Lawrence Livermore National Laboratory

Science & Technology REVIEW

April/May 2012

TRACKING SPACE DEBRIS

Also in this issue:

Rapid Isotopic Measurements

Mitigating Brain Trauma for Soldiers

Physics of Shock Waves Revealed

About the Cover

Space debris orbiting Earth consists of everything from spent rocket stages and defunct satellites to lost astronaut tools. Although in the last 20 to 30 years only a handful of collisions have occurred between tracked objects, as regions of space become more crowded, the threat of collision is expected to rise. The article beginning on p. 4 describes a concept developed by Laboratory physicists and engineers with support from a multi-institution joint venture to improve the accuracy of collision warnings by a factor of 100.

Cover design: Amy E. Henke. Rendering: Kwei-Yu Chu

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure 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 eight 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.

The Laboratory is operated by Lawrence Livermore National Security, LLC (LLNS), for the Department of Energy's National Nuclear Security Administration. LLNS is a partnership involving Bechtel National, University of California, Babcock & Wilcox, Washington Division of URS Corporation, and Battelle in affiliation with Texas A&M University. More information about LLNS is available online at www.llnsllc.com.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the Web at str.llnl.gov.

© 2012. Lawrence Livermore National Security, LLC. All rights reserved. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. To request permission to use any material contained in this document, please submit your request in writing to Public Affairs Office, Lawrence Livermore National Laboratory, Mail Stop L-3, P.O. Box 808, Livermore, California 94551, or to our e-mail address str-mail@llnl.gov.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

NNSA
National Nuclear Security Administration
LAWRENCE LIVERMORE NATIONAL SECURITY LLC

Prepared by LLNL under contract
DE-AC52-07NA27344

Science & Technology REVIEW

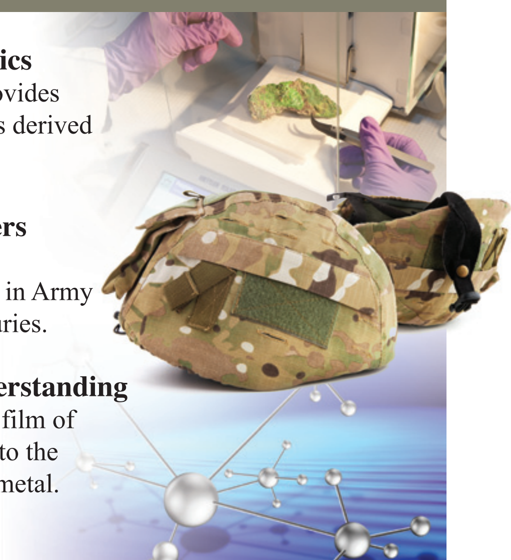
April/May 2012

Lawrence Livermore National Laboratory

Contents

Feature

Research Highlights



Departments

S&TR Staff

Scientific Editor
Lisa A. Poyneer

Managing Editor
Ray Marazzi

Publication Editors
Pamela MacGregor and Caryn Meissner

Writers
Monica Friedlander, Kris Fury,
Arnie Heller, and Robert Kirvel

Art Director
Amy E. Henke

Proofreader
Carolin Middleton

Print Coordinator
Charlie M. Arteago, Jr.

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

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

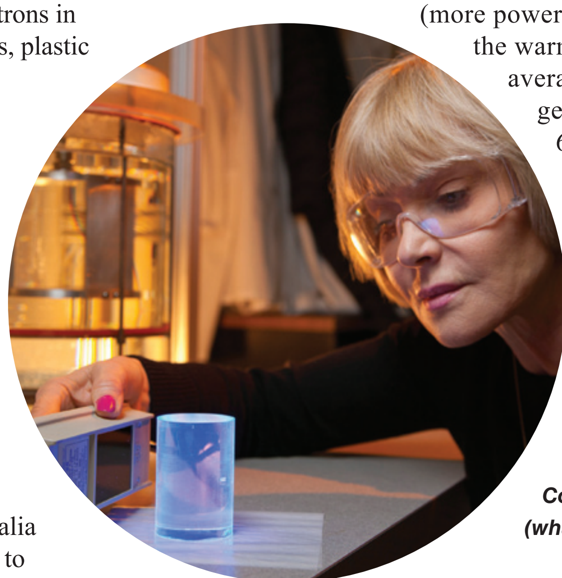
Printed in the United States of America

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

UCRL-TR-52000-12-4/5
Distribution Category UC-99
April/May 2012

A Breakthrough in Nuclear Material Detection

A team of Livermore researchers has developed the first plastic material capable of efficiently distinguishing neutrons from gamma rays. The new technology could assist with the detection of nuclear substances that might be used by terrorists in improvised nuclear devices and could help detect neutrons in major scientific projects. For years, plastic materials have been used in large, low-cost detectors for portals and high-energy physics facilities. While these materials have been able to detect neutrons and gamma rays, they have been incapable of distinguishing one from the other, which is key to identifying nuclear substances such as uranium and plutonium from benign radioactive sources.



"When we studied mixed crystals and mixed liquids," says Livermore materials scientist Natalia Zaitseva (shown), "we found that to achieve neutron discrimination from gamma rays, we had to increase the dye concentration in the plastics by at least tenfold than would typically be used." In their work, the scientists demonstrated a plastic scintillator that can discriminate between neutrons and gamma rays using a polyvinyltoluene polymer matrix loaded with a scintillating dye, 2,5-diphenyloxazole. Scintillators are special materials that light up when excited by ionizing radiation. Plastics have more flexibility in their composition and structure than crystals and none of the hazards associated with liquid scintillators. The results of the team's work were published in the March 11, 2012, edition of *Nuclear Instruments and Methods in Physics Research A*.

Contact: Natalia Zaitseva (925) 423-3537 (zaitseva1@llnl.gov).

Power Generation Is Blowing in the Wind

Wind farm operators could better estimate how much power is generated if wind forecasts included atmospheric stability impact measurements, according to Lawrence Livermore scientist Sonia Wharton and colleague Julie Lundquist of the University of Colorado at Boulder and the National Renewable Energy Laboratory. In a recent study, Wharton and Lundquist examined turbine-generated power data, segregated by atmospheric stability, to determine the power performance at a West Coast wind farm.

Wharton and Lundquist gathered a year's worth of power data from upwind modern turbines (80 meters high) at the multimegawatt wind farm. They considered turbine power information as well as meteorological data from an 80-meter-tall tower and a sonic detection and ranging (sodar) system, which provided wind profiles up to 200 meters above the surface, to look at turbulence and wind shear. Collecting data from upwind turbines removed any influence that turbine wakes may have on power performance.

The team found that wind speed and power production varied by season as well as from night to day. Wind speeds were higher (more power) at night than during the day and higher during the warm season than in the cool season. For example, average power production was 43 percent of maximum generation capacity on summer days and peaked at 67 percent on summer nights.

This work highlights the benefit of observing complete profiles of wind speed and turbulence across the turbine rotor disk, often available only with a remote sensing technology such as sodar or lidar (laser detection and ranging). "Wind energy resource assessment and power forecasting would profit from this increased accuracy," says Lundquist. The team's results were published in the January 12, 2012, edition of *Environmental Research Letters*.

Contact: Sonia Wharton (925) 422-9295 (wharton4@llnl.gov).

Scientists Create New Atomic X-Ray Laser

Laboratory scientists and collaborators aimed radiation from the Linac Coherent Light Source (LCLS) at a cell containing neon gas, setting off an avalanche of x-ray emissions to create a new "atomic x-ray laser." "X rays give us a penetrating view into the world of atoms and molecules," says physicist Nina Rohringer, a former Laboratory postdoctoral researcher, now a group leader at Max Planck's Advanced Study Group.

To make the atomic x-ray laser, LCLS's powerful x-ray pulses—each a billion times brighter than any available before—knocked electrons out of the inner shells of many of the neon atoms. When other electrons fell in to fill the holes, about 1 in 50 atoms responded by emitting a short-wavelength x ray. Those x rays then stimulated neighboring neon atoms to emit more x rays. This process created a domino effect that amplified the emission 200 million times and created the x-ray laser beam.

"This work is a significant advance in the quest for shorter wavelength lasers," says Livermore scientist Rich London. "In addition, the demonstration of the neon x-ray laser provides a sensitive test of the physics of intense x-ray interaction with atoms. By comparing theoretical modeling to the observed output signals, one can pin down the basic ultrafast processes occurring in the region where the LCLS beam interacts with the gas."

Rohringer and other Livermore scientists collaborated with researchers from Colorado State University and SLAC National Accelerator Laboratory. The research was funded by Livermore's Laboratory Directed Research and Development Program. Results of the study appeared in the January 26, 2012, edition of *Nature*.

Contact: Rich London (925) 423-2021 (london2@llnl.gov).

Commentary by Penrose (Parney) C. Albright

Lawrence Livermore as the "Go-To" National Security Laboratory

AVID readers of *S&TR* are keenly aware of the innovative work that goes on at Lawrence Livermore National Laboratory. Each month, they learn about the wide range of remarkable accomplishments made by our scientists and engineers, who apply ingenuity and skills to solve some of the nation's most pressing problems. As former Secretary of State George P. Shultz so succinctly put it in a recent visit to Livermore, our Laboratory's mission is to "make the world a safer place."

I was greatly honored to have been selected last fall to serve as Laboratory director. It is extremely exciting to lead an institution dedicated to serving the needs of the nation, with such an outstanding workforce and exceptional research capabilities. And it is particularly gratifying to be a part of the Laboratory at this time, when the world faces many daunting challenges that demand the best in science, technology, and engineering.

We have a clear mission and vision of what we need to do to serve the nation. In an all-hands meeting with Laboratory staff in February, I took the opportunity to articulate our mission, vision, and values in words I like to use when talking to others about Livermore. Here, I will focus on vision and make three basic points.

First, Livermore will "lead the nation in nuclear weapons stockpile science, innovation, and sustainment." Ensuring the safety, security, and performance of the nation's nuclear deterrent forces is and always has been our first and foremost responsibility. *S&TR* readers will remember that last month's issue featured the major effort we are undertaking to extend the service life of the W78 intercontinental ballistic missile warhead, and looked at how we are using the remarkable computational and experimental capabilities of the Laboratory to develop options and certify changes that are made. (See *S&TR*, March 2012, pp. 6–15.) Readers are also likely following the groundbreaking experiments being performed at the National Ignition Facility for stockpile stewardship and the progress being made to achieve fusion ignition and burn. (See *S&TR*, January/February 2012, pp. 4–11.)

Second, Livermore will "be the foremost national security laboratory—anticipating, innovating, and delivering solutions for the nation's most challenging problems." For example, in 2007, China shot down one of its own defunct satellites, creating 2,000 baseball-sized or larger pieces of trackable debris that would cripple a satellite on impact. This event provided the impetus for Livermore, Los Alamos, and Sandia national laboratories to work with the Air Force Research Laboratory to develop simulation tools that will improve the nation's capabilities for detecting and monitoring threats to U.S. space operations. (See *S&TR*, July/August 2009, pp. 4–11.) These tools were used to re-create and analyze the collision of two satellites in February 2009 and, more recently, the reentry of the failed Russian Mars probe.

As the article beginning on p. 4 describes, Livermore researchers have also taken an innovative step—beyond better simulation tools—to help satellite operators avoid collisions in space. The idea is to use nanosatellites—about the size of a 2-liter soda bottle—to determine more accurate trajectories for objects orbiting Earth. A project funded by the Laboratory Directed Research and Development Program was launched in 2010 to pursue this concept. As part of a joint venture with Boeing, Texas A&M University, the Naval Postgraduate School, and the National Reconnaissance Office (the federal sponsor of the first mission), the first payload will be launched in 2012.

This combination of focusing on sponsor needs, innovating, and forming a broad partnership to develop a new technology quickly is a unique strength of our Laboratory and helps us meet a broad set of national needs. We want sponsors both in government and in industry to think of Livermore first as the "go-to" place to get work done that is important and extremely challenging.

The creation of and rapid progress on the nanosatellite collision-avoidance project would not have been possible without the creative and skilled people who work at Livermore, which relates to the third piece of our vision: The Laboratory will "be the premier destination for our nation's best scientists and engineers." In addition to work sponsors, we want graduate students and postdoctoral researchers looking for a challenging career in service to the country to think of Livermore first.

Talented people are attracted to a place where they can work side by side with experts in a chosen field—and Livermore really stands out with the quality of its workforce. To attract such people, the Laboratory must also provide a first-class working environment. In addition to top-notch research capabilities, we envision a Laboratory where employees benefit from quality facilities with productivity enhancers such as wireless across the site, which we are installing, as well as business systems and operational practices that facilitate rather than impede progress in programmatic work.

With an outstanding workforce, excellence in science and technology, and a focus on national interests and sponsors' needs, Livermore has a bright future serving as the go-to national security Laboratory.

■ Penrose (Parney) C. Albright is director of Lawrence Livermore National Laboratory.

LAUNCHING TRAFFIC CAMERAS INTO SPACE

Livermore researchers are developing traffic cameras to augment their efforts to improve space-debris collision predictions.

Artist's concept courtesy of National Aeronautics and Space Administration (NASA).

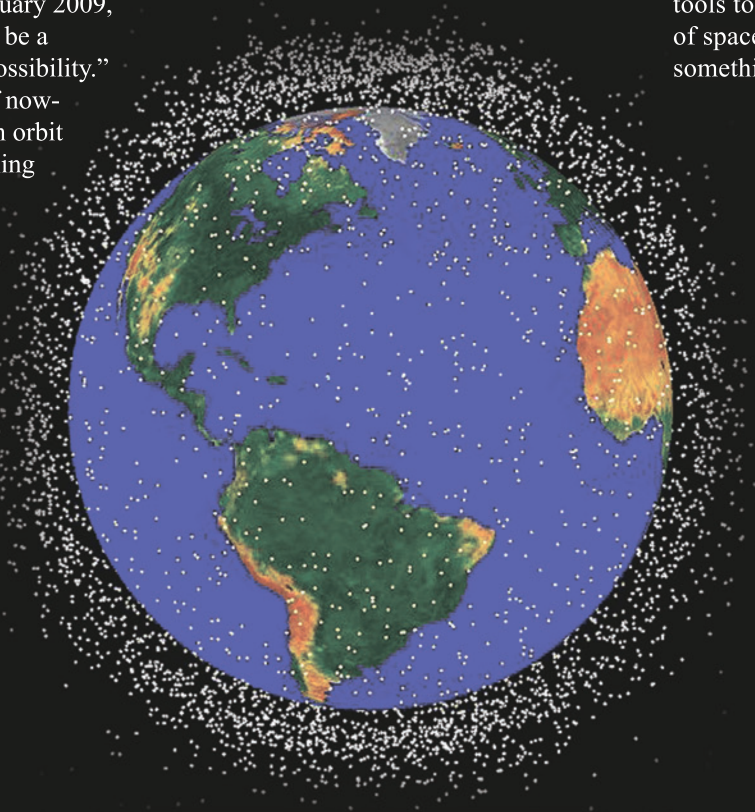
SINCE the Soviet Union launched the world's first artificial satellite, Sputnik I, in 1957, thousands of satellites have been sent into space to orbit Earth. Today, nearly a thousand active satellites are in orbit. The bulk of them are used for invaluable services, such as critical military and intelligence data collection, global positioning systems (GPSs), telecommunications, navigation systems, and weather and climate monitoring. These satellites are increasingly at risk of colliding with damaging space debris. Livermore engineer and lead systems developer Vincent Riot says, "Following the collision between an American Iridium communication satellite and a defunct Russian Cosmos satellite in February 2009, we now know that collisions can be a reality and not just a statistical possibility."

Space waste, the collection of now-useless, human-created objects in orbit around Earth, consists of everything from spent rocket stages and defunct satellites to collision fragments and lost astronaut tools. Space objects do not orbit in a perfect vacuum. Small amounts of gas from Earth's atmosphere extend far into space and act to slow down the motion of satellites through drag. Because the frictional forces are so small, a great number of useless objects remain in orbit.

Each type of space hardware is best suited to a particular orbital regime, or region. For example, low-Earth orbit—160 to 2,000 kilometers above Earth's surface—contains a higher proportion of space stations, upper rocket stages, and amateur satellites. In middle-Earth orbit, 2,000 to 35,876 kilometers in altitude, navigation satellites are positioned. Telecommunications satellites are sent to geostationary orbit, located at 36,000 kilometers. Current guidelines require that satellites either de-orbit or boost their orbits to a higher "graveyard orbit" within 25 years after the end of their service life.

Critical density occurs when new debris is created faster than frictional forces can remove these objects from orbit. In the last 20 to 30 years, only a handful of collisions have occurred between tracked objects, such as satellites and larger debris. Now, as regions of space become more crowded, the threat of collision is expected to rise. Eventually, some regions of space could become too crowded for future launches.

Physicist Willem De Vries of the Physical and Life Sciences Directorate says, "When we were designing a set of analysis, simulation, and visualization tools to improve situational awareness of space objects, we asked: Is there something we can do to prevent satellite



This NASA computer-generated debris plot depicts the number of tracked objects in low-Earth orbit alone. Approximately 95 percent of the objects in this illustration are debris. Low-Earth orbit is within 2,000 kilometers of Earth's surface and is the most concentrated region for orbital debris.

collisions with damaging space debris?" (See *S&TR*, July/August 2009, pp. 4–11.) "We considered using nanosatellites, an emerging technology that is transitioning from a university-oriented experimental platform to being seriously considered for operational use."

Cube Satellites Monitor Space Junk

One type of nanosatellite (defined as an artificial satellite with a launch mass between 1 and 10 kilograms, or 2.2 and 22 pounds) is the "cube satellite." CubeSats, as they are nicknamed, measure 10 centimeters on a side, just a bit larger than a Rubik's cube. A pair of three-unit CubeSats (called 3U CubeSats) equipped with optical imaging payloads will demonstrate the main elements of the Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE) concept.

During launch, large satellites require ballast to balance the spacecraft. By taking the place of ballast dead weight, CubeSats can ride along as auxiliary payload, making them fairly inexpensive to launch. However, CubeSat developers must show that their satellite adheres to a strict set of engineering standards, so as not to jeopardize the primary launch payload.

In the first phase of the STARE project, software tools are being developed for enabling operators to predict collisions with high accuracy, using the improved positional information that nanosatellites will provide. Later this year, in the proof-of-concept phase, the Livermore-developed technology that makes use of these common small satellites will be launched into space. The Laboratory's idea could be described as using traffic cameras in orbit to track space objects. A multidisciplinary team of physicists and engineers at Livermore developed the STARE project with funding from Livermore's Laboratory Directed Research and Development Program.

The STARE project is the story of an extraordinary partnership. To develop this new technology, Livermore established a multi-institution joint venture between Boeing, an aerospace company with a history of bringing satellite products to market; Texas A&M University and the Naval Postgraduate School, two academic institutions with research expertise in this area; and the National Reconnaissance Office, the federal sponsor of the first-mission CubeSats. The partnership relies on the strength of the Laboratory to demonstrate the proof of concept and produce a functional prototype.

Faster Than a Speeding Bullet

Space debris more or less maintains the orbit of its parent satellite. If a satellite was launched in low-Earth orbit, for example, any remaining debris will stay in this orbit, overlapping the trajectories of newer objects. Debris is a potential collision risk to active spacecraft; a piece as small as a marble can shatter a satellite. "Orbital speeds are about 7 kilometers per second, more than 10 times the speed of a bullet," De Vries says. In the last two decades, five satellites have been disabled by collisions with large debris.

The majority of the estimated tens of millions of pieces of space debris are small particles—dust from solid rocket motors and paint flakes that come loose from spacecraft surfaces, for example. The impact of these particles causes erosive damage, similar to sandblasting. The National Aeronautics and Space Administration's Debris Office estimates that as many as 300,000 objects larger than 1 centimeter are present in low-Earth orbit alone. A much smaller number of the debris objects are larger, more than 10 centimeters. The only protection against this larger debris is to maneuver the spacecraft to avoid a collision. If a collision with larger debris does occur, many of the resulting fragments from the damaged spacecraft will be the size of a softball or larger, and these objects pose a greater risk of damage from a collision. The 2009 collision between the Russian and American satellites over northern

A single cube satellite, or CubeSat, measures 10 centimeters on a side, just a bit larger than a Rubik's cube. This photo shows a three-unit (3U) CubeSat.

Vincent Riot holds the Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE) flight optical payload in its handling fixture.

Siberia produced a few thousand pieces of debris, still in orbit.

Removing defunct satellites is problematic. In 2007, China performed an antisatellite weapons test at almost 805 kilometers in altitude, destroying an aging weather-satellite target using a kill vehicle launched on board a ballistic missile. The result was 2,000 baseball-sized or larger pieces of junk that could cripple a satellite on impact and over 2 million pieces that could cause damage.

Space Base

At the start of the STARE project in May 2010, De Vries conducted an extensive conceptual study to determine whether monitoring the path of debris from space—as opposed to current ground-based monitoring—would be feasible and provide better results. "To observe space objects from the ground, the ground area must be dark, while the objects must be illuminated by the Sun. This requirement limits the debris-observation window to between 1 and 2 hours after sunset and before sunrise," De Vries says. Inclement weather further limits observation. "To see all the debris in a short period of time, about 48 ground stations around the world would be required, which would be expensive," he says. "However, satellites outside Earth's atmosphere orbit quickly, and space is always dark, providing multiple times to observe objects within a single day." The study included information on where to locate the CubeSats, how well they would work, and how many would be needed to provide valuable data.

The study concluded it would be easier and more efficient for satellites to obtain the needed observational images and data from space. A day's worth of data would give researchers better information regarding the orbit of debris and allow them to determine how close the debris might come to a satellite in its path. Only the orbits of objects that would come close to satellites within a couple of days would be refined with the knowledge gleaned from the observational data. Predictions cannot be made weeks in advance because orbits are not completely stable. "When the Sun flares, for example, the atmosphere puffs up, and creates drag that changes orbits," says De Vries.

Actionable Data

The U.S. Joint Space Operations Center (JSpOC) gathers ground-based observations of space debris. The primary source of the data is the Space Surveillance Network, a global network of 29 optical telescopes and radars operated by the U.S. Air Force. The Space Surveillance Network follows more than 20,000 manmade objects in orbit as big as a baseball or larger, each capable of destroying satellites.

Every day, JSpOC screens a list of satellites. The objects with the highest priority are human-related spacecraft, such as the International Space Station, followed by military and intelligence satellites. One sensor tracking an object in orbit and determining its position at a moment in time is called an observation.

Multiple observations strung together in the same pass as the satellite flies overhead are called a track. JSpOC determines how many tracks of data are nominally required to determine each object's orbit based primarily on the object's type and size and the change rate of its orbit.

These requirements are then fed into an algorithm along with the sensor availability. The algorithm assigns satellites to sensors in the network. During the next day, the sensors track their assigned satellites and transmit the data back to JSpOC. The data are then used to calculate a satellite's location and its predicted position forward and backward in time. The entire process is repeated daily.

Because JSpOC tracks space objects, it can warn satellite operators when they may need to maneuver their satellites to prevent a collision with another space object. However, the level of positional accuracy for the complete set of tracked space objects is insufficient to predict collisions with an adequate degree of certainty. "Operators receive warnings if an object and a satellite are close, but the prediction may be accurate to within only a kilometer or so, which is not accurate enough," De Vries says. Large operations, such as the Iridium constellation, a group of 90 satellites providing voice and data coverage to phones, pagers, and integrated transceivers, would receive warnings to move 10 satellites per day at that accuracy level. Satellites cannot move repeatedly because they have limited fuel to maintain their orbits during their 5- to 10-year lifetimes. Once they use up their fuel, they become uncontrollable.

"Operators know that 9,999 of 10,000 warnings will be false alarms, so most are ignored," says De Vries. "With the STARE project, we intend to refine this by a factor of 100. So, instead of 1 in 10,000 warnings being accurate, 1 in 100 is accurate. Warning rates would be reduced to once per the lifetime of a satellite."

The STARE project will use the Boeing-built Colony II bus developed under a contract with the National Reconnaissance Office. "A Colony II bus is a nanosatellite containing a radio, batteries, attitude control unit, solar panels, and other parts with an empty space inside, roughly half the volume," explains Riot, who coordinated the effort. A payload can be inserted into this space to accomplish something useful, such as STARE's miniature telescope with GPS tagging. "Think of Boeing's Colony II bus as a carriage with wheels, suspension, steering, and a frame," says Riot. "The carriage performs the basic capabilities of driving around and turning. Our creation, the payload, is placed on the carriage to deliver images of orbital debris."

Refinement of Ephemeris

"We need to know the position of observed satellites or pieces of debris we're targeting at a given time," says Physical and Life Sciences postdoctoral

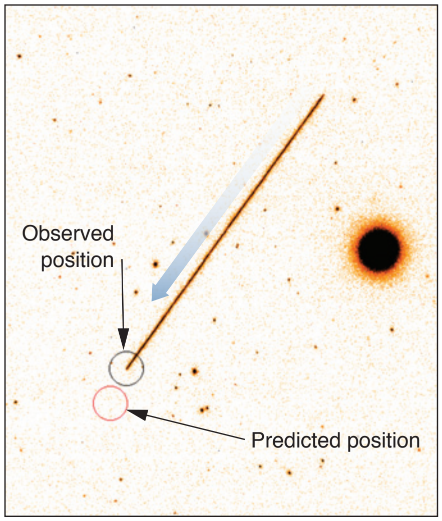
This 3U CubeSat contains the Livermore-developed optical payload. The unit will ride along as auxiliary payload when launched later in 2012.

scholar Lance Simms. "When we take a picture, we get the object's location in our camera's pixel frame. But we still have to map that information to the celestial frame of the stars. To accurately locate satellites, we need to measure the positions of the stars in the image and the start and end position of the debris track to subpixel accuracy." Timing is important because multiple frames are required at the time the observed satellite is expected to arrive and because the exact times of the exposures are used to refine the orbit parameters.

Another camera will take pictures of the sky and compare those to the star catalog onboard to find the best match. Because the positions of the stars are known, the 3U CubeSat uses these data to report its coordinates and which way it's pointing with respect to the Sun or Earth. Then researchers can calculate how much the satellite needs to rotate to look at a certain part of the sky. Because objects in space cannot push themselves, the 3U CubeSat uses wheels that rotate in one direction and cause the bus to move the other way. Many external forces, such as solar winds, will hit the unit, so it must keep controlling its position and taking images of its location.

The 3U CubeSat is tasked with acquiring observations of objects for 24 hours. These data are then processed and aggregated to improve the orbital parameters. Once the uncertainty has been reduced, the data are used to update the forecast to the closest approach between satellites and debris and the probability of collision.

"Making sure we could successfully capture images with a camera within a CubeSat was the main constraint," Riot says. That small space also has to contain an attitude control system, a radio system to send data, a power system consisting of batteries and solar panels, and a GPS. "Attitude control is the most complicated part of the system," he says. "We need to know where the 3U CubeSat is and have a way of rotating it so it points at a star field without drifting."



This image taken in Livermore November 22, 2011, depicts the start and end positions of India's Polar Satellite Launch Vehicle Rocket Body tracked to subpixel accuracy. The path is captured by the camera's pixel frame and then mapped to the celestial frame of the stars (dots).

Tiny Telescopes

Optical engineer Brian Bauman and mechanical technician Darrell Carter designed and fabricated the optical payload, which includes the telescope and camera. The team chose to use Boeing's star-tracker camera because the Colony II bus already supports the device. In the images captured by the camera, stars appear as dots, and the nanosatellite uses them to calibrate where to point. (See the figure above.) When pieces of debris drift through the field of view, they look like streaks or lines. Images—one set of frames per orbit—are stored until the 3U CubeSat passes over the ground stations.

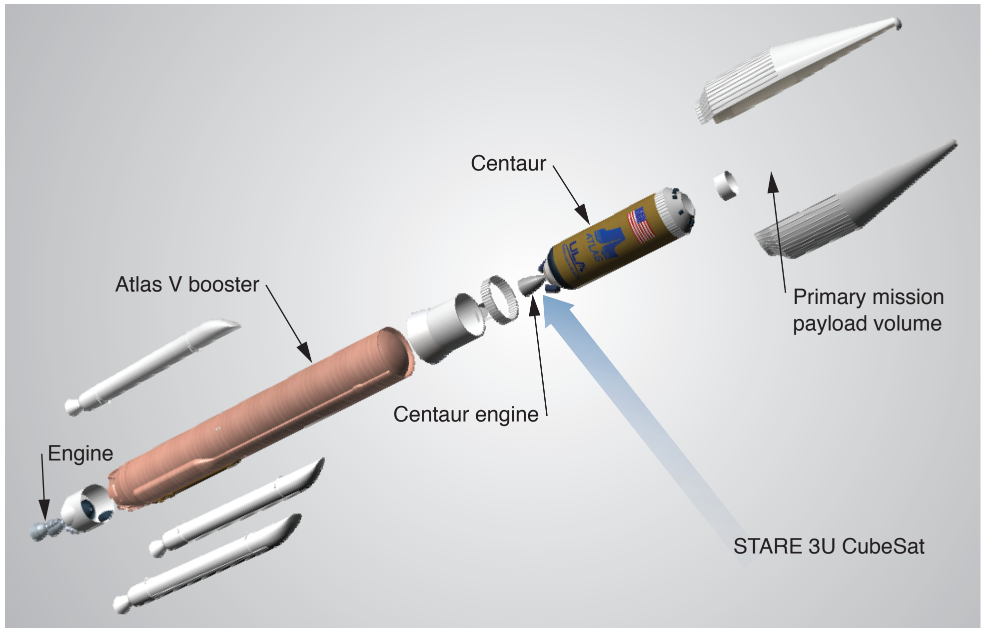
Says Riot, "Once the Colony II bus is launched, it's autonomous, circling Earth every 90 minutes, or 15 times per day. It sends data collected from objects once a day. The unit even preprocesses images so they don't have to be downloaded, an important advantage considering the limited data rate available."

The field of view must be wide enough for researchers to see the entire streak with both end points to determine the orbital path of the debris. "Shapes become elongated at the edges of the view, appearing as teardrops rather than round dots," Bauman says. "Because of the short timeline, an initial two-mirror telescope was built. A soon-to-be-built unit will include lenses that correct for the curved focal plane and other aberrations, making the shapes more distinct. An important aspect of the telescope's viability relies on using modern manufacturing techniques to reduce costs."

Once the Livermore telescope leaves the lab, new challenges begin. "CubeSats have never held optical telescopes requiring precision alignment," Bauman says. "It's a very tall order. Our 3U CubeSat will be located near the engine during launch and will experience a high level of vibration, which is a concern because very small changes in the distance between the two mirrors will produce out-of-focus images. In optical design, the challenge is often in the constraints." As images come in from the mission, researchers will learn how to improve future designs. "We'll need to tweak the design," says Bauman. "Recently, I've been inspired by cell-phone camera configurations, which use only one mirror but bounce light off that mirror many times."

Simms began work on the project by developing the algorithm that detects the debris tracks from end point to end point, one unlike any other he had seen in research. "Finding stars is common in astronomy," says Simms. "However, in that field, researchers are not really concerned with finding the track end points. We need to be able to find the streak end points to a precise level. If we were using a perfect camera and set of optics, we could capture

The STARE CubeSats are integrated into the main box that bolts to the launch vehicle.



This artist's rendering shows where the STARE 3U CubeSat will be positioned on the launch vehicle, an Atlas V rocket.

a perfect line with perfect ends. In reality, the telescope causes the image to blur. Within that blur is the real end point." The team does not want to send all the data back to Earth because it would become expensive in terms of time and resources. "Our idea is to perform all the processing on the satellite and send down only the stars' locations and the tracking points," says Simms. "These data are all we need to refine the orbit of the satellite or piece of debris."

Simms also wrote the firmware code for the payload. "We have a small microprocessor in the payload of the 3U CubeSat that talks to the larger processor on the Colony II bus," says Simms. "The vehicle performs attitude control and points at the stars, and the payload is strictly responsible for taking the pictures and processing them." He wrote the entire code that runs the payload processor; acquires the GPS location, time, and images; and runs the satellite algorithm on the images. The processor returns the information to the vehicle, which sends it to the ground.

The code took a year to write and to ensure it is error free and responds to all commands. At the Naval Postgraduate School, the team ran the processor through a battery of tests and found no obvious bugs. "We've also taken the processor out at night and pointed at the stars," says Simms. "It has successfully sent back images and coordinates."

While the researchers wait for the STARE 3U CubeSat to launch into low-Earth orbit on an Atlas V rocket, they will refine their algorithms and develop software to automate data capture and delivery. These data will tell the team how well CubeSats on the Colony II buses are doing. "Our main concern is jitter from noise in the satellite attitude system," says De Vries. Once it's launched, the researchers will also get telemetry data—voltages, currents, energy uses—from the Boeing vehicle. The lifetime expectancy of the 3U CubeSat is nominally one year. Many of the parts are not particularly sophisticated, such as the radio and the sensor, which Boeing uses because they are space-qualified. Next-generation STARE satellites will feature an improved cooled imaging sensor to enable observations at longer ranges.

Constellation of Possibilities

If the initial mission is successful, Livermore could begin building nanosatellites for various applications, such as space weather and other scientific missions. Eventually, the Laboratory could develop a full constellation of nanosatellites proposed as a later phase of STARE. For an 18-nanosatellite constellation, STARE has the capability to reduce the collision false-alarm rate by 99 percent, up to 48 hours ahead of the closest approach, which would be attractive to satellite owners or providers.

The team will be looking for sponsors for the constellation. "While typical single satellites cost several hundred million dollars to one billion dollars, a full constellation of 18 nanosatellites to track space debris costs only a fraction of that— about $30 million," Riot says. The constellation may prove a good candidate for technology transfer.

—Kris Fury

Key Words: nanosatellite, optical payload, satellite, Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE), space debris, telescope, three-unit cube satellite (3U CubeSat), track-detection algorithm.

For further information contact Vincent Riot (925) 422-9798 (riot1@llnl.gov).

An Improved Tool for Nuclear Forensics

IN the aftermath of an aboveground nuclear explosion, measuring the isotopic compositions of fallout can provide important forensic information, including data pertaining to the production and irradiation histories of key materials. Livermore scientists working with collaborators at Argonne National Laboratory and the University of California at Berkeley have recently demonstrated rapid and high-accuracy isotopic measurements of plutonium and uranium using a laser-based technique known as resonance ionization mass spectrometry (RIMS).

Resonance ionization uses pulsed laser light to first excite an atom or molecule and then remove an electron to create an ion. Although scientists have understood the basic physical principles involved in the process for many years, it was not until the mid-1990s that a method was developed to provide unprecedented analysis of stellar nucleosynthesis processes captured in grains of star dust. Lawrence Livermore researcher Kim Knight, whose background is in cosmochemistry, and colleagues theorized that the RIMS technique could also be applied to study samples derived from nuclear events on Earth.

Postdetonation nuclear forensics is primarily concerned with detecting the presence of uranium (U) and plutonium (Pu) and measuring isotopic ratios, $^{235}U/^{238}U$ for example. Conventional mass spectroscopy cannot distinguish between different isotopes of identical mass—in particular, ^{238}U and ^{238}Pu—in the same sample. As a result, the two actinides must be extracted from a forensic sample and separated from each other in a process that can take longer than decision makers would want to wait. The challenge is that postdetonation nuclear forensics demands rapid answers. RIMS uses lasers to separate elements, thus circumventing the lengthy steps of chemical separation and sample preparation. As a result, several actinides can be measured from virtually unprocessed samples in only a few hours.

Calming the Jitters

RIMS works in three stages. First, a focused laser or ion beam desorbs or sputters material from the surface of a sample, forming a cloud of ions, neutral atoms, and molecules. (See the figure on p. 12.) Ions are removed from the cloud using a brief voltage pulse, and the neutral atoms are left behind. Next, a set of wavelength-tunable lasers selectively excites atoms in the cloud, promoting them to an intermediate excited state. A final laser further excites electrons, knocking them off the atoms and creating ions. Because the laser wavelengths are precisely tuned to match an element's unique intermediate excitation and ionization states, only atoms of the desired element are ionized. Finally, the photo ions are accelerated in a mass spectrometer to obtain isotopic measurements.

Building lasers for demanding forensics applications has been a significant challenge. Even tiny fluctuations in laser wavelength, power, and bandwidth can introduce errors that affect the reproducibility of results. According to Knight

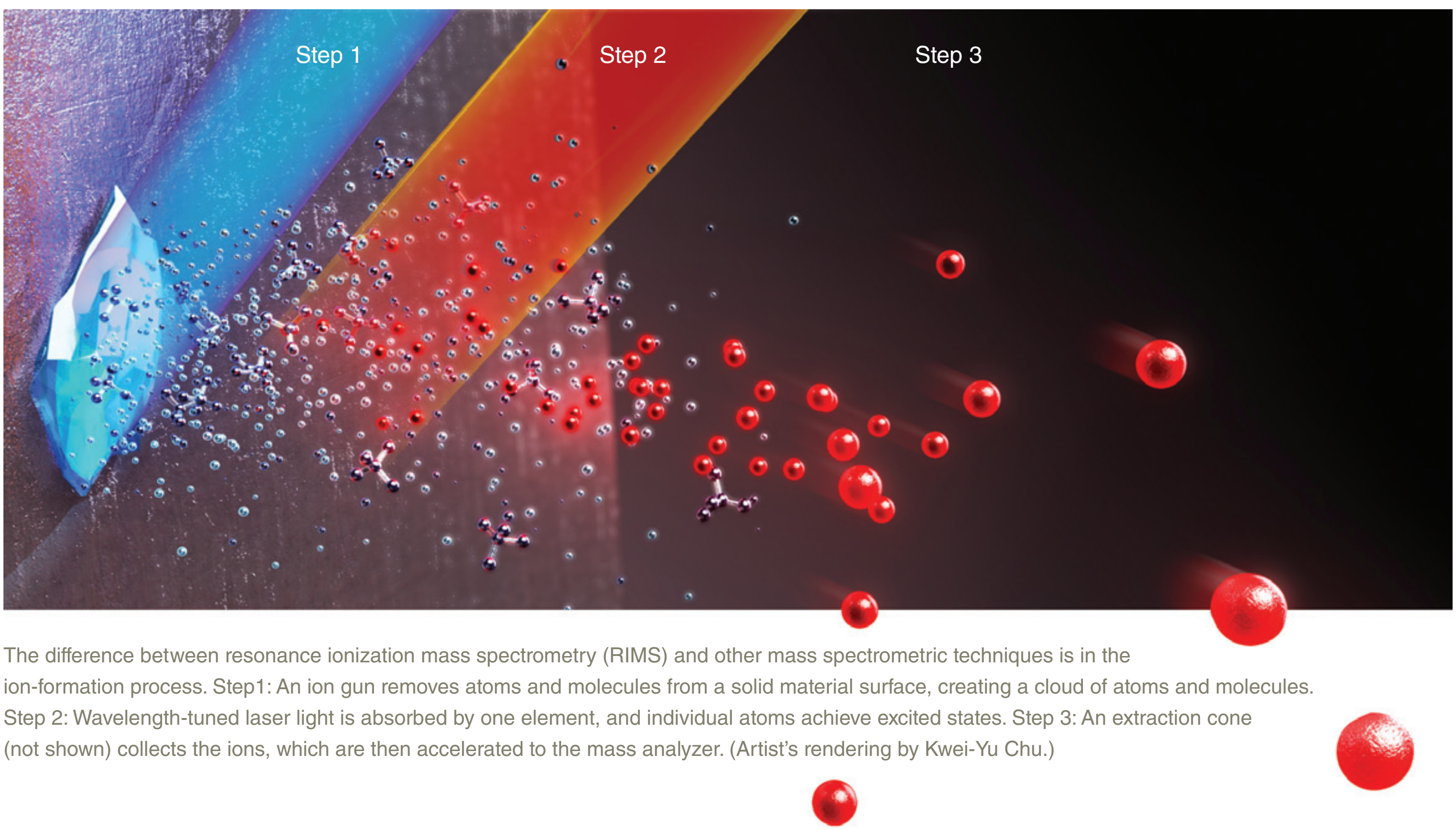
and Argonne collaborator Michael Savina, stabilizing the lasers and reducing jitter has greatly improved the quality of the measurements. By precisely controlling wavelength, pulse timing, power, and pointing stability in the lasers and making adjustments to bandwidth (the spectral range of laser wavelengths present in the laser beam), the team achieved more uniform ionization in experiments and thus better detection and measurement of multiple isotopes.

Speeding Up the Process

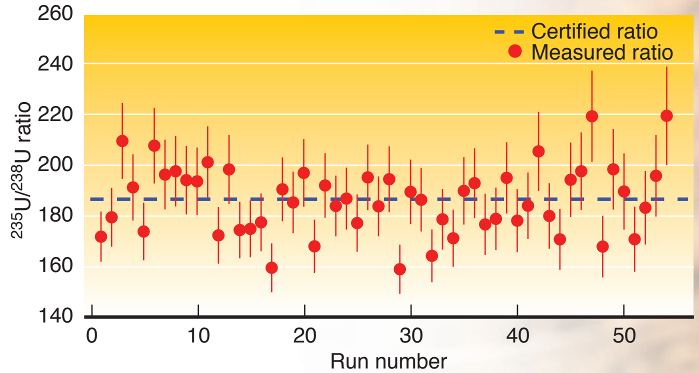
In a breakthrough study, the RIMS team, which includes Livermore postdoctoral researcher Brett Isselhardt, used Argonne's CHARISMA (Chicago-Argonne Resonance Ionization Spectrometer for MicroAnalysis) time-of-flight mass spectrometer—originally designed to study grains of star dust recovered from meteorites—to rapidly assess natural uranium metal and oxide targets. The relative abundances of uranium isotopes (in particular, the $^{235}U/^{238}U$ ratio) were measured from solid uranium samples with known isotope ratios. Virtually no sample preparation was required. The idea was to minimize and stabilize laser-induced isotope fractionation, which can be severe.

Variability in the measured isotope ratio means that each isotope has responded differently to the ionization process and can lead to incorrect conclusions. By broadening the laser bandwidth from 1 to 5 picometers (10^{-12} meters) in the first of three resonance lasers, while holding the second and third resonance lasers fixed, the team decreased measurement uncertainty from 10 percent to less than 0.5 percent. The tiny adjustment works because the 5-picometer-wide range of laser wavelengths overlaps the peak energy region needed to excite both ^{235}U and ^{238}U with equal intensity. This study shows that laser bandwidth has an enormous effect on the precision of isotope ratio measurements and demonstrates how to optimize that particular parameter.

In a subsequent study, the team completed the first in situ analysis of a complex natural uranium silicate (uranium ore) with RIMS using seven experimental configurations. Both two- and three-color laser schemes were assessed along with different methods for dislodging uranium atoms from a sample. To improve precision, the team used an automatic feedback system to track and correct drift in the laser wavelengths and broadened the laser bandwidth to as wide as 10 picometers. Results were achieved in a few hours with precisions of 1 percent for uranium isotope



The difference between resonance ionization mass spectrometry (RIMS) and other mass spectrometric techniques is in the ion-formation process. Step1: An ion gun removes atoms and molecules from a solid material surface, creating a cloud of atoms and molecules. Step 2: Wavelength-tuned laser light is absorbed by one element, and individual atoms achieve excited states. Step 3: An extraction cone (not shown) collects the ions, which are then accelerated to the mass analyzer. (Artist's rendering by Kwei-Yu Chu.)



RIMS permits accuracies to better than 1 percent while measuring the ratio of uranium-235 (^{235}U) to uranium-238 (^{238}U) over timescales of several hours. Analysis times to collect data, such as these from a highly enriched uranium sample, are less than 4 hours per sample, including preparation time.

A sample of glass formed in a historic U.S. nuclear weapons test is selected from bulk soils for direct analysis using the RIMS method.

compositions measured directly from the uranium silicate after minimal sample preparation.

To measure both uranium and plutonium isotopes in a single material for the first time, the RIMS team prepared samples from a solution of 25 percent each of ^{238}Pu, ^{239}Pu, ^{242}Pu, and ^{244}Pu that also contained ^{235}U and ^{238}U. Sample material was electrodeposited onto a titanium stub to promote reduction. The CHARISMA spectrometer was used with lasers tuned for a three-color excitation and ionization. The challenge was that ^{238}U, which is the most common uranium isotope in nature, creates isobaric (same-mass) interference with plutonium, making the two isotopes difficult to differentiate. By making improvements to the excitation lasers and changing the laser wavelengths between measurements, the team demonstrated excellent discrimination against isobaric interferences. When the lasers were tuned to excite plutonium, the uranium signal was essentially absent, and inversely, the plutonium signal was essentially absent when lasers were tuned to excite uranium. All of the plutonium and uranium isotope ratios were accurately measured.

Inside Desert Glass

The RIMS technique has most recently been demonstrated on fallout debris taken from the Nevada National Security Site. The samples pieces of glass formed during post nuclear tests contained isotopes of both uranium and plutonium. Sample preparation consisted of fragmenting the glassy material and pressing the fragments into soft indium metal to help reduce sample charging. RIMS measurements were again highly successful, detecting both uranium and plutonium at parts-per-million concentrations in fallout glasses from multiple tests. Rapid detection of the isotopic composition of multiple elements in a single sample with almost no sample preparation lays the foundation for rapid isotopic analyses using RIMS.

The team's research findings demonstrate how RIMS can be adapted to measure different elements in a sample and discriminate against interfering masses. As a result, RIMS holds considerable promise for applications in nuclear forensics. Knight and her colleagues continue to explore ways to improve stability and reproducibility in their measurements. Future studies may include developing techniques to increase the amount of atomic—as opposed to molecular—material in the cloud, suppress molecule ionization, and increase sensitivity to desired elements, improving detection in low-concentration materials.

—Robert Kirvel

Key Words: Chicago-Argonne Resonance Ionization Spectrometer for MicroAnalysis (CHARISMA), fallout debris, nuclear forensics, plutonium isotope, resonance ionization mass spectrometry (RIMS), uranium isotope.

For further information contact Kim Knight (925) 422-9396 (knight29@llnl.gov).

A Simple Way to Better Protect Soldiers against Head Trauma

WHEN Livermore scientists Michael King and William Moss set out to conduct an Army-commissioned study of helmet pad designs, their primary goal was to make a straightforward determination: Could the pads used by the National Football League (NFL) protect against military-relevant impacts better than the current pads in Army combat helmets? Experiments and sophisticated computer simulations showed they would not. But in the process of conducting the study, King and Moss made a more valuable and unexpected finding. The Army helmets could work even better—a lot better, in fact—with only minimal improvement. Adding as little as 3.2 millimeters (one-eighth of an inch) of foam to existing helmet pads could reduce the severity of the impact on the skull by an estimated 24 percent. "It was surprising to us how little it takes to move the injury threshold so dramatically," says King, a mechanical engineer in Livermore's Engineering Directorate.

This finding could significantly improve the military's ability to lessen the severity of traumatic brain injuries (TBIs), a growing concern for soldiers serving in combat zones in Afghanistan and Iraq. Moreover, the understanding gleaned from this analysis of pad behavior could have implications for nonmilitary helmet design, including that of children's helmets and headgear for a variety of sports.

The one-year study was funded by the U.S. Army and the Joint Improvised Explosive Device Defeat Organization. King and Moss, a physicist in the Weapons and Complex Integration Principal Directorate, were selected for the task because of their previously published work on the mechanics of blast-induced brain injuries. (See *S&TR*, March 2010, pp. 14–17.) The goal of this study, however, was to better understand how padding protects against head trauma in impact situations and, in turn, find ways to optimize helmet cushioning for soldiers.

The Physics of Protection

A helmet does its intended job of absorbing impacts when the foam inside its shell compresses upon hitting an object, absorbing the impact and dissipating the energy quickly and efficiently. This process unfolds over a limited distance—the foam thickness—before the foam densifies as its pores collapse. The now-dense foam becomes very resistant to additional compression, and the force on the head increases dramatically, which can result in injury to the head. How much energy the foam can dissipate before it densifies depends on the speed of impact and the makeup of the pad.

At high speeds, the Livermore study confirmed, harder foam performs better, while at lower speeds, softer foams offer better protection. Because no single foam is optimal for all scenarios, compromises must be made, such as combining hard and soft foam into a bilayer pad like the one in the Army's advanced combat helmet (ACH).

Regardless of the foam used, however, the study found that thicker foams always performed better than thinner foams by absorbing more energy before densifying. This finding by itself may seem like common sense. What is less intuitive is that the added value of increasing foam thickness is not the same for all impact speeds. At low speeds of 3 meters (10 feet) per second or less, adding thickness to the standard Army pad results in only marginal benefits. (See the figure on p. 15.) At speeds above 6 meters (20 feet) per second, the impact can be blunted with extra foam, but the benefit to soldiers is questionable. No helmet designed for military use at this time can prevent serious head trauma at those speeds, considering that the energy on impact increases dramatically with the square of the velocity.

But military-relevant speeds, defined by the Department of Defense as 1.5 to 4.6 meters (5 to 15 feet) per second, fall within that optimal range where adding a small amount of foam can make a huge difference in the helmet's ability to act as an effective cushion. "I've earned my lifetime salary many times over with this finding if the Army implements our recommendation," Moss says.

That small amount, in fact, is all that is needed. Increasing foam thickness by more than 6.3 millimeters (one-quarter of an inch) at these speeds would result in quickly diminishing returns. That is why discovering this window of opportunity for Army helmets was so important. "For the military-relevant range, we have this nice scenario where protection earns its keep," says King. (See movie of a compression test at str.llnl.gov/AprMay12/king.html.)

Recommendations and Army Response

The simplest and least expensive solution for improving protection is to use one-size-larger helmets to accommodate pads slightly thicker than those used in the current ACH. Going up one size, however, adds extra weight to the approximately 1.6-kilogram (3.5-pound) helmet. That's bad news for soldiers, for whom every extra ounce is a burden considering the heavy loads of equipment they carry onto the battlefield. Larger helmets could also impair mobility and visibility, arguably offsetting the benefits of additional protection. "To make a concrete decision, one must look at the threat envelope and make a risk-and-reward analysis," King says.

Fortunately, the Army is in the process of redesigning the helmet shell—an ideal opportunity, Moss says, to resize the helmet. Each size could be made only slightly larger, thereby allowing for extra padding with only a minimal increase in weight.

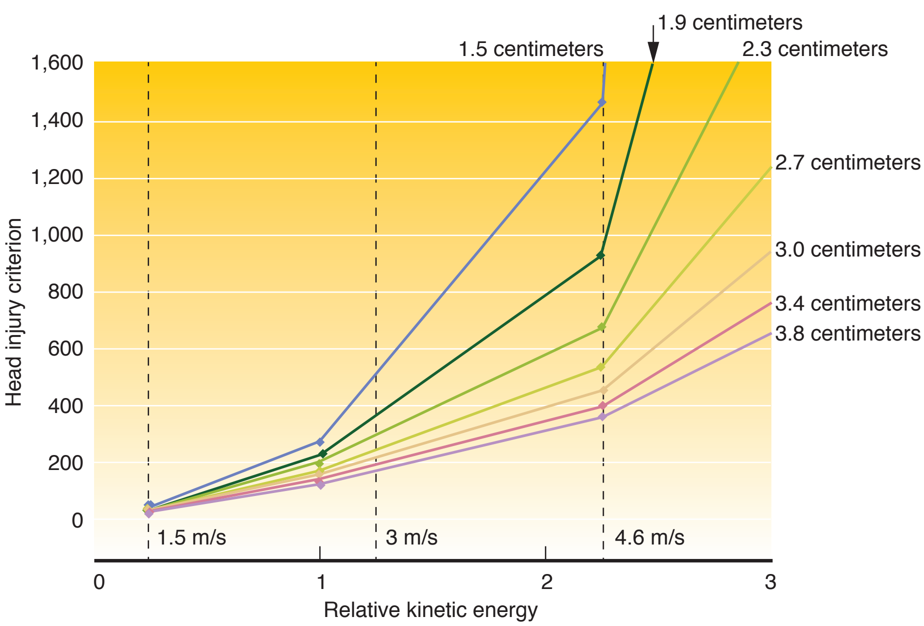
The study recommendation was passed on to the Army, which recently made the first set of implementations. According to Army Colonel R. Todd Dombrowski of the Joint Improvised Explosive Device Defeat Organization, 5 percent of the soldiers were fitted with an extra 3.2 millimeters (one-eighth of an inch) of padding on each side of the temple. The helmets worn by this small group allowed for the extra padding because of a looser fit. For everyone else, the Army decided against immediate implementation because of the extra weight such a change would incur. But with a lighter-weight helmet design now under consideration, the suggested improvement may be implemented on a larger scale soon. "The study gave us valuable information for helmet redesign in the future," Dombrowski says. "Every year, we want to get a better helmet, period."

Livermore's Unique Capabilities

Moss and King's expertise was a key factor when the Army considered Livermore for this study, as was the Laboratory's role as an unbiased evaluator. But Livermore was ultimately chosen for the task because of its advanced computational simulation capabilities, a result of the institution's core weapons design capabilities. "The billions that have been invested in weapons calculations and the resulting tools that were developed here can be applied to these problems," says Moss, who at one time was responsible for containment calculations for nuclear tests. "We're using the same tools now. They're very robust and can address problems of national interest."

The helmet pad simulations were conducted using the PARADYN software for modeling thermomechanical behavior. The software is an advanced version of the DYNA3D code developed at Livermore in the 1970s and later commercialized worldwide as LS-DYNA.

In addition to the advanced technology, Livermore offers what Moss refers to as a systems approach to solving problems by making use of the wide range of capabilities available onsite. For this study, King and Moss collaborated closely with the Mechanics of Materials Group in the Engineering Technologies Division to design the experimental components of the study. "It's not just doing simulations," Moss says. "It's the all-encompassing approach that keeps the work grounded in reality. We have experts in all the required areas of theoretical, computational, and experimental physics as well as in chemistry and engineering. This is a collective process, something not many places can do."



Foam thickness has a dramatic effect on pad response at high speeds. At a military-relevant speed of 4.6 meters per second (m/s), for example, increasing the current pad thickness in Army helmets (represented by the dark green line) from 1.9 centimeters to 2.3 centimeters reduces the head injury criterion from a high value of 917 to a moderate value of 665. The head injury criterion quantifies the severity of impact.

Conducting the Study

The Livermore study compared the performance of four pad systems: Team Wendy, currently used by the Army; Oregon Aero, a former Army pad; and two NFL pads, made by Xenith and Riddell. King and Moss performed experiments to characterize the material properties of each foam and then used the material parameters for computer simulations. The team constructed a geometrically accurate model of an ACH using computer tomography scans of an actual helmet shell.

To validate the applicability of simulations to this kind of study, the scientists first simulated a set of experiments performed by the U.S. Army Aeromedical Research Laboratory, in which an inverted ACH with padding was dropped onto an anvil at impact velocities of 1.5 to 6 meters (5 to 20 feet) per second. Using simulations, King and Moss calculated the response of the entire helmet system and compared their results to the data from the Aeromedical Research Laboratory. The two sets matched closely, confirming the accuracy of the simulations.

For the main part of the study, the scientists examined the response of foam compression using a simplified cylinder simulation. This method was designed to compare the performance of pads with different geometries, because football pads are approximately twice as thick as Army pads and could not fit inside the ACH shell. The compression test also served to isolate material response from other factors, such as pad interactions and the geometry and deformation of the helmet shell.

The compression test consisted of a 5-kilogram cylindrical impactor (the approximate weight of a human head) striking identically shaped and sized circular pads from each manufacturer. The scientists ran hundreds of simulations, adjusting the various parameters (such as speed, foam material, pad thickness, and pad area) in numerous configurations. "Simulations allow us to test for a wide variety of impacts that would be too difficult or too costly to re-create experimentally," King says.

Michael King (left) and William Moss perform a compression test on a helmet pad.

Team Wendy Wins the Day

For comparable thickness and at the specified impact speeds, none of the pads tested outperformed Team Wendy. The stiffer football pads, however, did absorb energy better at high speeds, an important consideration on the football field where the entire body hits the equivalent of a brick wall when players collide. These results suggest that each helmet design needs to be optimized for its intended use and expected type of impact.

King and Moss caution that their findings cannot be used to predict injury rates given the difference between the cylinder test and a full-helmet response, in which the impact is spread over a larger area. The intent of the study was to compare the impact response of different pads, not to give absolute quantitative estimates of injury. Nevertheless, both scientists feel confident that their findings are accurate and fully applicable to real-life scenarios. Since the results were published, Team Wendy performed its own tests and confirmed the finding that thicker pads improve impact mitigation for the helmet and pad system.

Moss notes that if compared with the cost to treat veterans for TBI over the course of their lifetimes, improvements in helmet design that can lower the rate or severity of injury by any amount is money well spent. "It's essentially a no-cost solution," he says about adding extra foam to the helmet. "The return on investment is virtually infinite."

Noncombat Applications

The fact that certain kinds of foams provide optimal protection when used under different impact conditions has huge implications for a wide range of civilian helmet designs—from sports headgear to children's helmets. Says Moss, pointing to a bulky NFL helmet on the table, "If I take this piece of equipment made for a pro and put it on a kid, that may not be a good thing to do. This pad system may not be tuned for the kind of impact mitigation that a child needs compared with an adult. This study also suggests that the various players on a football team should perhaps be wearing different kinds of helmets, depending on the types of impacts to which they are typically subjected."

More research is needed to determine the optimal helmet design for every situation, civilian or military, and Moss hopes to have the opportunity to follow up in the future. In the meantime, the study he and King conducted for the Army has demonstrated the value of applying advanced simulation techniques, borne out of the Laboratory's historic mission, to helmet design and to the very physics of protecting people who may come in harm's way.

—Monica Friedlander

Key Words: Advanced Combat Helmet (ACH), head injury criterion, Joint Improvised Explosive Device Defeat Organization, PARADYN, traumatic brain injury (TBI), U.S. Army.

For further information contact Michael King (925) 422-0627 (king74@llnl.gov) or William Moss (925) 422-7302 (wmoss@llnl.gov).

Shocking Aluminum for Greater Understanding

LIVERMORE researchers have long investigated the properties of materials (especially metals) under extreme pressure by conducting shock compression experiments. These experiments help determine metals' fundamental properties, such as strength, and show how their behavior changes at pressures that occur in extreme environments such as explosive detonations or planetary interiors.

A Livermore team recently conducted experiments with a tabletop laser that afforded an unprecedented look into the physics of shock waves in aluminum. The team observed how aluminum responded to dynamic compression at strain rates of 10^{10} per second—1,000 times higher than previously measured. The study also showed that two important laws governing the behavior of shocked solids extend to higher strain rates than previously applied.

Strain rate is the dynamic (shock) compression applied to a material divided by the time to compress that material. Strain rates can be useful for inferring material strength properties, which are particularly important in stockpile stewardship for ensuring the reliability of the nation's nuclear deterrent. Although these rates have been historically difficult to measure, the Livermore team's laser-based system allows strain rates to be calculated much more easily.

Compression experiments apply either dynamic (gas-gun or laser) or static (diamond anvil cell) techniques to achieve high pressures. Each experimental platform yields slightly different but complementary information. While static compression can produce up to about 3 million times Earth's atmosphere, or 300 gigapascals, dynamic shock compression can produce pressures in the terapascal range.

For the past few years, the Livermore team has been examining various materials under extreme conditions that have included combinations of both static and dynamic pressure. For example, they have used their technique to dynamically compress deuterium that has been precompressed in a diamond anvil cell. By precompressing, they can control the initial density and thereby tune the final state. This method allows them to access a wide range of pressures and densities that may otherwise be difficult or impossible to achieve without precompression.

The Livermore team includes Jonathan Crowhurst, Michael Armstrong, Kim Knight, Joseph Zaug, and Elaine Behymer. Most of the scientists belong to Livermore's Extreme Chemistry Group, part of the Physical and Life Sciences Directorate. The group's collective expertise includes physics and chemistry under extreme conditions of pressure, temperature, and timescale. With funding from the Laboratory Directed Research and Development (LDRD) Program and the Department of Energy's Office of Science, the researchers are currently using lasers to study the time-dependent evolution of shock waves. These shock waves travel at supersonic speeds to produce irreversible "plastic" deformation where the

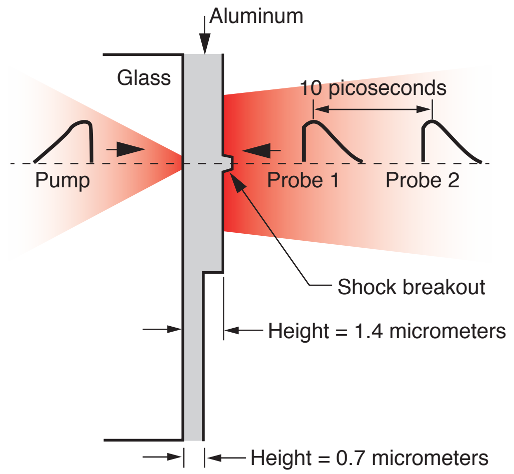
Shock compression experiments help determine metals' fundamental properties and show how their behavior changes at pressures that occur in extreme environments such as in Jupiter and other planetary interiors.

material is permanently altered. (In contrast, weaker shock waves produce elastic deformation, in which a material resumes its original shape and internal structure when a stress is removed.)

Little is understood about the behavior of metals during the initial phase of strong shock compressions. To resolve the details of a shock wave traveling through a solid in the first few 100-trillionths of a second, the team designed a compact, low-cost experimental laser system that simultaneously launches as well as probes shock waves in pure metal films. The system has also been used in experiments involving transparent materials, including deuterium and high explosives such as pentaerythritol teranitrate.

Technique Tracks Evolution

In one set of experiments, the team obtained data on the dynamic strength of aluminum and the evolution of shock waves at the highest strain rates recorded to date—10^{10} per second. The team used the experimental results to test for the first time at ultrahigh strain rates the validity of two fundamental scaling laws.



The experimental configuration consists of a stepped aluminum film deposited in two thicknesses onto a glass slide. The lower aluminum step measures about 0.7 micrometers, and the upper step is about 1.4 micrometers. A 270-picosecond pulse derived from the 100-femtosecond output of a tabletop laser produces and measures the shock waves driven into each step (test of upper step shown) with a time resolution of about 10 picoseconds (1 picosecond equals 10^{-12} seconds, 1 femtosecond equals 10^{-15} seconds). A pair of laser probe pulses measured the acceleration of the free aluminum surface driven by the shock wave as well as the strain rate.

The researchers chose aluminum because it is commonly used in compression experiments. In addition, the team had been studying it in experiments in which aluminum was precompressed in a diamond anvil cell before being shocked by a laser. No strain rate data have existed for aluminum subjected to rates greater than 10^7 per second, and even recent theoretical models were based on data obtained 40 years ago.

The experimental sample consisted of a stepped aluminum film deposited in two thicknesses onto a glass slide. The lower aluminum step measured about 0.7 micrometers, while the upper step measured about 1.4 micrometers.

The scientists used an instrument designed and built by Armstrong to both produce and characterize shock waves on an ultrafast timescale. The instrument is based on a stable commercial laser system that can generate compression waves reproducibly. “This ability is critical to the measurement of shock wave speeds using this technique,” Armstrong says. For the experiments, compression waves were driven into each of two steps in a metal sample and characterized with a time resolution of about 10 picoseconds. The peak of the pump pulse centered at 800-nanometer wavelength, with pulse duration of about 270 picoseconds and rise time of about 12 picoseconds. Pump energies ranged between 100 and 150 microjoules.

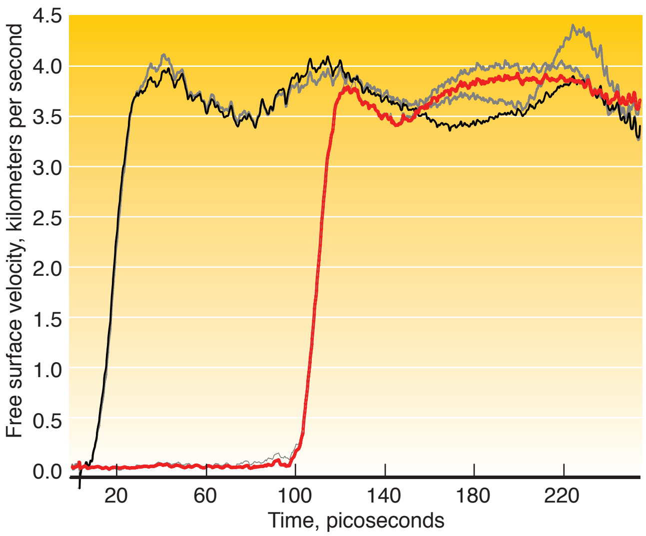
The highly repeatable laser directs nearly identical shots on two different thicknesses. A pair of laser probe pulses measure the acceleration of the free aluminum surface driven by the shock wave as well as the strain rate. Using this technique, researchers measure a Doppler shift in light reflected from a moving surface, which is proportional to the speed of the surface. When a shock wave hits the aluminum free surface, the surface starts to move, which generates an optical phase shift between a pair of probe pulses. This phase shift changes an interference pattern generated by the probe pulses, which is detected through spectral interferometry. The diagnostic thus records the early time history of the compression wave. Because the timing of the pump pulse in relationship to the two probe pulses is very accurate, the results obtained are highly reproducible.

The team measured stresses that reached 43 gigapascals (or 430,000 times Earth’s atmospheric pressure) in some tens of picoseconds, which corresponds to strain rates in excess of 10^{10} per second. The experimental data reveal at lower strain rates a compression wave consisting of an initial elastic zone followed by a plastic zone, and then at higher strain rates only an apparent plastic zone. The shock velocity was obtained by dividing the known thickness of the upper step by the difference in shock-wave arrival times at the two thicknesses.

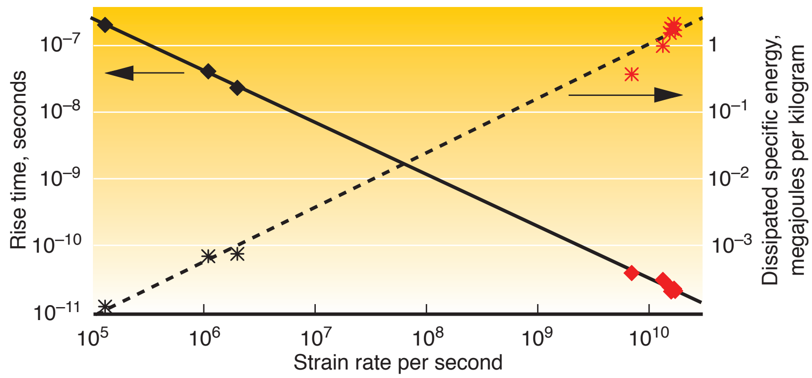
Crowhurst notes that the resolved time and length scales of the experiments are similar in scale to molecular dynamics simulations, which depict the interactions of atoms and molecules in less than a nanosecond (billionth of a second). As a result, the team’s findings are expected to increase the accuracy of current models.

Validating Two Laws

In achieving their experimental goals of examining the shock properties of aluminum at high strain rates and extremely short timescales, the scientists also confirmed the validity of two fundamental scaling laws that had been previously demonstrated at strain rates 1,000 times lower. The historic lack of sufficient time resolution had precluded testing the laws at high strain rates. “The details of how solid materials rapidly deform on submicrometer length scales have been the subject of speculation for decades,” Armstrong says. “For the first time, our experiments can test



This graph shows a rapid rise in the strain rate resulting from strong laser pulses directed at an aluminum film measuring 0.7 micrometers thick and an aluminum film measuring 1.4 micrometers thick. Black line is a three-shot average at the 0.7-micrometer thickness, and red line is a three-shot average at the 1.4-micrometer thickness. Gray lines are examples of single shocks.



Results confirmed the validity of two fundamental scaling laws previously demonstrated at much lower strain rates. The first law states that the energy dissipated by a shock wave (stars), multiplied by the time over which it takes place (diamonds), is a constant. The second law states that the strain rate is proportional to the fourth power of the peak stress for steady-state shock waves. Combining the ultrahigh strain-rate measurements with results from gas-gun experiments at lower strain rates indicated that both laws hold over at least five orders of magnitude (10^5–10^{10} per second) of strain rate. Red denotes current data, and black denotes previous data.

fundamental scaling laws on time and length scales where they may start to break down at strain rates that are orders of magnitude greater than previously examined."

The first scaling law, the invariance of dissipative action, states that the energy dissipated by a shock wave multiplied by the time over which it occurs, is a constant. The second, the fourth power law, states that the strain rate is proportional to the fourth power of the peak stress (that is, the peak stress multiplied by itself four times) for steady-state shock waves. The team tested the laws by combining their ultrahigh strain-rate measurements with results from lower-strain-rate gas-gun experiments on thicker samples of aluminum. The team concluded that both the fourth-power scaling and the invariance of the dissipative action are maintained at ultrahigh strain rates of up to 10^{10} per second, and that both relationships hold for at least five orders of magnitude (10^5–10^{10} per second).

"Gas-gun experiments remain the 'gold standard' for studying shocked materials," says Armstrong. However, experimenters have yet to obtain the same time resolution with gas guns as those using lasers. "Our experiments fill a niche; they complement other efforts."

Crowhurst notes that these small-scale compression experiments are relatively inexpensive, and the shots are easily reproducible. In fact, because such little material is required (the shocked regions on the aluminum surface can only be clearly seen under a microscope), hundreds of shots can be done on the same sample. As a result, the team is exploring the design of an automated process for conducting hundreds of experiments per hour.

Currently, the team is performing laser-shocked compression experiments on other metals such as iron and vanadium. Experiments on aluminum are also being conducted with the goal of achieving strain rates of up to 10^{12} per second. Meanwhile, Armstrong is working on an LDRD-funded project to study shocked deuterium, an isotope of hydrogen. Other shock-compression experiments are being conducted as part of the Department of Defense's Joint Munitions Command. Because these experiments involve extremely small amounts of high explosives, they do not present the potential hazards of larger-scale experiments.

Scientists from other national laboratories have visited the Laboratory to observe the experimental setup and study the team's data-analysis procedures. "Our work builds on previous research at other national labs and universities," says Crowhurst. "We believe that the number of groups who have adopted the ultrafast approach to study shock waves will continue to grow. The technique has a bright future." Scientists can expect even more insight into the ultrafast aspects of shock compression and, in turn, a deeper understanding of materials under pressure.

—Arnie Heller

Key Words: aluminum, diamond anvil cell, Joint Munitions Command, shock compression, strain rate.

For further information contact Jonathan Crowhurst (925) 422-1945 (crowhurst1@llnl.gov).

In this section, we list recent patents issued to and 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.

Awards

John Edwards, associate program director for Inertial Confinement Fusion (ICF) and High Energy Density (HED) Science at Lawrence Livermore, was selected as a 2011 **American Physical Society** (APS) **fellow**. Edwards was cited in the plasma physics category for fundamental contributions to hydrodynamics in HED physics and for his leadership in the National Ignition Campaign (NIC) on the Laboratory's National Ignition Facility.

Edwards joined Livermore in 1998 and, over the course of his first five years, played a leading role in developing much of the foundation for the HED laser program in place today. He has since turned his focus almost entirely to ICF, leading groups in target physics, serving as the ignition team leader, and in his latest role, defining the direction of NIC experiments.

The APS selection process is exhaustive, and election to the fellowship is limited to no more than one-half of one percent of the society's membership for a given year. In 2011, APS designated nearly 250 fellows.

Christopher Barty, chief technology officer for the Laboratory's National Ignition Facility and Photon Science Principal Directorate, was selected as a **fellow** by the international optics and photonics society **SPIE**. He is recognized for his achievements in a leadership role in the advancement and development of new laser technology.

Barty has published more than 150 manuscripts and presented more than 200 invited talks, spanning topics in lasers, optics, materials science, medicine, chemistry, engineering, and physics. During his career, he has founded both the Biennial International Meeting on Ultrafast Optics and the International Conference on Ultrahigh Intensity Lasers. Currently, he serves as cochair of the International Committee on Ultrahigh Intensity Lasers.

SPIE includes more than 180,000 members from more than 170 countries to advance an interdisciplinary approach to the science and application of light. Fellows are members of distinction who have been selected based on their significant scientific and technical contributions in the fields of optics, photonics, and imaging.

Erik Swanberg, a graduate student working in the Laboratory's Experimental Nuclear Physics Group, received the **Margaret Burbidge Award** from the **American Physical Society** (APS) **California Section** at the organization's fall 2011 meeting. Swanberg, who will earn a Ph.D. in nuclear engineering from the University of California at Berkeley in May, has been conducting research at Livermore for three years. He was recognized by APS for "Searching for the Decay and Half Life of the 7.6 eV Excited State in the Thorium-229 Nucleus," which placed first in the graduate student awards Best Experimental Research category.

The study focuses on thorium-229, a radioactive isotope with the lowest known nuclear excited state. The state has been known to exist for 35 years, but its decay to the ground state has never been directly observed. Because it has an extremely low energy for a nuclear state, a unique set of applications are possible with it. Swanberg's initial work was funded by Livermore's Laboratory Directed Research and Development Program.

Don Roberts of the Weapons and Complex Integration Principal Directorate received the **Employee of the Quarter Award** by the **National Nuclear Security Administration's Defense Programs**. Roberts was recognized for leading a multidisciplinary, international team in the first-ever insensitive high-explosive velocimetry pin hydrotest in the Contained Firing Facility at Site 300.

The hydrodynamics experiment studied what happens to metal adjacent to a high-explosive detonation. The multimillion dollar test, conducted last October, was the culmination of three years of work by a team that included researchers from Livermore, Nevada National Security Site, Los Alamos National Laboratory, and the United Kingdom's Atomic Weapons Establishment.

The **Laboratory's Counterintelligence Program** (SAFE) garnered the **Department of Energy Office of Intelligence and Counterintelligence Director's Award for Exceptional Service for 2011**. Each year, only one DOE field intelligence element or counterintelligence field office receives this award for exceptional service. The Counterintelligence Program was specifically recognized for its urgency, dedication, and exemplary skills in imposing risk and consequences on those who would threaten the Department of Energy and for providing value for the American taxpayer's dollar.

Laboratory geophysicist **Arthur Rodgers** of the Physical and Life Sciences Directorate received an award from the **Defense Threat Reduction Agency** (DTRA) for his work in nuclear forensics. Rodgers was named the **top contributor of the quarter** for the first quarter of fiscal year 2012 for a forensic analysis project. The DTRA program seeks to develop methods for improved forensic analysis of signals, such as sound and light, from nuclear explosions.

Abstract

Launching Traffic Cameras into Space

Space waste, the collection of now-useless, human-created objects in orbit around Earth, consists of everything from spent rocket stages and defunct satellites to collision fragments and lost astronaut tools. In the last 20 to 30 years, a handful of collisions have occurred between tracked objects, such as satellites and larger debris. However, as regions of space become more crowded, the threat of collision is expected to rise. Later in 2012, nanosatellites equipped with Livermore optical imaging devices will be launched as rocket payload. Data collected from space will demonstrate the main elements of the Space-Based Telescopes for Actionable Refinement of Ephemeris concept, developed by a Laboratory team of physicists and engineers with support from a multi-institution joint venture. The researchers intend to improve the accuracy of collision warnings by a factor of 100, thereby reducing warning rates to once per the 5- to 10-year lifetime of a satellite.

Contact: Vincent Riot (925) 422-9798 (riot1@llnl.gov).

U.S. Government Printing Office: 2012/570-075-50013

Bringing Earth's Climate into Focus

By comparing past climate records with results from computer simulations, Livermore scientists can better understand why Earth's climate has changed and how it might change in the future.

Also in June

• Computer scientists at Livermore have developed innovative methods to understand the vulnerability of codes to small errors and to detect and handle these errors before they cause unrecoverable failures.

• Recent improvements to the tiny targets used for experiments at the National Ignition Facility are an important mark of progress toward ignition.

• A new generation of implantable prosthetics offers hope to patients with debilitating conditions caused by injury or neurological disease.

Coming Next Issue

Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

PRSRT STD
U.S. POSTAGE
PAID
San Bernardino, CA
PERMIT NO. 3330

Printed on recycled paper.