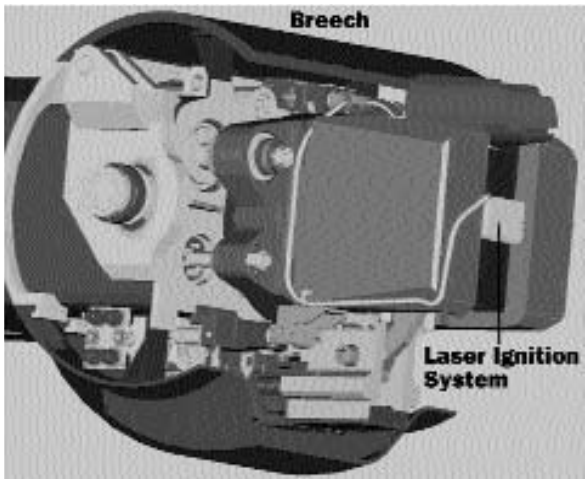
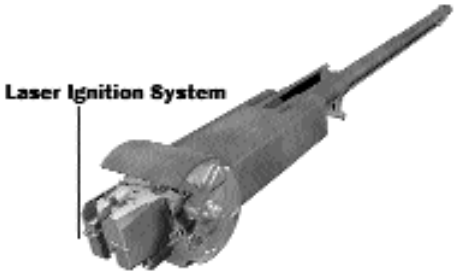


Figure 7. Laser ignition system of breech-mounted laser.





Figures 8 and 9. Basic concept of laser ignition.

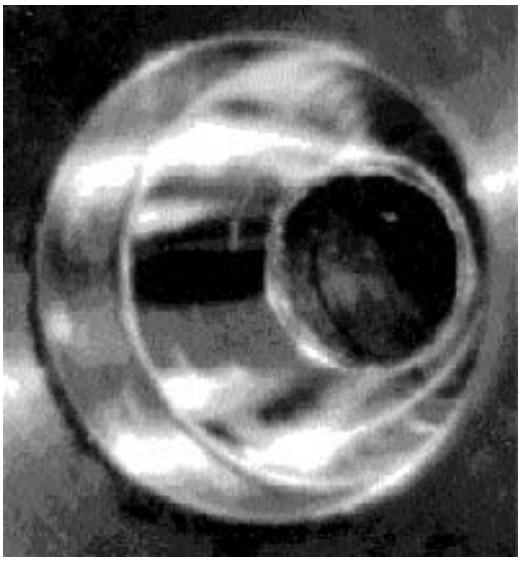


Figure 10. The sapphire window used in the LIS.

Besides the safety aspects implicit in no longer requiring the presence of a soldier to stand behind a weapon to fire it, the LIS provides the military with numerous other advantages, the effectiveness of which make safety only relative to whoever is doing the shooting. Since a manually loaded primer is no longer a necessity, the LIS can provide much higher firing rates than conventional large caliber weapon systems. In addition, the LIS eliminates any accidental off-target firing by allowing military personnel to have full computer control of the laser interfaced to the automatic fire control system.

On account of its efficiency, Army officials have selected the LIS as the igniter for the Crusader 155mm self-propelled howitzer. The LIS will provide Crusader with the capability of delivering projectiles accurately

Figure 11. Laser ignition provides Crusader with the capability of delivering projectiles accurately from five to more than 40 kilometers at rates of fire of up to 10 rounds per minute.

Figure 12. Apache helicopters.

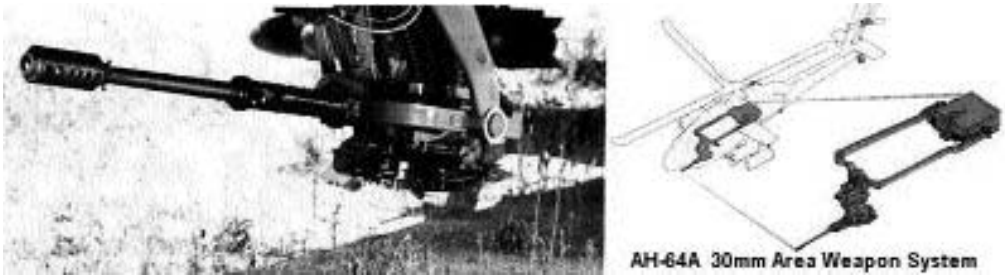


Figure 13. Apache AH-64A 30mm area weapon system.

from five to more than 40 kilometers at rates of fire of up to 10 rounds per minute. The multi-lug, slide-block breech on Crusader is light, compact, and provides fast, automated actuation to support high rates of fire. The LIS is integrated for compatibility with breech automation to deliver firing reliability at high rates for long periods of time. With this technology, Crusader provides extremely responsive, long range, and accurate firing capabilities. Crusader's ability to fire the first rounds of a mission in 15 to 30 seconds ensures rounds will strike where the enemy is—not where he was.

Widespread use of the LIS as an igniter seems plausible since the system can be retrofitted. The LIS is already being modified for use with the Apache helicopter M230 30mm automatic cannon. Gun targets are similar to rocket targets, but the gun is usually the best self-defense weapon as it can easily and rapidly be fired in directions other than where the helicopter is facing. The Apache, a twin-engine attack helicopter, was first used in combat in December 1989 in the US military action in Panama. In the 1991 Gulf War, 15 battalions were equipped with 288 Apaches. The helicopter has also supported low intensity and peacekeeping operations worldwide, in areas including Turkey and Bosnia.

The Apache 30mm automatic Boeing M230 Chain Gun now provides a rate of fire of 625 rounds per minute and has a capacity for up to 1,200 rounds of ammunition. The rounds used by the Apache 30mm canon are one-piece bullets that possess a hard case, a projectile, and inside, a propellant. The case acts as the pressure seal. To make the Apache 30mm canon LIS compatible, the ARL has successfully developed a bead-like glass window as part of the 30mm cartridge. Since the window is actually a part of the cartridge, it is used only once, before being thrown away with the spent cartridge case. Costing only pennies, these windows will make the use of laser-ignited Apache 30mm rounds feasible. With the aid of the LIS, these multi-mission helicopters are expected to become even more lethal and combat effective.

Now that much of the fundamental work on the LIS is complete, the system has been transitioned over to the Army Armament Research, Development, and Engineering Center (ARDEC) for additional development. Forch and his team are now looking for new and more efficient materials to downsize the LIS in the ongoing Army drive to achieve lighter, more mobile weapon systems.

AOTF-based hyperspectral imaging

A variety of military imaging sensors are being developed to detect, recognize, and classify objects and backgrounds. These objects and backgrounds can be identified because they reflect and/or emit light with a rich spectral content that is captured in a number of spectral bands by the sensors. Another way sensors discriminate targets and backgrounds is to make use of polarization signatures: man-made objects have more defined polarization signals than natural objects such as soil and vegetation. Since the choice of a specific spectral band for imaging is made on the basis of both the object and its background, an adaptable hyperspec-

AOTF Imager Development Program at ARL

Imager	Spectral Band (μm)	Material Used	FPA
Vis/NIR	0.4–1.0	TeO_2	Si – CCD 640 × 480
SWIR	0.8–1.7	TeO_2	InGaAs 320 × 240
MWIR	2.0–4.5	TeO_2	InSb 256 × 256
LWIR	8–11.5	TAS	HgCdTe 256 × 256

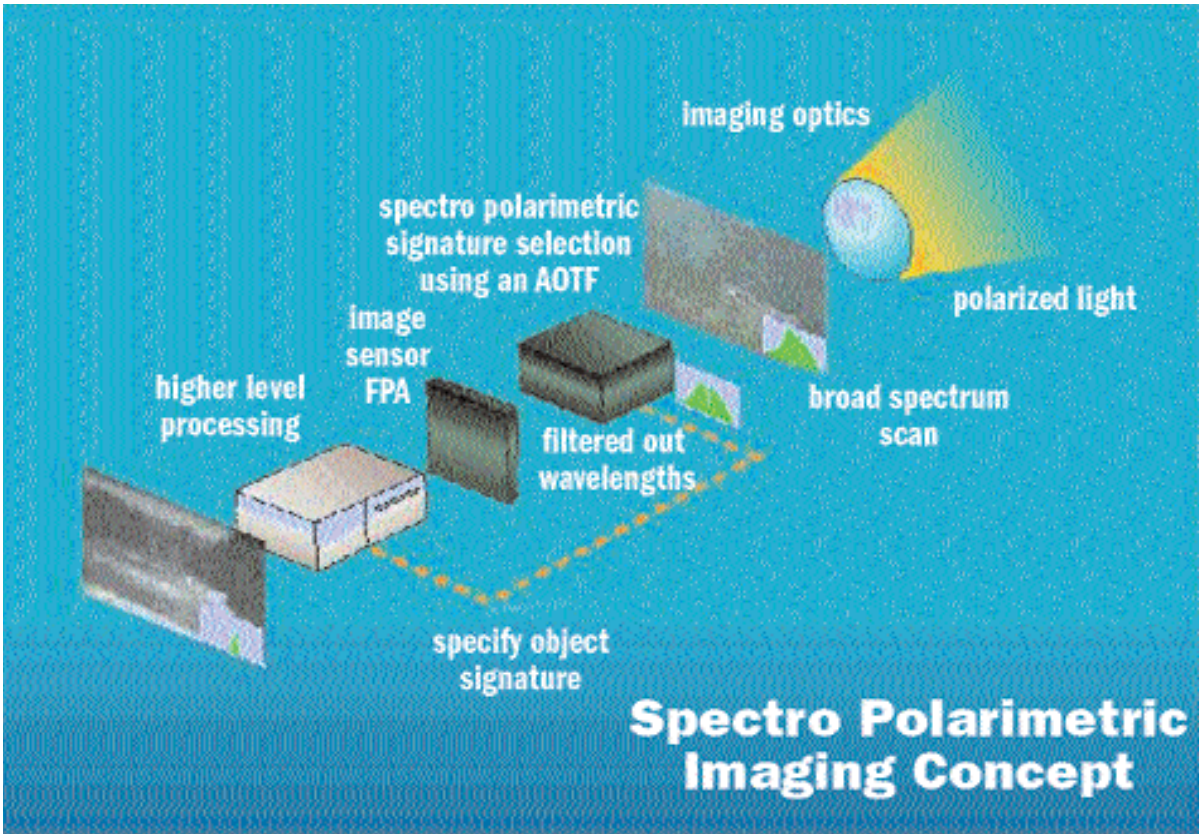


Figure 14. Operation of an AOTF Hyperspectral Imager.

tral imaging system with spectral and polarization discrimination capabilities is required to accomplish the Army's remote sensing tasks. At the ARL, another team of researchers, this one led by Dr. Neelam Gupta, is developing such imagers using acousto-optic tunable filters (AOTFs). This work is part of the demonstration program for the Third Generation Infrared Imaging Technology thrust being pursued by ARL and the Army Communication and Electronics Command (CECOM).

An AOTF is an electronic filter in which a grating is set up in an anisotropic crystal by the propagation of a sound wave generated by an applied radio frequency (rf) signal. The wavelength of the diffracted light is selected by tuning the applied rf. An AOTF is a programmable grating that allows the fabrication of a hyperspectral imager that can be rapidly tuned, either sequentially or randomly. Rapid tuning makes AOTFs useful in situations where target and background scenarios may change rapidly.

AOTF-based imagers developed by Gupta's team have numerous advantages over traditional imaging systems. Designed for Army field operations, these AOTF imagers are compact, rugged, vibration-insensitive, programmable, and can operate from the visible to the long infrared wavelengths.[8-13] An AOTF imager can also be operated in a multispectral mode by simultaneous application of multiple rf signals. This feature will allow military personnel to measure complex spectral signatures of objects and backgrounds in cases in which a single spectral band is not sufficient for accurate discrimination and identification. ARL is developing AOTF imagers in the visible-to-near IR (VNIR, 0.4-1 μm), short-wave IR (SWIR, 0.8-1.7 μm), mid-wave IR (MWIR, 2-5 μm), and long-wave IR (LWIR, 8-12 μm) spectral regions.

One example, the VNIR imager, uses a TeO_2 AOTF cell that covers the spectral range from 400 to 1000 nm with an Si-CCD camera. It is compact, portable and has been used to carry out AOTF imaging experiments in the laboratory and the field. The VNIR hyperspectral and polarimetric imaging system uses a non-collinear TeO_2 AOTF cell, a liquid crystal variable retardation (LCVR) plate, and an off-the-shelf CCD camera. Other hardware includes: an rf drive unit; a host computer; and a frame grabber. All of the optical instruments (including the lenses, the retardation plate, the AOTF cell, and the CCD camera) are mounted on a platform as a unit with a light-tight cover.[14] The rf drive and host computer are separate units, with the imaging board located inside the host computer.

The VNIR AOTF-based hyperspectral imaging systems, developed by the Carnegie Mellon Research Institute (CMRI) and the Advanced Materials Corporation (AMC) of Pittsburgh, PA, have been used in several laboratory and field tests. The tests covered scenar-

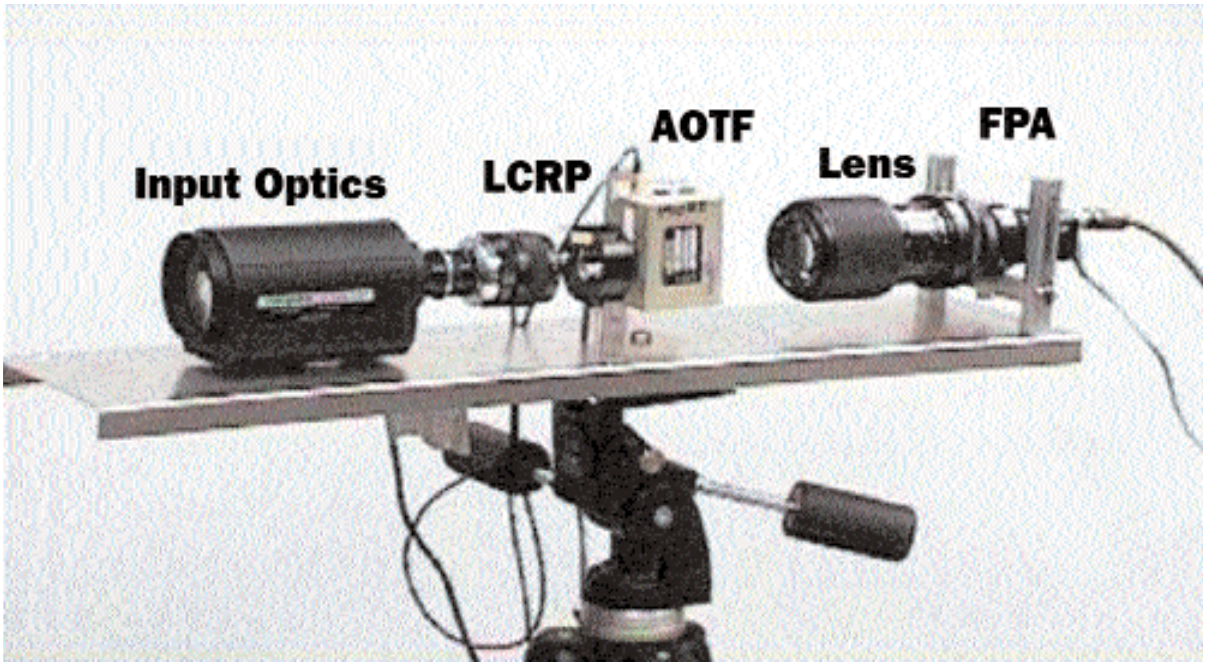


Figure 15. The VNIR AOTF-based hyperspectral/polarimetric imager.

ios of single or multiple targets in a variety of backgrounds. The targets included vehicles, buildings, roads, vegetation, and a vehicle covered by a camouflage net. Spectral images were recorded at 10- or 20-nm spectral intervals in the spectral range from 450 to 1000 nm. During these field tests, researchers acquired a significant body of hyperspectral and polarimetric imagery data that illustrated the distinct target detection and discrimination capabilities of the VNIR imaging system.

A full-color camcorder image of a truck concealed under a net, compared with a spectral image taken at 660 nm of the same truck, is just one example of the effectiveness of AOTF-based imaging: the full-color camcorder image does not reveal any sign of the concealed truck. But the spectral image brings it into view. This field test shows that camouflage netting, while very effective visually, can be easily defeated by hyperspectral imaging.

Gupta's team is now working to finish development of the electronics, control, and image processing software. She plans to use a laptop computer to control the imager with a menu-driven Labview 5.1 based environment. A digital camera may be used for image acquisition with an IEEE-1394 bus. The rf control will be achieved by sending an input control word from the computer to a direct digital synthesis (DDS) rf synthesizer to generate a single tone rf output. Gupta feels that these features will allow researchers to obtain high quality images at a frame rate of 30 Hz without any image compression.

VNIR image analysis illustrates the capabilities of AOTF-based imaging for target detection and discrimination, and validates ARL's research of hyperspectral imaging for such purposes. Gupta and other researchers at ARL are in the process of extending the AOTF-based hyperspectral imager's capabilities to the infrared, where there are more spectral signatures and the polarization content is much more significant than in the VNIR range.

When AOTF imagers are completed, it will be possible to mount them on manned and unmanned ground and air vehicles. Applications are set to include remote detection of chemical and biological warfare agents; detection of low-visibility targets; detection of freshly dug ground; and mine detection.

Conclusions

Optical research and development have become critical to the high-tech weapon and sensing systems used by today's Army. Research performed at the ARL reflects the extent to which optical technology is used in Army operations. Optics are certain to make a dramatic difference in how military forces in the 21st century conduct combat operations. Optical sensors that can provide real-time toxic gas measurement, laser ignition systems that provide constant, more accurate fire power, and mountable AOTF-based hyperspectral imagers that can detect and discriminate targets regardless of background or camouflage are just some of the ways the Army is striving for technological superiority. Although ARL optical research and development are equated with a more lethal and invulnerable land force, as new uses develop, civilian applications such as detecting pollutants in the environment and fire sensing will also emerge. In this regard, optical initiatives clearly play a large part in the future of the Army and the country it protects.

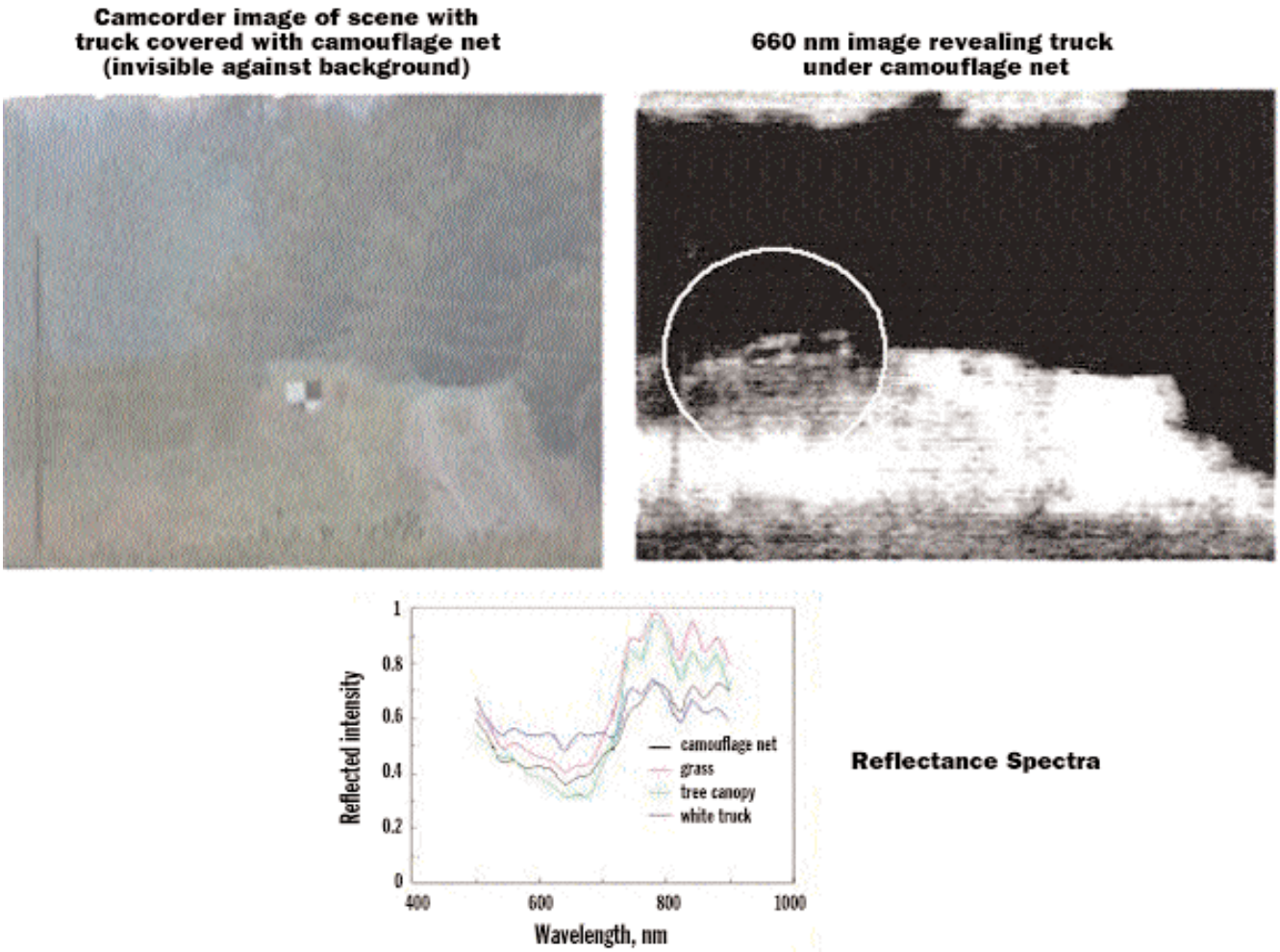


Figure 16. Spectral identification of a hidden truck at 0.7 km.

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