Science & Technology REVIEW

May 2006

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Seeing Gamma Rays More Clearly

Also in this issue:

- **Rapid Detection of Animal Diseases**
- **Measuring Temperatures in Extreme Environments**
- **A Small Perturbation with Big Results**

About the Cover

Gamma-ray detection is an important technology for homeland security because it allows security agencies to search for and detect illicit radioactive sources. With funding from the Department of Homeland Security, Livermore scientists are using their expertise in radiation detection to improve the nation's capabilities in this area. The article beginning on p. 4 describes two Livermore-developed imagers that can depict gamma rays without mirrors or lenses. The first, a large-area gamma-ray imager, detected millicurie quantities of a cesium isotope from 85 meters away. The second imager is a portable system that relies on Compton scattering to pinpoint the location of a gamma-ray source. The cover shows one version of the Compton imager (foreground) and an example of its results superimposed on a photograph of the surveyed area.

Cover design: Daniel Moore

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on ensuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Prepared by LLNL under Contract No. W-7405-Eng-48

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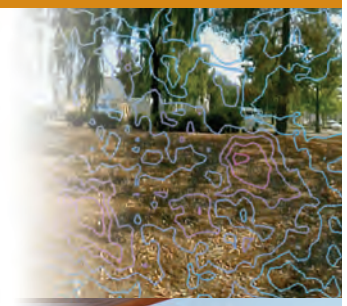

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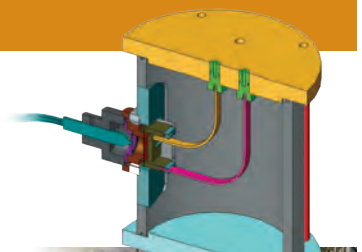

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S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Policy, Planning, and Special Studies.

S&TR is available on the Web at www.llnl.gov/str.

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-06-5
Distribution Category UC-99
May 2006

Simulating the future water supply in California

Collaborative research involving Livermore scientists indicates that if concentrations of atmospheric carbon dioxide double from preindustrial levels, the resulting warming may dramatically change river flows in California. The simulations show that in a hypothetical El Niño season—a naturally occurring climate oscillation—state water managers may have to contend with an increased risk of both flooding and water shortages. For the simulations, researchers assumed that the strength of an El Niño event, as measured by increased sea-surface temperatures over long-term averages, would be the same in this warmer future as today. In California, an El Niño season typically brings more rain, which increases river flows and flood risk.

California's water infrastructure is efficient at providing an adequate water supply and minimizing flood risk. The system, however, works well only in a climate that includes large amounts of mountain snow. Melting snow keeps reservoirs full in the late spring and summer, after rain and snowfall have stopped. Too much water falling in the rainy season causes flooding, but too little will decrease levels in the state's reservoirs.

If winter temperatures warm because of carbon concentrations, more rain than snow will fall at higher elevations. In areas where snow does accumulate, it will melt sooner than it does in a normal year. These changes will result in higher river-flow rates during winter and lower rates during spring and summer, when flows normally are from snowmelt. In addition, if river-flow rates are too high during the winter, water managers will have to reduce reservoir levels to capture the increased winter flood surges. Those releases would further reduce the overall water supply for the entire year. The collaboration, which was led by professor Edwin Maurer from Santa Clara University, published its results in the January 27, 2006, issue of *Geophysical Research Letters*.

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Demonstration checks readiness for biological attack

In January, researchers from Lawrence Livermore and Sandia national laboratories participated in a two-day demonstration at San Francisco International Airport to test the response and restoration protocols that would be undertaken following a biological attack. This demonstration was part of a three-year collaboration focused on shortening the time line for restoration after an illicit bioagent attack. Funded by the Department of Homeland Security, the Bio Restoration Demonstration Project included participants from several federal, state, and local agencies.

Livermore and Sandia researchers developed a restoration plan with templates that help airport personnel prepare for a biological terrorist attack. Using a mock scenario developed by an interagency team, participants implemented the plan to demonstrate how a facility could be quickly decontaminated and reopened.

Restoration plans include protocols to acquire samples after an attack, analyze the results, decontaminate affected areas, reopen facilities for public use, and if necessary, provide longer-term monitoring. To reduce the cleanup time after an attack, the Livermore–Sandia team also upgraded several technologies, including a Geographic Information System–based indoor sample tracking system, a rapid viability test procedure to determine within days whether anthrax spores are dead or alive, and sampling methodologies to better understand the percentage of anthrax spores collected in samples. As part of this project, the National Academy of Sciences is conducting a study to determine acceptable cleanup levels for anthrax, smallpox, and plague.

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Volcanoes curbed rise in sea level

Simulations using 12 new climate models show that the 1883 eruption of the Krakatoa volcano in Indonesia substantially reduced ocean warming and sea-level rise during the 20th century. This study, which included researchers from Lawrence Livermore, the National Center for Atmospheric Research, the University of Reading in the United Kingdom, and the Hadley Centre for Climate Prediction and Research, examined the effects of volcanic eruptions on climate. The models include climate-forcing mechanisms such as changes in greenhouse gases, solar irradiance, and volcanic aerosols. The research team used each model to simulate the climate from 1880 to 2000 and compared the simulated data with available observations from that period.

Oceans expand and contract with changes in temperature. When the water is warmer, sea level increases; when cooler, it recedes. In recent decades, the volume average temperature of oceans (down to 300 meters) worldwide has warmed by about 0.037°C because of increased atmospheric greenhouse gases. Although seemingly small, this increase corresponds to a sea-level rise of several centimeters and does not include effects from such factors as melting glaciers.

The team's results, which were published in the February 9, 2006, issue of *Nature*, indicate that the sea level would have risen much more had the Krakatoa eruption not occurred. Because volcanic aerosols scatter sunlight, an eruption typically causes the ocean surface temperature to cool, an anomaly that is gradually subducted into deeper layers where it persists for decades.

The research team also studied the 1991 Mount Pinatubo eruption in the Philippines, which was comparable to Krakatoa in terms of its size and intensity. Although similar ocean surface cooling resulted from both eruptions, the heat-content recovery occurred much more quickly after the Mount Pinatubo eruption. The observed warming of the upper ocean, which is primarily due to human influences, more than offsets the volcano's effects.

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Science and Technology Help the Nation Counter Terrorism

WITH the Cold War receding into memory, the U.S. faces a geopolitical environment that is far more complex, less predictable, yet every bit as dangerous as before. Although the U.S. remains a military superpower, traditional models of nuclear and conventional deterrence do not apply to terrorist groups or insurgencies. Al Qaeda and other terrorist organizations have repeatedly stated their desire to acquire and use weapons of mass destruction (WMD) against the U.S. and its allies and interests.

At Lawrence Livermore, we are dedicated to ensuring and enhancing national security within the global context. In addition to our historical responsibilities related to maintaining the U.S. nuclear deterrent, we also strive to reduce the threat posed by the proliferation or terrorist acquisition of WMD. In particular, we are a national leader in the development of technologies, systems, and capabilities to strengthen the nation's ability to prevent, detect, interdict, and recover from WMD incidents or terrorist attacks.

Different approaches are needed to counter the various WMD threats. With the nuclear threat, the goal is to prevent terrorists from acquiring nuclear materials or, barring that, from reaching their intended target with their device. The very nature of radioactive materials makes them detectable at a distance, giving us a technological approach to locating and interdicting such materials. The article beginning on p. 4 describes the development of gamma-ray imagers that can detect weak sources amidst a sea of background radiation. Our large-area gamma-ray imager offers the capability to detect millicurie quantities of a radioactive material at distances approaching 100 meters. A portable system we developed relies on Compton scattering to pinpoint the location of a gamma-ray source. Such imaging detectors will significantly improve the ability of border agents, customs inspectors, law-enforcement officers, and incident response personnel to search for, locate, and identify illicit nuclear material.

A different approach must be taken to address the threat of biological terrorism. Because the materials and equipment needed to make biological weapon agents are widespread and have many legitimate uses, the likelihood of preemptively detecting a biothreat is very low. Therefore, our efforts are directed at developing monitoring systems that can detect a bioagent release in time to contain a disease outbreak. Many of these systems can also be applied to protect public health and the nation's agricultural industries. Additionally, the collaborations and procedures involved in dealing with a livestock-disease outbreak provide real-world experiences that are directly applicable to the response needed to control a naturally occurring or deliberate human-disease outbreak. The article beginning on p. 11 describes Livermore's work to develop assays to rapidly detect foot-and-mouth disease and differentiate it from other diseases with similar symptoms.

The current world situation presents enormous challenges for U.S. national security. WMD terrorism is a potent, ever-present danger that we can help mitigate by developing methods for countering the threats, even as diplomats and others work to address the underlying issues that motivate terrorist groups. Although technology cannot eliminate the WMD terrorism threat, it is a critical force multiplier that increases the effectiveness of our countermeasures.

■ Raymond J. Juzaitis is associate director for Nonproliferation, Homeland, and International Security.

Imagers Provide Eyes to

Gamma-ray imagers with improved detection capabilities help security agencies search for illicit radioactive sources.

THE ability to detect gamma rays is a vital tool for many areas of research. Gamma-ray detectors allow scientists to study celestial phenomena and diagnose medical diseases, and they have been used to determine the yield in an underground nuclear test. Today, these detectors are an important tool for homeland security, helping the nation confront new security challenges. Government agencies need detectors for the scenarios in which a terrorist might use radioactive materials to fashion a destructive device targeted

See Gamma Rays

against civilians, structures, or national events. To better detect and prevent terrorist attacks, the Department of Homeland Security (DHS) is funding projects to develop a suite of detection systems that can search for illicit radioactive sources in different environments.

Livermore researchers have been applying their expertise in radiation detection for more than 30 years. For example, detectors designed for use in treaty inspections can monitor the location of nuclear missile warheads in a nonintrusive manner. (See *S&TR*, October 1995, pp. 14–26.) These detectors measure the gamma rays emitted from the isotopes of nuclear elements contained in weapons. Over the years, Laboratory researchers have developed a range of radiation detection instruments, including detectors on buoys for customs agents at U.S. maritime ports (see *S&TR*, January 2004, pp. 19–22), cargo interrogation systems (see *S&TR*, May 2004, pp. 12–15), and high-resolution handheld instruments that emergency response personnel could use to search for a clandestine nuclear device (see *S&TR*, September 2004, pp. 4–11).

Gamma rays have the highest energy in the electromagnetic spectrum. They tend to go straight through matter, rather than reflect or bend as visible light does. Mirrors or lenses cannot be used to depict, or image, gamma rays, but their energy can measured indirectly by observing how photons interact with a detector material. For many applications, however, researchers need to accurately determine

where gamma rays originate, and doing so requires imaging technology.

For example, many radiation detectors have excellent energy resolution and sensitivity to sources within a range of several meters. At greater distances, however, the source can be lost in a clutter of background gamma-ray emission from the environment, including concrete, natural mineral deposits, and some foods.

Detector developers want to design instruments that quickly survey large areas at a distance and accurately distinguish illicit from background signals. However, when a detector covers a large area, the signal from an object in the background can mimic the signature from a source of interest, even though the sources are widely separated. For example, a concrete building 20 meters from the detector may register the same as an illicit source located farther away. This similarity makes the detection of weak signals impossible unless the characteristics of the background are known in advance—unlikely in searches for clandestine radioactive materials.

Two current projects at Lawrence Livermore are focused on creating gamma-ray images without mirrors or lenses. A multi-institutional collaboration led by Laboratory researchers has developed a large-area gamma-ray imager that significantly increases detection capabilities. Another Livermore team is designing a portable system that relies on Compton scattering to locate gamma-ray sources.

Accurate and Quick Detection

The technology to image gamma rays was introduced in 1957 by Hal Anger, an electrical engineer who worked at Lawrence Berkeley National Laboratory. The camera he developed uses gamma radiation to image metabolic processes within humans, allowing researchers to observe, for example, how blood flows and kidneys function. Biomedical and nuclear medicine research has resulted in improved technologies for gamma-ray imaging. Livermore scientists have partnered in several of these research efforts, such as the small animal radionuclide imaging system. (See *S&TR*, November 2004, pp. 4–11.) Advancements in nuclear medicine are thus contributing to the development

The Livermore-designed gamma-ray imager can be placed inside a small truck. Two coded-aperture masks (gray bars shown in the top photo) allow the instrument to image both sides of a road. In the bottom photo, Klaus Ziock (left) and Lorenzo Fabris (right) assemble and calibrate the masks and detectors (cylinders shown in the middle).

of gamma-ray imaging systems for homeland security.

In 2003, Livermore's Laboratory Directed Research and Development (LDRD) Program funded a project to demonstrate that imaging techniques could enhance the search capabilities over a large area. Led by Laboratory engineer Lorenzo Fabris, the project team included researchers from Pacific Northwest and Oak Ridge national laboratories, the Massachusetts Institute of Technology, and the University of California's (UC's) Space Sciences Laboratory at Berkeley. The collaboration demonstrated a large-area gamma-ray imager that can detect millicurie quantities of a cesium isotope located 85 meters away, even while the imager is traveling at 16 kilometers per hour.

With funding from DHS, the team developed the next-generation prototype imager in 2005. The instrument, which is approximately the size of a sofa, can detect gamma-ray energies ranging from 50 to 3,000 kiloelectronvolts—the energy range of interest in most national security applications—and its sensitivity is much greater than that of nonimaging instruments. Fabris says, "Because we are making an imager that can capture and distinguish many signals within a large area, we can design the radiation detector to be larger." The prototype instrument, which costs about $400,000, can be mounted on a small truck and used to surveil large areas quickly.

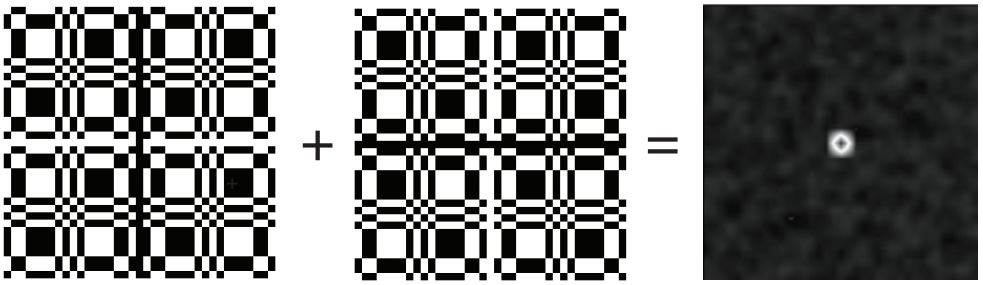
Masks Reveal True Signals

In designing this imager, the team adapted an imaging method originally developed for high-energy astrophysics. With this method, a coded aperture—a lead mask with holes drilled in a special pattern—is placed in front of a detector array. As the detector picks up gamma-ray signals, the photon energy passing through the mask casts shadows on the detector elements, which the imager records. The detector elements also measure the signal count and position. As the instrument travels through an area, it accumulates several shadow patterns, or "shadowgrams," and creates a pixel map of the radiation field of the surveyed region.

"Each pixel represents an area in the field of view," says Fabris. "The pixels are small enough that, when combined, they generate a detailed image of a source of interest. With one map of pixels, we can cover distances out to 100 meters."

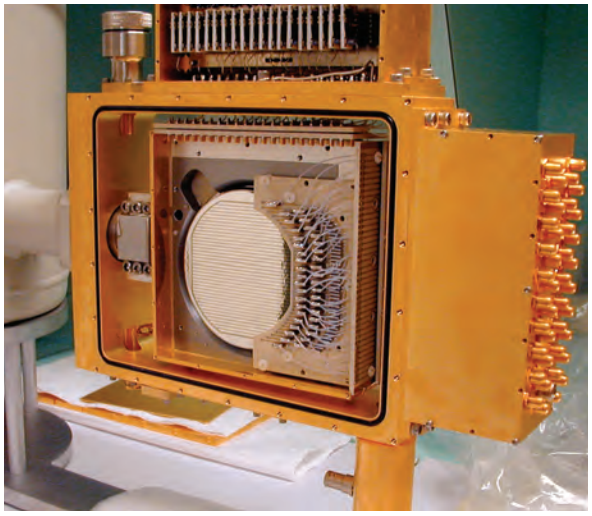
The image generated from a coded-aperture process is derived from the variation in gamma-ray signal counts versus signal position on a detector. In an ideal situation, only the shadow cast by the mask would cause these variations. However, one shortfall of coded-aperture imagers is that gamma-ray sources outside an instrument's field of view can contribute to the signal count. This incident radiation may create shadows that cause the image to blur.

To compensate for the incident radiation, the team designed an antimask whose hole pattern is the inverse of the



Combining a mask with an antimask whose hole pattern is the inverse of the mask's pattern effectively removes background signals outside the surveyed area.

(a)



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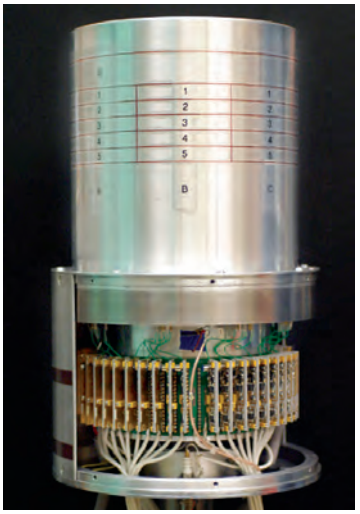


(a) In the disk configuration, the Compton imager has orthogonal strips on each side connected to a preamplifier and a digital data-acquisition system to determine the three-dimensional (3D) position for each gamma-ray interaction. (b) In the cylindrical configuration, the outside contact is divided into pixels that, when analyzed with a digital signal processor, provide the necessary 3D information.

pattern on the mask. Fabris explains, "The mask and the antimask are exposed to the source at the same time. Background signals outside the field of view would be extraneous signals. By subtracting the measurement taken with one mask from the inverse measurement taken with the antimask, we are left with only those signals that passed twice through the masks—once through the mask and once through the antimask." Each lead mask is 2 meters long and weighs 1,000 kilograms, comprising the bulk of the instrument's weight.

Pacific Northwest performed modeling studies to determine the best detector configuration. Fabris says, "The most practical material for the large-area gamma-ray detector is cesium iodide. It's less sensitive to potential damage induced by temperature changes than detector materials such as sodium iodide, and it is fairly inexpensive to produce in the large sizes necessary for this instrument." The cesium iodide is arranged in two arrays, one for the mask and one for the antimask. Researchers at the Space Sciences Laboratory and Oak Ridge provided navigational data and the image reconstruction and mapping algorithms. Physicist Klaus Ziock, who previously worked on the Livermore team and is now at Oak Ridge, contributed his expertise on coded-aperture systems.

The imager provides one-dimensional images simultaneously from both sides of a vehicle—a design choice based on its intended use in suburban or light-urban areas. The team is also considering a two-dimensional (2D) system that could image both gamma rays and visible light for use at choke points such as border crossings and tollbooths. "Ideally," says Fabris, "we want to integrate several small imagers that could track moving targets, for example, cars changing from one lane to another. In addition to serving homeland security, the technology could be used in imagers designed for medical research, by replacing the pinhole, or collimator, with coded-aperture masks.

Tracking Every Gamma Ray

Livermore's large-area gamma-ray detector has demonstrated that imaging can greatly improve detection sensitivity. Recent advances in semiconductor detector manufacture and signal processing are allowing Livermore researchers to increase detection sensitivity further by designing gamma-ray imagers with omnidirectional capability. In another LDRD project, a Livermore team, led by physicist Kai Vetter, developed a gamma-ray imager that operates without a collimator or coded aperture. Instead, it relies on the principles of Compton scattering—the effect that occurs when a high-energy photon interacts with an electron in a material, resulting in a free electron and shifting the photon's energy and direction. If the gamma-ray photon still has enough energy after the interaction, the scattering process is repeated until the photon is stopped by the photoelectric effect, an atomic process that fully absorbs photons. (See the box below.)

Livermore's Compton imager can also merge images of gamma rays with visual images. In one experiment, the team combined a camera and a Compton imager to demonstrate that the system can visually identify a gamma-ray source containing an isotope of sodium.

The Principles behind Compton Scattering

The Compton imager is named after Arthur Holly Compton, who in 1923 observed that the wavelength of high-energy photons, such as x or gamma rays, increases when the photons interact with electrons in a material. This phenomenon is known as the Compton effect. According to quantum theory, a photon can transfer part of its energy to a loosely bound electron when the two collide. Because x- and gamma-ray photons have high energy, such collisions may transfer so much energy to an electron that it is ejected from its atom. The scattering of photons as they pass through and interact with a material is called Compton scattering. Compton won the Nobel Prize in physics in 1927 for his work on the scattering of high-energy photons by electrons.

Compton scattering is the principal absorption mechanism for gamma rays between 100 and 3,000 kiloelectronvolts. Uranium and plutonium both naturally emit radiation within this energy range. Below this range, photoelectric absorption is the dominant interaction type.

Compton imaging systems can be designed using various detector materials in different configurations. The key to optimizing imaging efficiency is to induce multiple interactions between the gamma ray and the detector material so the system can detect the full energy of the incident gamma ray. The gamma-ray interactions must be separated in space sufficiently so that they can be easily distinguished from each other and their positions can be accurately measured to obtain high angular resolution.

One requirement for Compton imaging is that a gamma ray must interact with electrons at least twice—once to induce Compton scattering and once to allow photoelectric absorption—although more than one scatter can occur. For example, a 1-megaelectronvolt gamma ray averages three Compton scattering interactions before it is finally photoelectrically absorbed by germanium. When an x- or gamma-ray photon is scattered or absorbed, high-energy electrons are ejected. The subsequent deposition of electron energy produces a large number of ionized atoms. The ionization from Compton scattering or photoelectric absorption is then recorded by the detectors.

Because the imager does not require gamma rays to enter the detector through a mask, it can identify radiation from all directions. Vetter says, "Compton scattering occurs whenever photons in the energy range of about 150 to 5,000 kiloelectronvolts are present. Our imager takes advantage of this effect. It calculates the angle of the incident gamma ray by measuring the positions and energies of the first two interactions with the detector."

Imaging systems based on Compton scattering were proposed 30 years ago for astrophysics and nuclear medicine applications. However, technology to improve sensitivity and reduce the system's size became available only in the past 10 years. Until recently, a Compton imager could not differentiate photon interactions in the scattering process because it could not determine the three-dimensional (3D) position of a gamma ray with sufficient fidelity. One technology breakthrough has been the 2D, segmented semiconductor detectors, which use materials such as germanium and silicon to improve energy resolution. The digital signal-processing equipment that is now available provides the necessary 3D position capability.

Designing the Optimal Imager

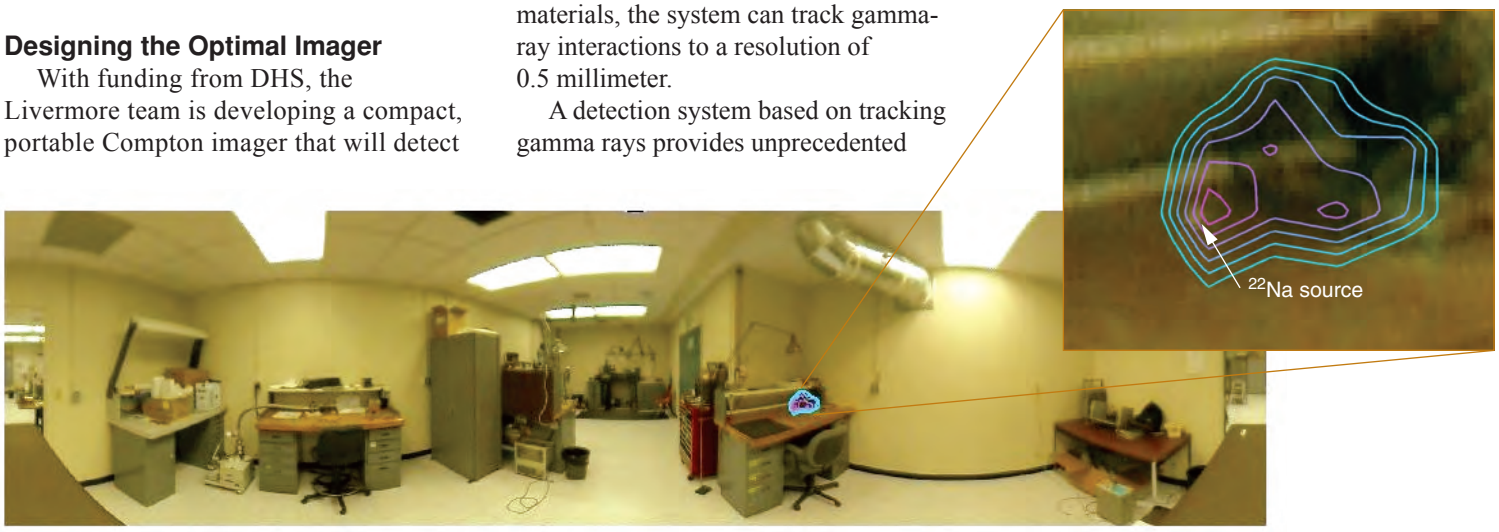
With funding from DHS, the Livermore team is developing a compact, portable Compton imager that will detect and identify sources between 120 to 3,000 kiloelectronvolts and provide unsurpassed sensitivity. The team has planned three generations of the instrument so design changes can be evaluated at each stage. Monte Carlo simulations showed that the highest sensitivity could be achieved by combining high-energy and position-resolution semiconductor detectors to maximize efficiency. Vetter explains, "For the imager to create an image based on data from the Compton effect, incoming gamma rays must interact with the detector at least twice—once to scatter the photon energy and again to absorb the photon. A semiconductor with a low atomic number, such as silicon, induces scattering very well, while one with a high atomic number, such as germanium, is effective at absorbing gamma rays."

Livermore's Compton imager uses four layers of detectors: two silicon crystals and two germanium crystals, together measuring about 8 by 8 by 6 cubic centimeters. The detectors are manufactured at Lawrence Berkeley National Laboratory and the Research Centre Jülich in Germany. With its 3D position capability and combined detector materials, the system can track gamma-ray interactions to a resolution of 0.5 millimeter.

A detection system based on tracking gamma rays provides unprecedented sensitivity not only for Compton imaging but also for nuclear spectroscopy, which is used to identify nuclear materials. "The Compton imager can distinguish gamma rays that deposit only partial energy in the detector from those that are fully absorbed," says Vetter, "so background signals can be more easily eliminated." The system applies the Compton scattering formula to the positions of the first and second interactions to deduce the angle of the incident gamma ray to within a certain cone-shaped area.

According to Vetter, the ultimate gamma-ray detector would be one that can precisely determine the path of an electron after a gamma ray initially impacts the detector. Such a system would require a resolution of better than 10 micrometers. He adds, "If we could measure the electron's path, we could determine the direction of the incident gamma ray unambiguously, rather than within the area of a cone."

The high-resolution silicon and germanium detectors must remain at low temperatures to operate, so UC's Space Sciences Laboratory built cryostats cooled by liquid nitrogen for the Compton imager. The second-generation instrument



A Compton imager combined with a camera produced this image, which pinpoints the location of the radioactive source—an isotope of sodium (^{22}Na).

uses two cryostats—one for the two silicon detectors and one for the two germanium detectors. The third and final Compton imaging system, which the team plans to complete in 2008, will have one cryostat for all four detectors.

Future Design Possibilities

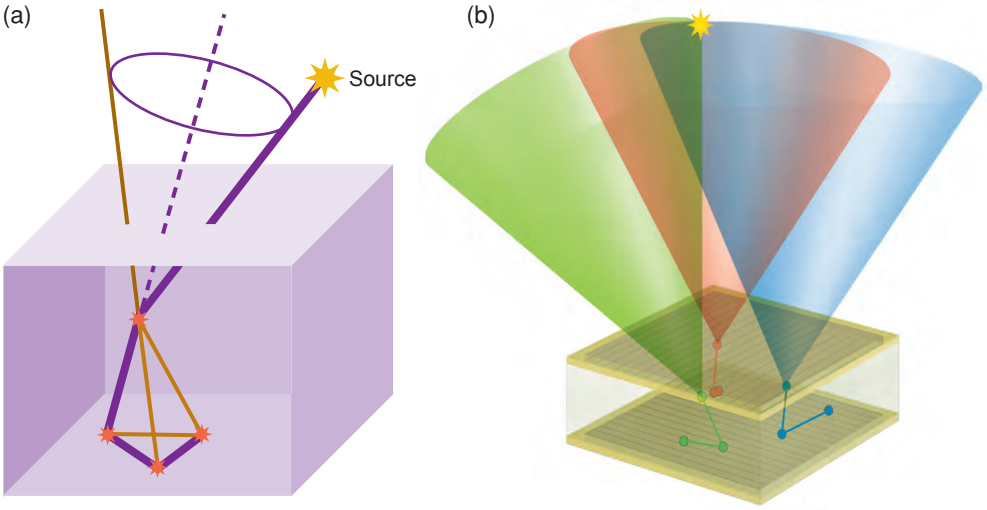
One drawback to using liquid nitrogen is that it requires frequent refills and large dewars, which complicate the instrument's operational capabilities. The team will explore the use of mechanical cooling for future systems. With mechanical cooling, the imagers could be used remotely for a wider range of applications. The Laboratory has developed portable radiation detectors, such as Cryofree/25 and RadScout (licensed by ORTEC under the name Detective®), which use germanium detectors that are mechanically cooled. The team will also research the possibility of using materials such as silicon and cadmium–zinc–telluride so the detector could operate at room temperature. The overall effort will define a Compton imaging module that is best suited for homeland security. "Once we complete the design of the third-generation Compton imager," says Vetter, "scaling to larger systems would just be a matter of assembling multiple modules."

The team is using measurements taken with the first-generation system to calibrate such parameters as energy, depth, and position interpolation and is assembling the second-generation instrument. Livermore's imager is the most efficient and sensitive, fully operational Compton imaging system that has been built. The only other deployed system is the National Aeronautics and Space Administration's COMPTEL telescope. COMPTEL, built in 1989 to study gamma-ray sources such as pulsars and supernova remnants, uses large-volume sodium iodide detectors, which provide limited sensitivity.

Ultimately, Livermore's Compton imager will provide a spatial resolution of about 3 by 3 square meters or less at a distance of 100 meters, with a 500-meter-diameter field of view. Weighing less than 460 kilograms, this portable system will allow security officials to conduct wide-area surveillance from the ground or in the air.

The goal for researchers designing radiation detection instruments is to maximize an instrument's sensitivity in detecting and identifying gamma rays from illicit sources in the midst of radiation from other sources. Livermore's large-area gamma-ray imager and its Compton imager add two powerful instruments to the DHS arsenal of equipment designed to help keep the nation safe.

—Gabriele Rennie



Incoming gamma rays interact with the detector through Compton scattering. (a) The energies and positions of the first two interactions define a cone of incident angles. (b) The cones can be projected onto a plane or sphere (one circle per gamma-ray event) to produce a two-dimensional image of the source.

Key Words: coded aperture, Compton imager, gamma-ray imager, large-area gamma-ray imager, radiation detector.

For further information on the large-area gamma-ray imager contact Lorenzo Fabris (925) 423-1258 (fabris1@llnl.gov); on the Compton imager contact Kai Vetter (925) 423-8663 (vetter4@llnl.gov).

Protecting the Nation's Livestock

A Livermore-developed assay rapidly detects foot-and-mouth disease and look-alike livestock diseases.

SINCE 2001, the U.S. has improved its ability to prevent and respond to terrorist attacks, but the nation's agricultural infrastructure could be vulnerable. Although the nation has never experienced an attack targeted at agriculture, such an incident, called agroterrorism, could have devastating consequences.

America's sheep, cows, pigs, and chickens are particularly vulnerable to diseases that are endemic in other parts of the world but have not appeared in this country for many decades. If allowed to gain a foothold in the U.S., a foreign animal disease (FAD) could spread rapidly and be difficult to contain. It could thus severely affect millions of animals and the national economy.

Agroterrorism poses a threat because U.S. farms and feedlots are rarely guarded and widely dispersed across the country. Should an infection occur, normal livestock and personnel movement, including interactions with other herds, could lead to widespread dissemination of a disease before it is diagnosed. In addition, the clinical signs of FADs closely mimic many diseases that regularly occur in the nation. Homeland security experts are thus concerned that farmers, local veterinarians, and others will not be able

to recognize and report a FAD before it spreads out of control.

A great concern centers on foot-and-mouth disease (FMD), a highly contagious livestock disease that has not been seen in the U.S. since 1929. During the past decade, however, outbreaks of FMD in the United Kingdom, Asia, and South America have heightened awareness of the potential danger. The U.S. clearly needs the capability to identify FMD early and provide a rapid, large-scale response, including the diagnostic support for controlling the outbreak.

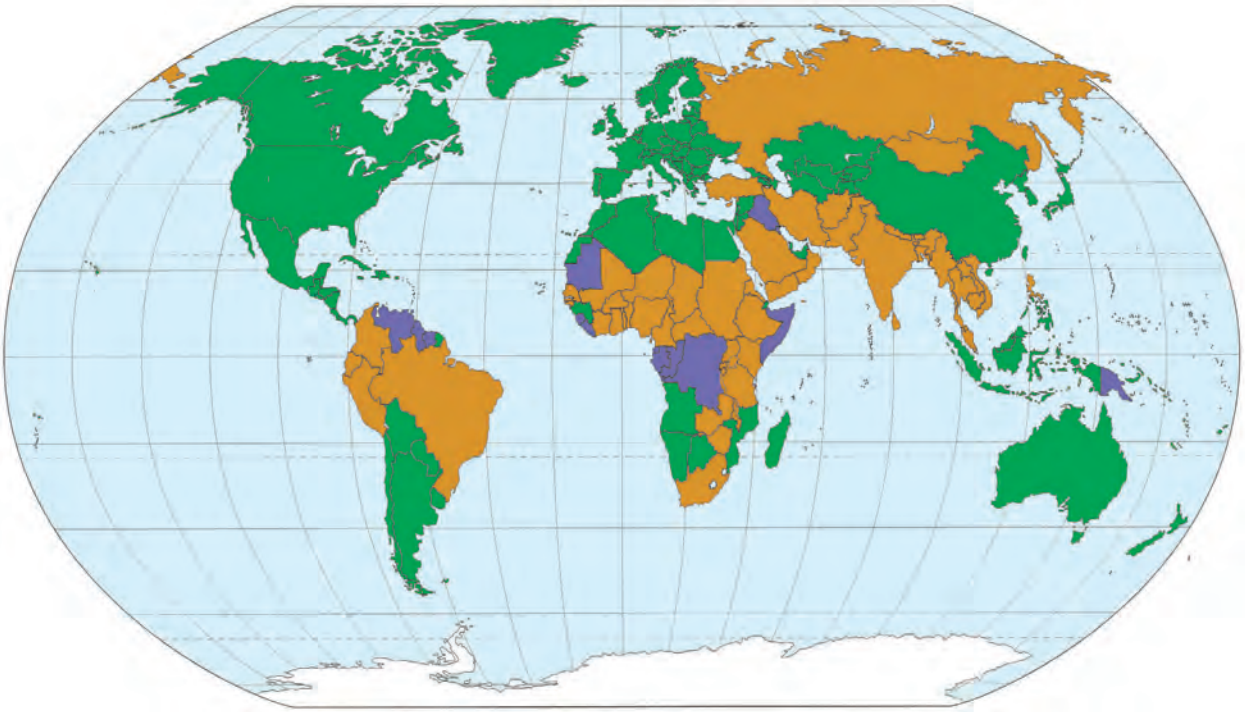
To address this need, a Livermore team, with support from the Department of Homeland Security (DHS) and the U.S. Department of Agriculture (USDA), has developed a rapid assay that simultaneously detects FMD and other foreign and endemic diseases with similar symptoms. The assay is being evaluated by 13 laboratories within the National Animal Health Laboratory Network (NAHLN) and by the National Veterinary Services Laboratory (NVSL) at Plum Island, New York. Once validated and accepted by the USDA, the Livermore assay will allow laboratories to quickly diagnose FMD and diseases that mimic its symptoms.

"Our goal is to provide federal and state stakeholders with significantly improved detection, identification, and response capabilities for foreign and endemic agricultural diseases," says Ray Lenhoff, a molecular virologist in Livermore's Biosciences Directorate. The FMD assay development team, which is led by Lenhoff, also includes analytical chemist Ben Hindson and veterinarian Pam Hullinger of the Laboratory's Physics and Advanced Technologies Directorate; toxicological immunologist Max Rasmussen, also in Biosciences; and other Livermore experts in homeland security, pathogens, and advanced detection methods. The team is part of the Bioassays and Signatures Program, which develops and implements methods to diagnose agents of bioterrorism. This program operates within the Laboratory's Chemical and Biological National Security Program, whose mission is to improve the nation's capabilities to prevent, prepare for, detect, and respond to terrorist use of chemical or biowarfare agents.

On the Front Lines

Lawrence Livermore has been on the front lines of the nation's biodefense effort since the mid-1990s. Laboratory-developed signatures—specific regions of DNA or RNA that uniquely identify a pathogen—have been used for homeland defense since 2001. For example, Livermore assays are incorporated in DHS environmental monitoring systems such as BioWatch.

The Laboratory has teamed with state and federal departments of agriculture in the past. In 2002, Livermore, the California Animal Health and Food Safety Laboratory at the University of California at Davis, and USDA scientists worked together to contain a natural outbreak in southern California of exotic Newcastle disease, an extremely contagious and fatal viral disease affecting all species of



Foot-and-mouth disease (FMD) is endemic in many parts of the world. In this map, brown indicates countries that reported FMD occurrences in 2004, green shows those with no reported occurrences, and purple denotes those for which data are incomplete or unavailable. (Data from the World Organisation for Animal Health.)

birds. At the time of the outbreak, existing assays required 6 to 12 days to identify the disease. A key signature isolated by a team of Livermore researchers allows the virus to be identified within 4 hours.

In February 2001, during the height of the FMD outbreak in the United Kingdom, a Livermore team analyzed the virus's tiny genome of 8,000 RNA bases. The team determined that only one region of the FMD genome can support a signature-based assay. (See *S&TR*, April 2004, pp. 4–9.)

FMD: An Enormous Threat

FMD is an extremely contagious viral disease of pigs and domesticated and wild ruminants such as cattle, sheep, goats, deer, and water buffalo. Animals afflicted with FMD usually do not die, but the disease is debilitating and animals do not recover. An infected animal begins to drool, and virus-filled blisters develop in its mouth and at the junction where skin connects to the hoof wall, making it painful for the animal to walk. In addition, the virus attacks the mammary glands, leading to reduced milk production. The vaccine for FMD only reduces the severity of symptoms; it does not prevent infection or completely stop transmission of the disease. Humans do not get sick, but they can act as carriers of the virus.

FMD is endemic in many nations and remains the most important barrier to world trade in live animals and animal products. In 2000 and 2001, a Pan-Asian strain caused outbreaks in Korea, Japan, Russia, Mongolia, South Africa, the United Kingdom, France, and the Netherlands.

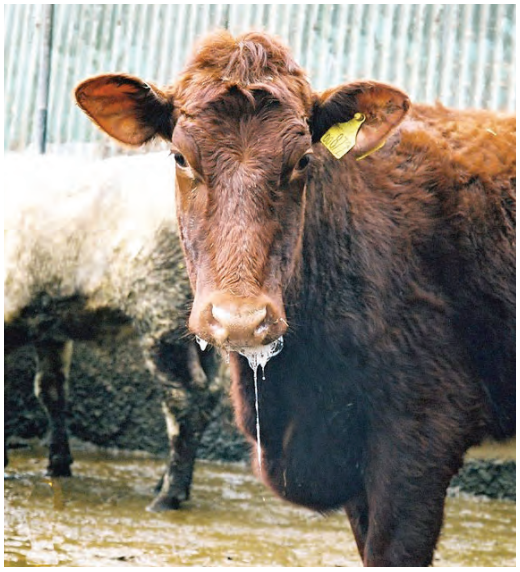
Economic losses from an agroterrorist incident, especially one caused by an extremely contagious disease such as FMD, could be enormous. (See the box on p. 16.) The potential costs include testing thousands (perhaps millions) of animals, destroying and disposing of infected animals, quarantining uninfected premises, and disinfecting and repopulating farms. In addition, such an outbreak would jeopardize the business continuity of the domestic livestock industries, including many jobs in agriculture, food processing and production, domestic and export markets. "Early detection is critical to limiting the scope of an outbreak," says Hullinger. One estimate is that the U.S. would lose up to $3 million in direct costs for every hour's delay in diagnosing FMD.

Currently, a veterinarian or farmer who suspects a case of FMD contacts the USDA or a state agricultural department, which sends a veterinarian who has been trained by the USDA to diagnose FADs. This diagnostician questions the farmer, examines the animals, and if warranted, sends specimens to the Plum Island laboratory for definitive analysis.

Plum Island averages about 300 FAD investigations a year. Many of the tests it uses, such as those to isolate the FMD virus, are time-consuming and laboratory intensive. During an FMD outbreak, the demand for analytic services would almost certainly far exceed the capacity at NVSL. "In such cases, the NAHLN

Livermore's assay for foot-and-mouth disease is being evaluated by 13 National Animal Health Laboratory Network laboratories (blue stars) and the National Veterinary Services Laboratory (NVSL) at Plum Island, New York (red star). Without a fast and accurate assay, an outbreak could rapidly overwhelm NVSL's diagnostic capabilities.

(a)



(b)

When this shorthorn heifer in the United Kingdom became afflicted with foot-and-mouth disease, (a) she began to drool, and (b) virus-filled blisters developed in her mouth and at the junction where skin connects with the hoof walls.

labs could provide regional and scalable diagnostic support under the direction of the USDA," says Hindson. "The availability of a validated, rapid test for detecting and identifying FMD and differentiating it from other diseases that present similar clinical signs would be invaluable."

A Tool for Homeland Security

The Livermore animal assay research, which began in early 2005, is funded by DHS's Agricultural Assays and Agricultural Security Domestic Demonstration and Application Program. DHS is charged with coordinating U.S. efforts to protect against agroterrorism, while the USDA is responsible for responding to major outbreaks of disease involving agriculture.

Within the USDA, the Animal and Plant Health Inspection Service (APHIS) is responsible for protecting animals and plants from agricultural pests and diseases, including the introduction of FADs, and for coordinating the response to an agricultural disease outbreak. NVSL, which is part of APHIS, coordinates the state and university veterinary diagnostic laboratories belonging to NAHLN.

In developing signatures for bacterial and viral pathogens, Livermore scientists use the KPATH technique, which was developed by Laboratory computer scientist Tom Slezak. KPATH compares the genome of a target pathogen to the existing library of microbial genomes, searching for areas that are unique to the target organism. The DNA or RNA regions selected are present in every strain of the pathogen and absent in all other organisms sequenced to date. The assay development team also takes advantage of advances in rapid polymerase chain reaction (PCR). This technique makes multiple copies of a particular RNA or DNA segment from a sample so that enough exists to be detected and identified.

Multiplexing Speeds the Process

"Traditionally, the USDA labs look for one disease at a time," says Lenhoff. Separate tests are made for each disease, using a variety of laboratory techniques. If the reading is negative for FMD, the test does not identify the disease agent that is present. To speed diagnosis, the Livermore team developed a multiplexed assay—one that simultaneously tests a single sample for all similar diseases, both endemic and foreign. Thus, a negative reading for FMD will likely be accompanied by a positive response identifying a similar disease. "With our technology, laboratories will be able to screen for many diseases at one time," says Lenhoff. "In this way, our assay provides more confidence in the negative FMD diagnosis."

Multiplexing reduces labor and the costs of reagents. Compared with traditional diagnostic tests, the Livermore assay significantly increases speed and convenience of testing. The assay screens for both DNA and RNA viruses at the same time and detects the seven major subtypes of FMD. The test looks for 17 target signatures, including 2 that detect all 7 serotypes, or strains, of FMD. In all, the 17 signatures represent 7 diseases. Three of these are the foreign diseases FMD, vesicular exanthema of swine, and swine vesicular disease. Four are the endemic diseases bovine viral diarrhea, bluetongue, bovine herpes-1 (also known as infectious bovine rhinotracheitis), and bovine parapox virus complex (bovine papular stomatitis, contagious ecthyma, and pseudocowpox). The panel also incorporates five internal controls to increase confidence in the results.

The assay uses multiplex analysis technology developed by Bio-Rad Laboratories, a bead-based liquid array technology by Luminex Corporation, and components supplied by other companies. The assay first extracts nucleic acids from the sample and purifies them. RNA from RNA viruses is then converted to DNA, and all DNA is amplified.

(a)

(b)

To test the Laboratory's multiplexed assay, (a) analytical chemist Ben Hindson collected samples at a dairy farm near Davis, California, and (b) veterinarian Pam Hullinger collected them at the animal science facilities of the University of California at Davis.

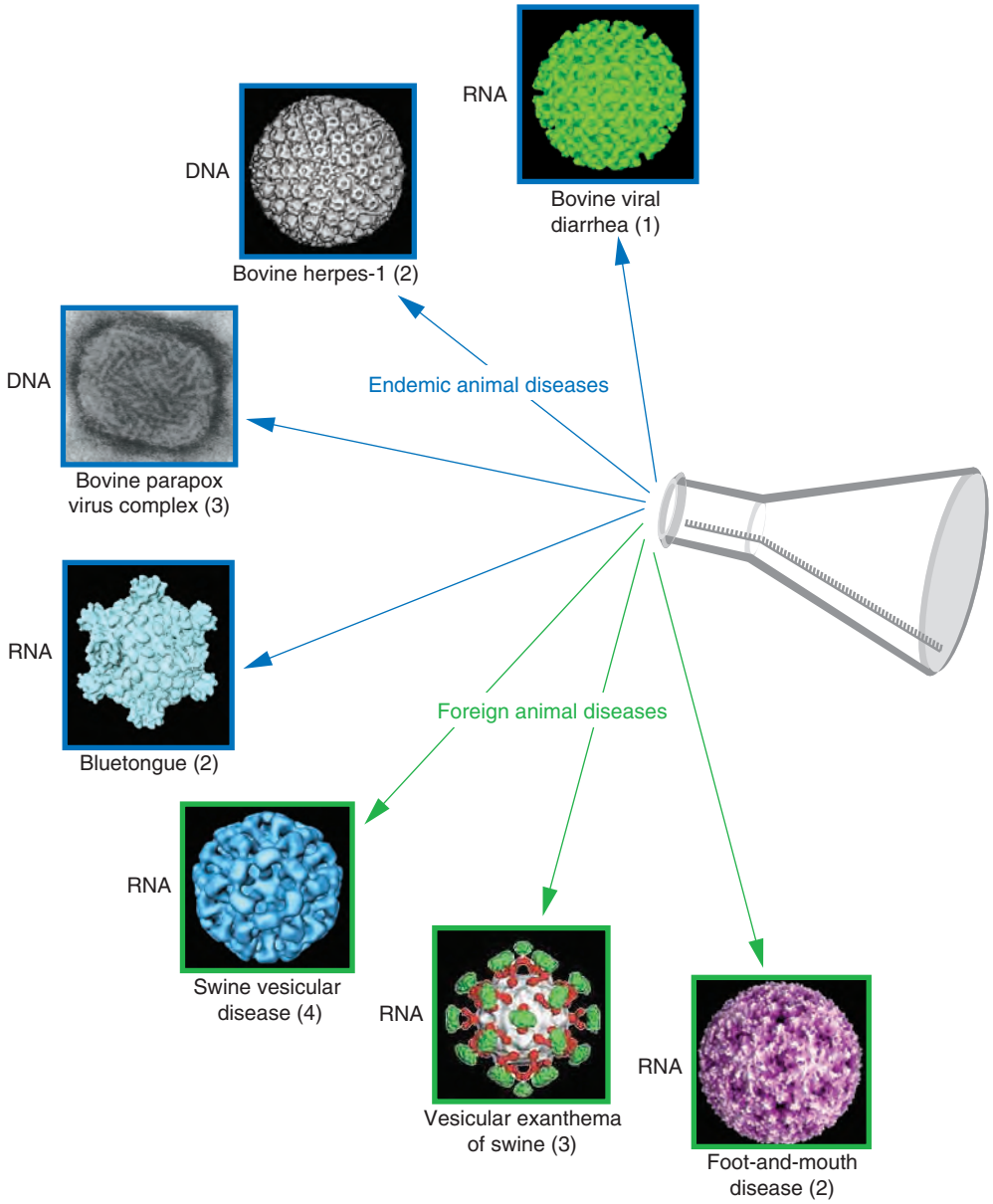
Luminex polystyrene beads are individually tagged with a sequence of nucleotides that complement the signatures of interest. The beads are embedded with precise ratios of two fluorescent dyes, each with a unique spectral address. Each microbead is then interrogated by a flow cytometer. A laser excites the dye molecules inside a microbead to indicate the kind of microbead—that is, the pathogen—it is screening. Another type of laser excites fluorescently labeled molecules bound to each microbead's surface during the assay, which indicate how much of the pathogen is present in the sample. The flow cytometer can read up to 400 beads per second and simultaneously test for 100 different pathogens in a single sample.

Extensive Performance Evaluation

The Livermore assay is undergoing thorough testing, which consists of an NAHLN interlaboratory comparison and follow-on evaluation. During October and November 2005, 13 NAHLN laboratories and NVSL were equipped with the necessary tools for performing the assay, including a specialized flow cytometer (Bio-Rad Bio-Plex Workstation), small disposable items such pipette tips and plastic ware, and reagents. The equipment became the property of the participating laboratories. Livermore personnel worked with Bio-Rad field service engineers and application specialists to conduct training at each NAHLN laboratory. The Livermore training team, which included Rasmussen, Christina Sanders, Jaqui Lee, James Thissen, and Celena Carrillo, gave instructions on operating the workstation, performing the assays, and analyzing and interpreting data.

Each laboratory then analyzed nearly 200 clinical samples "spiked" with known domestic viruses that mimic FMD. The samples were sent from Livermore in a viral transport medium that preserves the virus. "All of the laboratories ran the same tests on the new equipment using our assays and reported the results back to us," says Hindson, who oversaw training and equipment installation.

During the follow-on evaluation this year, NAHLN laboratories will analyze clinical diagnostic samples they receive from the field using their standard assays and Livermore's multiplexed assay. Results from the two analyses will then be compared. "The labs have reference tests that are not necessarily based on PCR," says Hindson, who is also coordinating the interlaboratory comparison. "The tests could be based on immunology, fluorescent staining, or scanning electron microscopy. Comparing



The Livermore assay tests for three foreign animal diseases (green border) and four endemic diseases (blue border). Electron micrographs of each virus are shown. Numbers in parentheses denote the number of signatures the assay uses to detect each disease.

A scientist at Indiana Animal Disease Diagnostic Laboratory at Purdue University learns to use the Livermore multiplexed assay.

results from the two methods will help us characterize the performance of our assay and establish an even greater level of confidence in its results. It also allows us to evaluate the assay's performance in the hands of the end users."

High Throughput Using Robots

The team has also developed a high-throughput, semi-automated system that uses two robotic workstations. Together, the workstations can analyze 1,000 samples in a 10-hour shift with two laboratory technicians. "If there is a disease outbreak, we need a high-throughput capability to process a large number of samples," says Lenhoff.

Two NAHLN laboratories are testing the robotic system in a seven-day exercise this spring to simulate an outbreak scenario. The demonstrations include field sample collection and identification, sample receipt, sample processing, data analysis, and a mechanism for reporting results.

The high-throughput system integrates the USDA's electronic sample identification technology with the laboratories' information management systems. "We want to demonstrate to state and federal authorities and laboratory personnel an integrated system that can function end to end during the response to a FAD outbreak, from collecting and processing samples through reporting the results," Hindson says. The portable system can be deployed to any location. The team is also developing a laboratory mounted inside a truck, which could provide mobile regional diagnostic support in the early phases of an outbreak response.

Calculating the Cost of Foot-and-Mouth Disease

The foot-and-mouth disease (FMD) virus consists of a single strand of RNA packed inside a tough protein coat. The hardy virus can live 28 days in cool soil and up to 180 days in a slurry of cow dung. It can be spread directly from animal to animal, or it can be transported indirectly by a person or vehicle traveling from one farm to another—for example, with mud containing the virus caked on boots or tires. Livermore's Pam Hullinger, a foreign animal disease diagnostician and veterinary epidemiologist, notes that FMD is so contagious, an animal can become infected after contact with as few as 10 virus particles.

Although the U.S. has not had an FMD outbreak since 1929, it is endemic in many parts of the world. In 2000 and 2001, a Pan-Asian strain caused outbreaks in Korea, Japan, Russia, Mongolia, South Africa, the United Kingdom, France, and the Netherlands. Economic losses from an agroterrorist incident, especially one caused by an extremely contagious disease such as FMD, could be enormous.

The 2001 outbreak of FMD in the United Kingdom is estimated to have caused about $5 billion in losses to the food and agriculture sector and even greater losses in tourism. Up to 10-million sheep, pigs, and cows were slaughtered, and for several months, the nation was banned from exporting livestock and animal products that could potentially transmit the virus.

Hullinger answered the call for expert veterinarians during the 2001 epidemic and saw many animals slaughtered. "There is no substitute for first-hand experience in gaining respect for the devastation that a foreign animal disease can inflict on a nation," she says. Many veterinarians were asked to decide whether a flock or herd was infected based solely on clinical signs observed during an initial visit without the aid of testing or laboratory support.

"We now know that many uninfected animals were destroyed because we lacked rapid diagnostics for FMD," says Hullinger. "I saw thousands of animals killed in Britain, and thousands of farmers lost their livelihoods. I don't want to see that happen here."

Up to 10-million sheep, pigs, and cows were slaughtered during the 2001 outbreak of foot-and-mouth disease in the United Kingdom.

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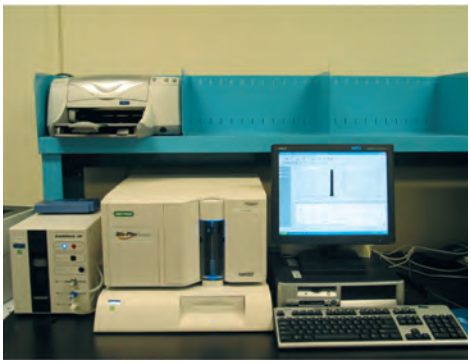

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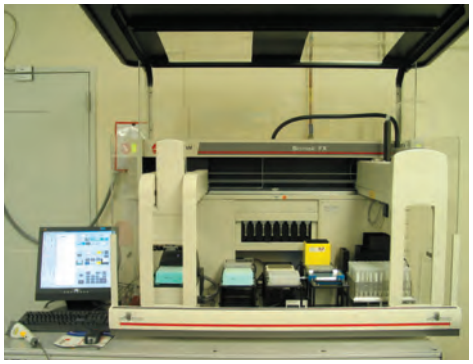

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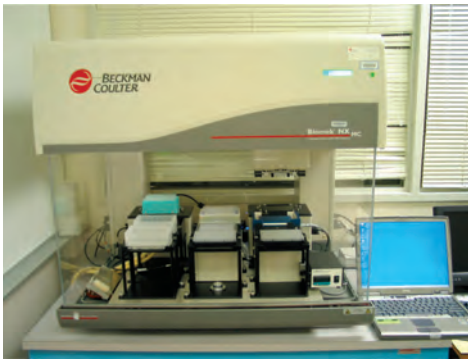

(a) A specialized flow cytometer, the Bio-Rad Bio-Plex Workstation, analyzes DNA using bead-based liquid array technology by Luminex Corporation. (b, c) To speed diagnosis during a disease outbreak, Livermore researchers designed robotic equipment to replace most manual operations.

Looking Ahead

Later this year, APHIS will examine the results of this extensive evaluation and determine whether the multiplexed assay will be permanently adopted nationwide. In the meantime, the Livermore team meets regularly with USDA officials to better understand their needs. Although the assay was developed with a focus on agroterrorism, it could also help federal and state agencies perform routine agricultural disease surveillance. If a FAD were suspected based on a surveillance screening, then a disease investigation could be initiated quickly and samples sent to Plum Island to confirm the diagnosis.

Because the Luminex bead technology can screen for 100 different signatures at a time, the Livermore assay has room to expand. The team plans to add diseases to the original assay and develop new assays. One possibility is a multiplexed panel focused on diagnosing bovine fetal abortion, which can be caused by both viruses and bacteria. “We also want to develop species-specific assays for pigs, cows, and sheep,” says Lenhoff. Plans are already under way to develop assays for poultry.

Livermore chemist Julie Perkins is working with the National Center for Foreign Animal Diseases in Canada to develop multiplexed assays that would determine both the type of FMD and whether animals vaccinated for FMD have also been infected by the virus. “Having a diagnostic tool available to rapidly and reliably determine if vaccinated animals have subsequently become infected is critical to the decision-making process involved in FMD vaccine use in the face of an outbreak,” says Hullinger.

Hullinger is also part of a Livermore effort to model FMD and other FADs so experts can evaluate different response scenarios to an outbreak. “We’re trying to give decision makers a better understanding of the effects of various disease control options,” she says.

“The labs are really excited,” says Hindson. “They can see a lot of value in the technology. For many applications, our multiplex technology can significantly improve their diagnostic capabilities.”

The Livermore team is just beginning to develop improved detection methods for animal diseases. National security and America’s agricultural industries are the clear winners.

—Arnie Heller

Key Words: agroterrorism, bioassay, foot-and-mouth disease (FMD), foreign animal disease (FAD), homeland security, National Animal Health Laboratory Network (NAHLN), National Veterinary Services Laboratory (NVSL), U.S. Department of Agriculture (USDA).

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Measures for Measures

DURING many physics-related experiments—especially those that involve the extreme pressures and temperatures of high-explosive detonations—scientists and engineers need to directly measure the temperature of a material's surface and, at the same time, its density or pressure. Investigators commonly use the infrared radiation emitted from a material's surface to infer its temperature. However, the accuracy of this approach is limited because the emitted radiation depends not only on a material's surface temperature but also on a property known as emissivity.

Emissivity is the ratio of the power radiated by a perfect emitter, called a blackbody, to the power radiated by the material in question. A blackbody is assigned an emissivity value of 1, and a material that does not radiate at all has an emissivity of 0. The values for all other materials fall between 0 and 1.

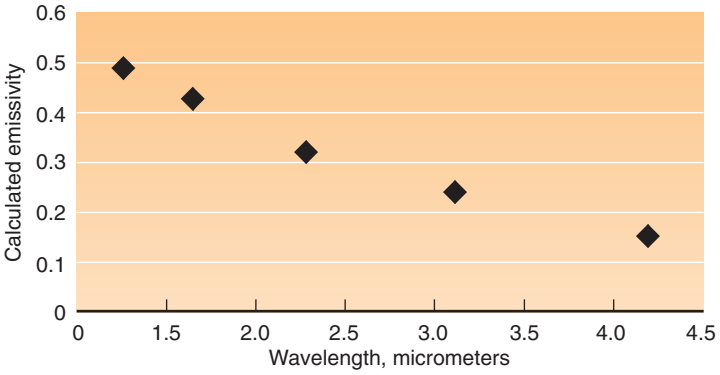
The emissivity of a radiating material depends on the type of material being studied, its surface conditions, and such properties as its roughness and color. A black surface radiates more than a shiny surface at the same temperature. Highly reflective materials have very low emissivities. For example, aluminum foil has an emissivity of about 0.03, one-thirtieth that of a blackbody.

Previous methods that use emissivity to determine temperature do not have the accuracy needed for many of today's applications. Rather than measure emissivity directly for each experiment, some researchers use data collected from past experiments in calculations that convert emitted power to temperature. However, this technique can result in errors ranging from 10 to 20 percent.

Livermore scientists need more accurate surface temperature measurements for their stockpile stewardship work. Such data help them better understand material properties at the microstructural level and how these properties change during a high-explosives shock. A highly accurate thermometry method for extreme temperatures will allow researchers to refine calculations of a material's equation of state.

Reducing the Error

To improve the accuracy of thermometry readings, Livermore physicists Peter Poulsen and Stanley Ault use the fact that emissivity and reflectivity must add up to one. The method they developed incorporates nearly simultaneous measurements of emitted and reflected radiation. With these measurements, they can compute the surface temperature and determine how emissivity varies with wavelength. For example, they can measure a metal's surface temperature with an error of less than 1 percent. "We developed this method to measure the temperature of shocked surfaces," says Poulsen. "Our readings are completed very quickly—in less than a millionth of a second."



The emissivity of a surface as a function of wavelength must be determined to achieve highly precise surface temperature measurements.

Conventional infrared measurements do not take into account that emissivity is normally a function of the wavelength of the emitted radiation. "Characterizing the emissivity with a single number independent of the wavelength is not sufficient," says Poulsen. Most metals have an emissivity that decreases significantly with increasing wavelength, so that more emission takes place at shorter wavelengths. Scientists may, thus, interpret the observed radiation spectrum as resulting from a higher temperature.

Putting Theory into Practice

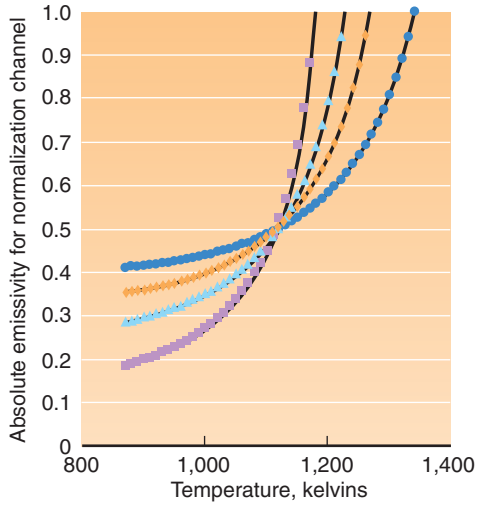
The Livermore approach uses a multichannel spectrometer and an external light source to measure, almost simultaneously, the emitted and reflected powers over a range of wavelengths. The experimental apparatus developed by Poulsen and Ault to test the method incorporates a pulse-heated molybdenum foil. Car batteries provide the current for heating the foil. An inert gas replaces the air within the device to prevent oxidation of the foil. A window that is transparent to light in the infrared range of wavelengths provides optical access to the foil for the detectors that measure the emitted and reflected radiation.

In the experiments, batteries heat the metal foil until it reaches the desired temperature, as determined by a thermocouple connected to the foil's surface. Samples of the radiation (light) emitted by the heated foil pass through six fiber-optic cables and are recorded for 200 nanoseconds by the detectors of a multichannel spectrometer. An external pulse of full-spectrum light is then directed from the end of a fiber-optic cable to the metal's surface. The spectrometer's six detectors also record this reflected light and provide the results as the sum of emitted and reflected light. The entire process takes only a few hundred nanoseconds. Each channel measures the signal over a known range of wavelengths. The external light source is located at

the same point in space as the detectors and illuminates the same area viewed by the detectors.

One detector serves as a reference channel, so that data and the governing relations from the remaining channels can be normalized to those from the reference channel. This process removes any dependency on the absolute magnitudes of the signals. Then for each nonreference channel, the normalized emitted-signal data are combined with the reflected-signal data to generate a curve that determines temperature as a function of assumed emissivity in the reference channel.

In an ideal experiment, the curves would intersect at one point, giving the temperature of the metal's surface as well as emissivity in the reference channel. However, because slight inaccuracies occur in setting up and performing experiments, the curves intersect at different points within a small area of deviation. Poulsen and Ault use this area of deviation to estimate the temperature and the uncertainty in the measurement. To validate their method, they compared the results obtained with the temperature recorded by the thermocouple. Poulsen notes, however, that the spectrum method can be used alone in applications that require noncontact measurement techniques.



The intersection of the four curves determines the measured temperature and its error. In this example, the temperature is 1,113 ± 1.8 kelvins. Emissivity in the reference channel is 0.490 ± 0.003. The thermocouple recording provided a temperature of 1,110.4 kelvins.

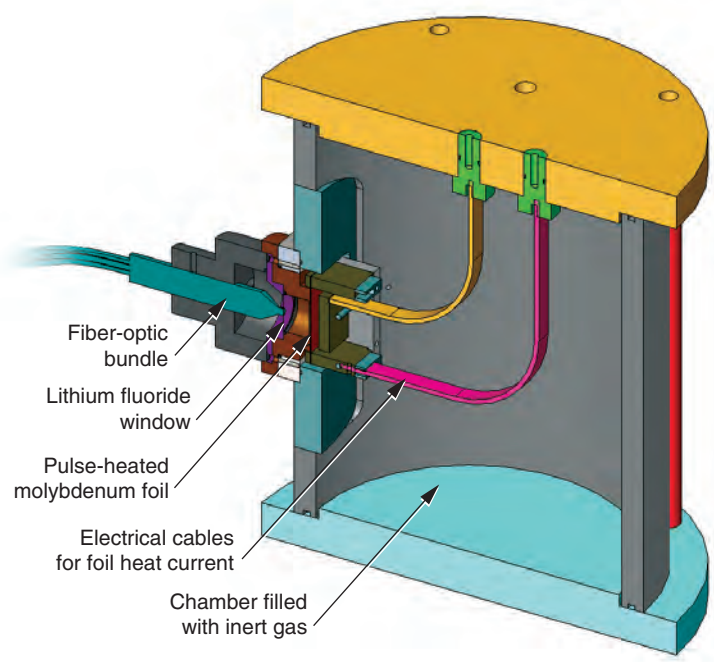
A Boon for Process Control

The accuracy of the spectrum method will allow Livermore physicists to acquire high-fidelity equation-of-state data on weapons materials undergoing high-explosives shocks. More applications abound in both research and industry. "This method will be beneficial in the field of process control," says Poulsen. "In the fabrication of steel, aluminum, plastics, or even silicon wafers, processes always depend on temperature." In fact, because materials can change phase as temperature changes, temperature often must be tracked dynamically during fabrication processes.

The ability to constantly monitor temperatures in jet-turbine engines is also of great interest to the aircraft industry. High-precision dynamic thermometry can help determine the optimum running temperature for jet engines. These high-performance engines run very hot—in fact, they are more efficient at higher temperatures. However, temperatures that are too extreme may cause safety and reliability problems. According to Poulsen, the spectrum method could be used to develop systems that constantly monitor and control the temperature of jet engines.

Because of its accuracy, the spectrum method can also be applied to determine when to replace parts. "Rather than routinely replacing parts when an average threshold for service has been reached, considerable resources could be saved by monitoring components and replacing them when their useful life is reaching the end," says Poulsen. "We developed this instrumentation for the Laboratory's shock experiments, but it can be useful across many fields, from defense to industry, because of its ability to improve safety and resource management."

—Maurina S. Sherman



To accurately determine the temperature on a metal's surface during a high-explosives shock, Livermore physicists developed an experimental device to measure the emitted and reflected radiation. Fiber-optic cables connected to detectors of a multichannel spectrometer record the data.

Key Words: emissivity, high-precision thermometry, infrared spectrometry, relative reflectivity method, spectrum method.

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Looping through the Lamb Shift

SOMETIMES in science, a small measurement can have big ramifications. For a team of Livermore scientists, such was the case when they measured a small shift in the spectrum of extremely ionized atoms of uranium.

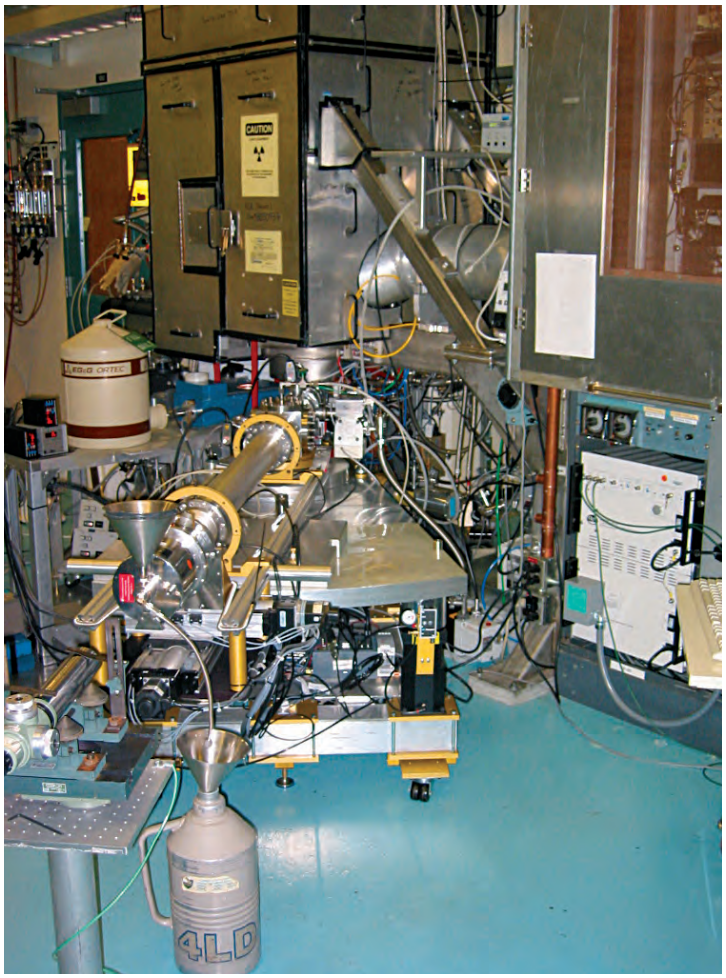
The measurement involves the Lamb shift, a subtle change in the energy of an electron orbiting an atom's nucleus. The precision of the Livermore result was 10 times greater than that of existing measurements, making it the best measurement to date of a complicated correction to the simplest quantum description of how atoms behave. The measurement introduces a new realm in the search for deviations between the theory of quantum electrodynamics (QED), which is an extension of quantum mechanics, and the real world. Such deviations, if discovered, would have far-reaching consequences, indicating that QED is not a fundamental theory of nature.

A Test of QED

The Lamb shift has nothing to do with sheep and everything to do with quantum theory, which deals with the world of the very small—atoms, electrons, neutrons, photons, and so on. According to quantum theory, energy is emitted and absorbed in tiny, discrete amounts, or quanta. When an electron changes from one energy level to another, it emits or absorbs a photon of light. This light can be observed through spectroscopy, and its frequency is directly proportional to the difference between the two energy levels.

Most of the Lamb shift can be explained by two basic QED phenomena: self-energy and polarized vacuum. The self-energy effect occurs when electrons subjected to electric and magnetic fields spontaneously and randomly emit photons and, within an incredibly short time span, reabsorb them. Through a technique called renormalization, QED theory provides a means to determine the energy of this electron self-interaction as a small, finite correction to the energy that binds the electron to the nucleus.

The polarized vacuum effect involves pairs of "virtual particles," one with a positive charge and one with a negative charge. Such pairs are created spontaneously from a vacuum in the presence of a positive or negative field and then are polarized, or aligned, by the field's charge. For example, say that a virtual electron–positron pair occurs in the presence of a positively charged ion. The virtual electrons, drawn to the positive charge, tend to align closer to the ion's nucleus than virtual positrons, which are repelled by the positive charge. Thus, an electron that orbits an ion travels with fickle companions—swarms of virtual photons and electron–positron pairs—randomly winking in and out of existence.



SuperEBIT, Livermore's electron-beam ion trap, can create and trap highly charged ions.

The Lamb shift is a tiny difference in the energy of an ion's electron between two quantum states that are otherwise identical except for the shape of the electron's orbit around the nucleus. Because of this dissimilarity in the electron's orbit in the two states, the electron interacts slightly differently with virtual particles—photons, positrons, and electrons—that appear and disappear in quantum fluctuations. The resulting energy difference, called the Lamb shift, can be measured when the electron jumps from one energy level to another.

Theory also predicts that even smaller, higher-order contributions to the Lamb shift exist. For the second-order Lamb shift, virtual

photons and electron–positron pairs interact with themselves and each other to generate two loops. (See the figure below.)

"For instance," says Livermore physicist Peter Beiersdorfer, "a photon could be emitted, and, before it is reabsorbed, another photon could be emitted or an electron–positron pair created. In a another instance, an electron–positron pair could be created, and the virtual electron from that pair could emit a photon, which is quickly absorbed." In all, 10 second-order interactions are possible. (See the background image on p. 22.) Measuring the higher-order correction to the spectrum with sufficient precision would validate the model.

Uranium Ion Takes the Field

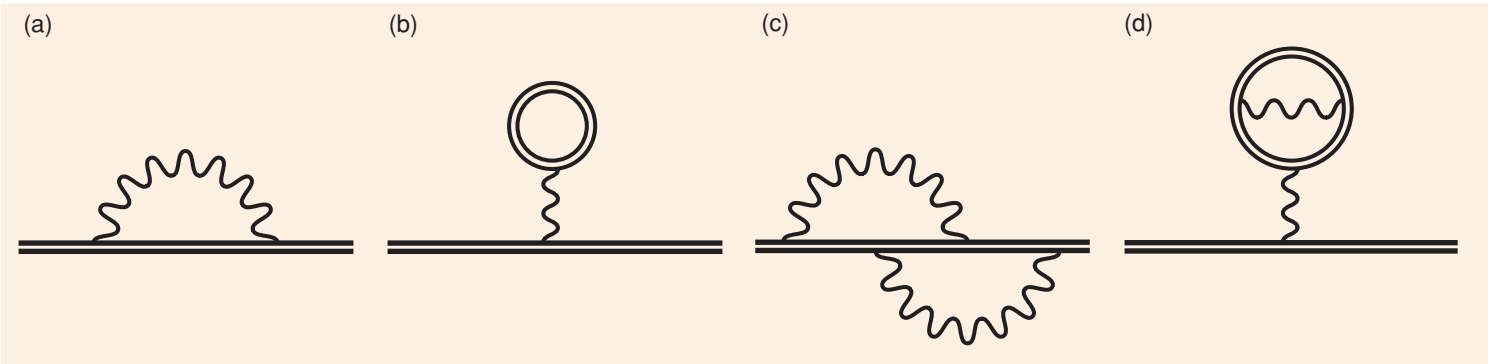
Previous experiments measured QED effects on hydrogen, which has a single electron but a very weak field. However, Beiersdorfer's team, which was funded by the Laboratory Directed Research and Development Program, decided to study the uranium atom, which has 92 electrons. "The stronger the electric and magnetic fields experienced by the electron, the stronger or more visible the interactions should be," says Beiersdorfer. "The electric field of a uranium ion is a million times stronger than that of hydrogen, which makes QED effects that much more pronounced."

Another advantage is that scientists know more about the size of the uranium atom's nucleus than they do about that of the hydrogen atom. Knowing the size of the nucleus is important in making a precise measurement, particularly when it is extended to many decimal places. A problem with hydrogen is the high degree of uncertainty in the size of its nucleus, the proton. Three measurements for the proton's radius are often quoted, but the error bars of the three do not overlap, thus forming a comparatively large band of uncertainty. "The precision in QED measurements of hydrogen has hit a wall," says Beiersdorfer, "because the measurements now outstrip the precision with which the hydrogen nucleus is known."

To measure highly charged uranium, the Livermore team used SuperEBIT, an electron-beam ion trap developed by Laboratory scientists. (See *S&TR*, November 2000, pp. 19–21; June 2002, pp. 20–24.) SuperEBIT uses a tightly focused and energy-tunable electron beam to create and trap highly charged ions. This beam, which has a current density of up to 5,000 amperes per square centimeter, passes through a series of three drift tubes to create ions of the element being studied. These positively charged ions are confined radially because they are attracted to the center of the electron beam. Voltages applied at each end of the drift-tube series trap the ions axially. When the beam's electrons collide with an ion, they strip electrons off the ion until the energy required to remove the next electron is higher than the beam's energy. Once created, the highly charged ions are held while the scientists record the spectra.

SuperEBIT is the only ion source that can create such highly charged ions at rest. Other sources produce highly charged ions; however, because they use accelerators, these sources increase an ion's velocity to extremely high energies.

For the Lamb shift experiments, the team stripped off 89 of the 92 electrons in each uranium atom, leaving uranium ions with only three electrons bound to each nucleus. High-resolution spectrometers developed at Livermore then recorded the light emitted by the electrons of these lithiumlike uranium atoms. Spectra were recorded for about two months to collect enough data for analysis. "The count rate for this event is quite low, something like four to five counts per hour," says Beiersdorfer, "and the signal is very faint."



Feynman diagrams, which are used to illustrate quantum theory, show contributions to the Lamb shift. Double lines represent bound electrons, wavy lines represent virtual photons, and double circles represent virtual electron–positron pairs. When an electron is subjected to electric and magnetic fields, it can (a) emit and reabsorb a virtual photon or (b) emit and reabsorb a virtual electron–positron pair. These interactions involve a single loop of virtual particles and are the first-order contribution to the Lamb shift. More complex interactions are possible, in which two or more loops of virtual particles are generated. Examples of a two-loop contribution to the Lamb shift are shown in (c) and (d). In (c), an electron emits one photon and then, soon after, another, so that the two overlap in time. In (d), when a virtual electron–positron pair is emitted, the virtual electron emits a photon that is reabsorbed.

Shedding Light on QED

The team measured the contribution of both the one- and two-loop Lamb shifts to the observed spectrum and improved the existing experimental precision by nearly an order of magnitude. In doing so, the team surpassed the precision achieved by researchers at the Heavy Ion Research Institute in Germany.

"These were the first measurements of the two-loop Lamb shift in a strongly bound system," says Beiersdorfer. The results, which were chosen as a 2005 highlight by the American Physical Society's *News Bulletin*, are stimulating new calculations in QED theory. Laboratory physicists K. T. Cheng and Mau Chen, in collaboration with Jonathan Sapirstein from Notre Dame University, are making calculations, which they will compare to the experimental results. Livermore physicist Elmar Träbert, together with Beiersdorfer, is leading a study to measure highly stripped bismuth. Bismuth's electric field is weaker than uranium's, but its nuclear magnetic field is very strong. Träbert's study, which includes Livermore physicists Hui Chen, Greg Brown, and Daniel Thorn, will examine the processes that create such strong magnetic fields inside the nucleus.

"In QED experiments such as these, we are looking for one of two outcomes," says Beiersdorfer. "If the measurements support theoretical calculations, they reaffirm that the theory fits reality. If the measurements and calculations do not agree, scientists are faced with a mystery to solve, because the discrepancies show us that we have more to learn."

—Ann Parker

Key Words: electron-beam ion trap, ions, polarized vacuum, quantum electrodynamics (QED), quantum fluctuations, quantum mechanics, self-energy, spectroscopy, SuperEBIT, two-loop Lamb shift, uranium, virtual particles, virtual photons.

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Each month in this space, we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Rapid Process for Producing Transparent, Monolithic Porous Glass

Paul R. Coronado
U.S. Patent 6,998,102 B2
February 14, 2006
A process for making transparent porous glass monoliths from gels. The glass is produced much faster and in much larger sizes than present technology for making porous glass. The process reduces the cost of making large porous glass monoliths because (1) the process does not require solvent exchange nor additives to the gel to increase the drying rates, (2) only moderate temperatures and pressures are used so relatively inexpensive equipment is needed, and (3) net-shape glass monoliths can be used. The process depends on the use of temperature to control the partial pressure of the gel solvent in a closed vessel, resulting in controlled shrinking during drying.

System and Method for Characterizing Voiced Excitations of Speech and Acoustic Signals, Removing Acoustic Noise from Speech, and Synthesizing Speech

Greg C. Burnett, John F. Holzrichter, Lawrence C. Ng
U.S. Patent 6,999,924 B2
February 14, 2006
The present invention is a system and method for characterizing human (or animate) voiced excitation functions and acoustic signals, for removing unwanted acoustic noise that often occurs when a speaker uses a microphone in common environments, and for synthesizing personalized or modified human (or other animate) speech on command from a controller. A low-power electromagnetic (EM) sensor is used to detect the motions of windpipe tissues in the glottal region of the human speech system before, during, and after speech is produced by a user. From these tissue motion measurements, a voiced excitation function can be derived. Furthermore, the excitation function provides speech production information to enhance noise removal from human speech, and it enables accurate transfer functions of speech to be obtained. Previously stored excitation and transfer functions can be used for synthesizing personalized or modified human speech. Configurations of EM sensor and acoustic microphone systems are described to enhance noise cancellation and to enable multiple articulator measurements.

Conductive Inks for Metallization in Integrated Polymer Microsystems

James Courtney Davidson, Peter A. Krulevitch, Mariam N. Maghribi, William J. Benett, Julie K. Hamilton, Armando R. Tovar
U.S. Patent 7,005,179 B2
February 28, 2006
A system of metallization in an integrated polymer microsystem. A flexible polymer substrate is provided, and conductive ink is applied to the substrate. In one embodiment, the flexible polymer substrate is silicone. In another, it is poly(dimethylsiloxane).

Compact Catadioptric Imaging Spectrometer Utilizing Immersed Gratings

Scott A. Lerner
U.S. Patent 7,006,217 B2
February 28, 2006
This imaging spectrometer has an entrance slit for directing light, a lens that receives the light and reflects it, a grating that defracts the light back onto a lens that focuses the light, and a detector array that receives the focused light. In one embodiment, the grating has rulings immersed into a germanium surface.

Parallel Object-Oriented Decision Tree System

Chandrika Kamath, Erick Cantu-Paz
U.S. Patent 7,007,035 B2
February 28, 2006
This data-mining decision tree system uncovers patterns, associations, anomalies, and other statistically significant structures in data by reading and displaying data files and extracting relevant features for each of the objects. The system recognizes patterns among the objects based on object features by using a decision tree that reads the data, sorts the data if necessary, determines the best manner to split the data into subsets according to some criterion, and splits the data.

Boattail Plates with Non-Rectangular Geometries for Reducing Aerodynamic Base Drag of a Bluff Body in Ground Effect

Jason M. Ortega, Kambiz Sabari
U.S. Patent 7,008,004 B2
March 7, 2006
An apparatus for reducing the aerodynamic base drag of a bluff body having a leading end, a trailing end, a top surface, opposing left and right side surfaces, and a base surface at the trailing end substantially normal to a longitudinal centerline of the bluff body. The based surface is joined to (1) the left-side surface at a left trailing edge, (2) the right-side surface at a right trailing edge, and (3) the top surface at a top trailing edge. The apparatus includes left and right vertical boattail plates, which are orthogonally attached to the base surface of the bluff body and inwardly offset from the left and right trailing edges, respectively. This produces left and right vertical channels that generate, in a flow stream substantially parallel to the longitudinal centerline, respective left and right vertically aligned vortical structures. The left and right vertical boattail plates each have a plate width defined by a rear edge of the plate spaced from the base surface. Each plate also has a peak plate width at a location between top and bottom ends of the plate corresponding to a peak vortex of the respective vertically aligned vortical structures.

Optical Probe with Reference Fiber

Luiz B. Da Silva, Charles L. Chase
U.S. Patent 7,013,173 B2
March 14, 2006
This system for characterizing tissue includes steps for generating an emission signal, generating a reference signal, directing the emission signal to and from the tissue, directing the reference signal relative to the emission signal, and using the reference signal to compensate the emission signal. In one embodiment, compensation is provided for fluctuations in light delivery to the tip of the probe due to cable motion.

Imaging Spectrometer Utilizing Immersed Gratings with Accessible Entrance Slit

Michael P. Chrisp, Scott A. Lerner
U.S. Patent 7,016,037 B2
March 21, 2006
This compact imaging spectrometer includes an entrance slit, a catadioptric lens with a mirrored surface, a grating, and a detector array. The entrance slit directs light to the mirrored surface of the catadioptric

lens. The mirrored surface then reflects the light back through the lens to the grating. The grating receives the light from the catadioptric lens and diffracts it to the lens away from the mirrored surface. The lens transmits the light and focuses it onto the detector array.

Near-Infrared Spectroscopic Tissue Imaging for Medical Applications

Stavros Demos, Michael C. Staggs
U.S. Patent 7,016,717 B2
March 21, 2006
Near-infrared imaging using elastic light scattering and tissue autofluorescence are explored for medical applications. The approach involves imaging using cross-polarized elastic light scattering and tissue autofluorescence in the near infrared coupled with image processing and interimage operations to differentiate human tissue components.

Speaker Verification System Using Acoustic Data and Non-Acoustic Data

Todd J. Gable, Lawrence C. Ng, John F. Holzrichter, Greg C. Burnett
U.S. Patent 7,016,833 B2
March 21, 2006
A method and system for speech characterization. One embodiment includes a method for speaker verification that collects data from a speaker, wherein the data comprise acoustic and nonacoustic data. The data are used to generate a template that includes a first set of "template" parameters. The method further includes receiving a real-time identity claim from a claimant and using acoustic and nonacoustic data from the identity claim to generate a second set of parameters. The first set of parameters is compared to the second set to determine whether the claimant is the speaker. The two sets have at least one purely nonacoustic parameter, including a nonacoustic glottal shape parameter derived from averaging multiple glottal cycle waveforms.

Abstracts

Imagers Provide Eyes to See Gamma Rays

Security officials are anticipating possible scenarios in which a terrorist might use radioactive materials to fashion destructive devices. To help mitigate this threat, the Department of Homeland Security is funding two Livermore projects to develop gamma-ray imagers that significantly increase detection capabilities. The large-area gamma-ray imager, which was developed in a collaboration led by Laboratory researchers, can detect millicurie quantities of a cesium isotope from a distance of 85 meters while traveling at 16 kilometers per hour. Livermore researchers are also designing imagers that rely on Compton scattering to determine a gamma-ray source. This imager is the most efficient and sensitive, fully operational Compton imaging system to be built to date. The portable instrument will allow security officials to conduct wide-area surveillance from the ground or in the air.

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Protecting the Nation's Livestock

America's livestock are vulnerable to diseases that are endemic in other parts of the world but have not appeared in this country for many decades. If allowed to gain a foothold in the U.S., these foreign animal diseases could spread rapidly and be difficult to contain. Much concern centers on foot-and-mouth disease (FMD), a highly contagious livestock disease that has not been seen in the U.S. since 1929. The nation needs the capability to identify FMD early, so it can provide a timely and effective response to control an outbreak. To address this need, a Livermore team, with support from the Department of Homeland Security and the U.S. Department of Agriculture (USDA), has developed a rapid assay that simultaneously detects FMD as well as several foreign and endemic diseases that mimic the symptoms of FMD. The assay is being evaluated by the USDA's National Animal Health Laboratory Network and the National Veterinary Services Laboratory at Plum Island, New York. If validated and accepted by the USDA, the Livermore assay will allow state and federal laboratories to quickly diagnose FMD and livestock diseases with similar symptoms.

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U.S. Government Printing Office: 2006/570-077-10018

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- *Genetically engineered viruses provide the base for "growing" tiny gold nanowires.*
- *Livermore scientists couple climate and carbon-cycle models to predict the effects of global warming.*

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